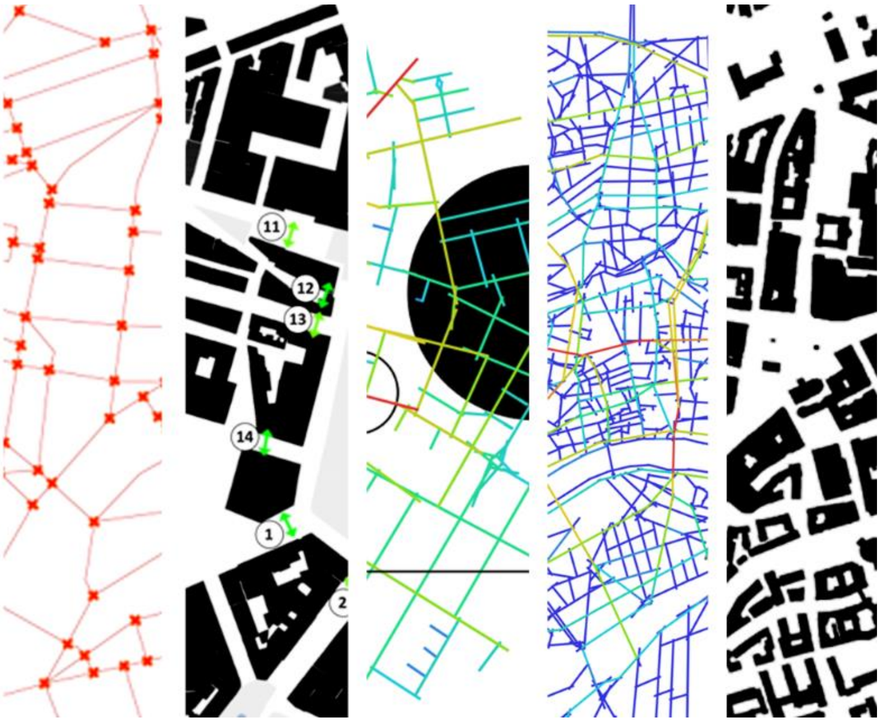
Lakshya Pandit

Measuring Multimodal Accessibility through Urban Spatial Configurations

Case Studies of three cities in the Rhein-Main Agglomeration



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Measuring Multimodal Accessibility through Urban Spatial Configurations

Case Studies of three cities in the Rhein-Main Agglomeration

at the Department of Architecture
of the Technischen Universität Darmstadt

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Doctoral thesis
by Lakshya Pandit

First assessor:
Prof. Dr.-Ing. Martin Knöll
Chair of Urban Design and Planning, Department of Architecture, TU Darmstadt

Second assessor:
Prof. Dr.-Ing. Martin Lanzendorf
Institute of Human Geography, Department of Geosciences/Geography, Goethe-Universität Frankfurt a. M.

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Finally, I would like to thank my family for their unconditional love, support and understanding.

ABSTRACT

This research investigates the relationship between multimodal accessibility and the spatial configuration of urban areas. The built environment of a city and its urban areas, including its streets, building layout, and open spaces, has a significant influence on its ability to provide an accessible environment for people's mobility. By studying the spatial characteristics of an urban area (such as city centres, transit areas and residential neighbourhoods), we can better understand how the built environment impacts accessibility and overall mobility in cities. For this purpose, the study is based within the urban agglomeration of Rhein-Main region in Germany, where cities have a polycentral system and the common objective of planning for an environment-friendly mobility region is prioritized. The research aims to identify parameters which connect and integrate different aspects of accessibility, through different modes, using a topological approach to bridge the gap between theory and practice in urban studies. The parameters cater to the principles of inclusive urban design for streets and variables which influence travel demand and trip generation. The parametric spatial assessment showcases how different urban areas performed based on the selected five aspects of accessibility: connectivity, intelligibility, closeness, directness and spatial freedom. Analysing the street network through the identified parameters corresponding to the aspects (including connectivity of street network, access to public transport, Space Syntax attributes assessing access to direct routes and ease of navigation, and ease of movement) narrows down the potential area for improvement in the cities. A pilot study was conducted in Darmstadt, a city in the agglomeration, for the initial spatial assessment. After the pilot study, urban areas in the cities of Frankfurt am Main and Offenbach am Main were selected for further study and inter-city comparison. The results reveal that different urban areas other than the city centres can have a better access to multimodal services, and that certain urban areas in a small city can outperform those in a big city on different aspects of accessibility. The objective characteristics of the urban areas from the spatial assessment were further compared with the subjective evaluation (via public survey) of the people (n=248) living in the agglomeration, which helps in understanding the mobility culture. The research outcomes confirm the difference between the objective and subjective perspectives, via ranking of urban areas based on their multimodal accessibility characteristics. This was more prevalent in urban areas showing low accessibility characteristics objectively. For instance, the city centre in Darmstadt and the transit areas in Frankfurt and Darmstadt remained on top of the urban area ranking hierarchy, both objectively and subjectively. In contrast, the urban areas showing low accessibility characteristics objectively i.e. the residential area in Offenbach am Main and the city centres in Frankfurt am Main and Offenbach am Main, varied in their subjective ranking. Overall, the residential areas in the three cities ranked lower subjectively.

In addition, the dissertation addresses how collaborative projects with city planning authorities can effectively disseminate the results of urban studies. For instance, the road-closure experiment on Frankfurt's Mainkai riverfront was used as an opportunity to examine the potential of Mainkai street for cycling (via spatial analysis), which supported the implementation of a new dedicated bicycle

pathway. The outcomes of the spatial analysis have been used in the dissertation to address certain future urban development plans of the cities and its impact on the accessibility characteristics (e.g. implementation of new streets and its impact on intelligibility, identification of movement restriction in future residential densification projects and more). Furthermore, the study identifies and clusters urban areas based on similar multimodal accessibility characteristics. This approach helps in identifying common development needs and apply targeted measures to improve a large number of urban areas in future research. The dissertation explores and lays a ground work to understand multimodal accessibility by measuring it through spatial analysis, and contributes to the domain of accessibility planning, i.e. planning for people and places.

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SECTION 1

INTRODUCTION AND LITERATURE REVIEW

CHAPTER 1

INTRODUCTION

1.1 Research Framework

1.1.1 Introduction

Mobility is one of the keystones for urbanization, and the associated infrastructure invariably shapes the urban form (where the spatial configuration is defined by streets, transport systems, spaces, and buildings) of the cities. It is predicted that by 2050, more than 6 billion people, which account to around 70 percent of the global population, will live in urban areas (UNECE 2020). The emerging urban convolution has led to a paradigm shift in mobility perception towards more diverse, multimodal transportation systems. In an urban environment, majority of trips include a sequence of travel modes in order to reach a destination. These modal integrations may differ in their functional capacities, in continuum, in different urban environments. A multimodal transportation system allows people to use a variety of transportation modes, including walking, biking, and other mobility devices (including wheelchairs), as well as transit where possible. Such a system reduces dependence on automobiles and encourages more active forms of personal transportation, improving health outcomes, and increasing the mobility of those who are unable or unwilling to drive (DIAUD & CBM 2016). This encourages many cities to have an accessible approach where the potential of the existing urban form can be utilized efficiently to provide a multimodal mobile environment through different origin and destination areas. Access to the urban environment initiates equity and inclusion, with accessibility being a quality of system which allows, includes and integrates diverse human cognitive and motoric capabilities and users within the system. Despite the importance of accessibility, the diverse perspectives followed by limited empirical knowledge and inability to put accessibility efficiently in the centre of urban development leads to a major disconnect between the ongoing research and present practise. Clustering the understanding of accessibility through different potential modes of movement

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UNECE (2020), A Handbook on Sustainable Urban Mobility and Spatial Planning Promoting Active Mobility, United Nations, Geneva, pp. 5-7.
DIAUD & CBM (2016), The Inclusion Imperative: Towards Disability-Inclusive and Accessible Urban Development - Key Recommendations for an Inclusive Urban Agenda Disability Inclusive and Accessible Urban Development Network, pp. 6-37.

and its corresponding measurement would assist in prioritizing different urban areas by identifying gaps between its existing and potential level of accessibility.

Assessing the multimodal accessibility within the travel chain (i.e. involving elements that make up a journey from the starting point to destination, including pedestrian access, modes of transport and transit points) would lead towards identifying, understanding and evaluating various urban factors which affect the mobility through different modes. This would consequently lead towards the prognosis stage of enhancing the present degree of accessibility in a city or a group of cities. In regards to a group of integrated cities, with their association evolving further from a competitive environment towards a competitive and cooperative environment, the urban phenomenon of agglomeration leads towards an approach where urban development benefits from the common objectives (e.g. planning for an environment-friendly mobility region). An urban agglomeration is a highly developed spatial form of integrated cities (Fang 2017). These integrated urban clusters, create an impact and even determine regional development. The urban agglomerations evolve under various driving factors, which include economic globalization, industrialization, science and technology development, with mobility and transport being one of the contributing factors. With the onset of urban agglomerations, measures have to be taken into consideration in order to provide and maintain accessibility, particularly in areas where people tend to commute regularly. While intermodal public transport is considered to be one of the major efficient modes of transport, there is a need to identify the accessibility parameter of these modal services through diverse parts of an urban agglomeration, focusing on multimodal mobility behaviour to address different modes individually and in equity.

1.1.2 Problem definition

A paradigm shift (a fundamental change in how problems are defined and solutions evaluated) is occurring in transportation planning (Litman 2014). Conventional mobility-based planning placed automobiles at the nucleus of the transport system. The new accessibility-based paradigm places people at the centre, where the public perspective towards urban development focusing on an alternative approach and less car dependency is taking shape (BMUB and UBA 2017). Accessibility measures have gained importance in recent years as a tool which involves various stakeholders in their respective decision-making process with focus on urban and transport planning. They have enabled our ability to conduct comparative studies between diverse mobility systems in different cities and or in a particular city through a defined timeline and observation limits. Once the modal accessibility is quantified, there are potential uses of this measure. It can lead to assessment of present state of accessibility and also identify the improvements to be prioritized in different urban areas within a city. It can be utilized in tracking the changes in the accessibility caused by deviations in the mode of travel, users utilizing the mode etc. People with disabilities (PwDs), elderly, and other users with reduced mobility require and utilize the urban space as other able-bodied humans do. Certain priorities in the existing assessment measures are required which help in identifying urban areas, which lack an acceptable level of accessibility towards a particular user-group, or do not meet their expected (or potential) accessibility attributes.

Fang, C. and Yu, D. (2017), Urban agglomeration: An evolving concept of an emerging phenomenon, Landscape and Urban Planning, Volume 162, ISSN 0169-2046, pp. 126-136.
Litman, T. (2014). Transportation and the Quality of Life. In: Michalos, A.C. (eds) Encyclopedia of Quality of Life and Well-Being Research, Springer, Dordrecht. DOI: https://doi.org/10.1007/978-94-007-0753-5_3053
BMUB and UBA (2017), Umweltbewusstsein in Deutschland 2016 Ergebnisse einer repräsentativen Bevölkerungsum-frage, Online Edition, Germany. Retrieved from https://www.umweltbundesamt.de

Global initiatives have focused towards ensuring accessibility and providing an inclusive environment. A multimodal transportation system is key to ensure that elements of the travel chain are consistently accessible and are easy to plan and follow (DIAUD & CBM 2016). A method of assessment measures how accessible a particular travel chain in an urban agglomeration is. There is a need to identify gaps in the structure, which is gained through the review of the existing accessibility tools with the assessment of best practises of accessibility and mobility measures. This is followed by the addition of new perspectives and attributes which haven't been addressed before exclusively through an intra-city or an inter-city perspective that can be utilized within urban agglomeration. The importance, understanding and measurement challenges of accessibility creates a need to identify certain aspects or attributes which can be utilized on a macro-scale for a long-term urban planning timeline, but also address certain micro-scale perspectives on a human eye-level. Measuring accessibility, within the perspective of the ease of reaching or accessing a destination, is conceptually and empirically challenging. For instance, Vale et al. (2016) in their study show how different methodologies measuring accessibility calculate a similar aspect, but in a different way. The issue is not what to measure, but how to measure. While there is literature to measure urban accessibility (Handy & Niemeier 1997; Handy & Clifton 2001; Coppola & Papa 2012), majority of them focus on accessibility through different approaches (often focusing on different opportunities, travel distance and (or) time) which can be a compromise between its simplicity and ease of understanding the measure. Many problems can be explained through data limitations. There is a gap between data required to measure different approaches and the data which is available (Handy & Clifton 2001; Vale et al. 2016), which demands an alternative approach to measure accessibility (further adding to the challenges of measuring accessibility). The availability of data influences and limits the choice of measurability to be incorporated in the initial stages. Due to its poor understanding and measurement, it also acts as a barrier to sound urban development policies. This leads to different stakeholders, approaching accessibility through different perspectives, which at times loses its overall purpose of identifying and improving different urban areas based on their accessibility characteristics. With accessibility linking land use, housing and transportation, a greater focus in urban research on accessibility will avoid disintegration of urban knowledge (Duranton and Guerra 2016). The approach to analyse different urban areas and identify multimodal accessibility attributes is required to be done in a manner which not only creates less gap between required data for measurement and data availability, but also addresses different modal scales for an urban development objectively and subjectively, through intra-city and inter-city perspectives for an urban agglomeration.

1.1.3 Conceptual framework and research focus

The research focuses on delivering a conceptual approach to bring measurability into accessibility by identifying and integrating different benchmarking tools, along with the introduction of different perspectives and improvements to the existing set of measures. In order to address different aspects

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Vale, D. S., Saraiva, M., and Pereira, M. (2016), Active accessibility: A review of operational measures of walking and cycling accessibility, Journal of Transport and Land Use, 9(1), pp. 209–235.

Handy, S. L., & Niemeier, D. A. (1997), Measuring Accessibility: An Exploration of Issues and Alternatives, Environment and Planning A: Economy and Space, 29(7), 1175–1194. DOI: https://doi.org/10.1068/a291175

Handy, S.L., & Clifton, K. (2001), Evaluating neighborhood accessibility: possibilities and practicalities, Journal of transportation and statistics, 4 (3), pp. 67-78.

Coppola, P. & Papa, E. (2012), Accessibility Planning Tools for Sustainable and Integrated Land Use/Transport (LUT) Development: An Application to Rome, Procedia - Social and Behavioral Sciences, Volume 87, pp. 133-146. DOI: https://doi.org/10.1016/j.sbspro.2013.10.599.

Duranton, G. and Guerra, E. (2016), Developing a common narrative on urban accessibility: An urban planning perspective, Moving to Access, Brookings, Washington D.C., pp. 1-41.

of accessibility within the urban planning domain, developing a multimodal approach of measurability influenced by the configuration of spaces is important. The parameters of accessibility and mobility have been seen to be influenced by it (i.e. design and layout of buildings and street infrastructure) in an urban environment (Evans 2009). This identifies the need to have an approach which addresses certain parameters for measuring accessibility through a data-driven and (or) data-informed route involving different urban viewpoints via intra-city and inter-city perspectives. Involving cities within an urban agglomeration narrows down the focus towards the cluster of urban areas where the urban development benefits from the common objectives. The improvement within the accessibility planning for a multimodal behaviour (i.e. utilizing multiple modes of mobility over a course of time) would cater to the urban development timeline planned for the future of the cities and its urban areas.

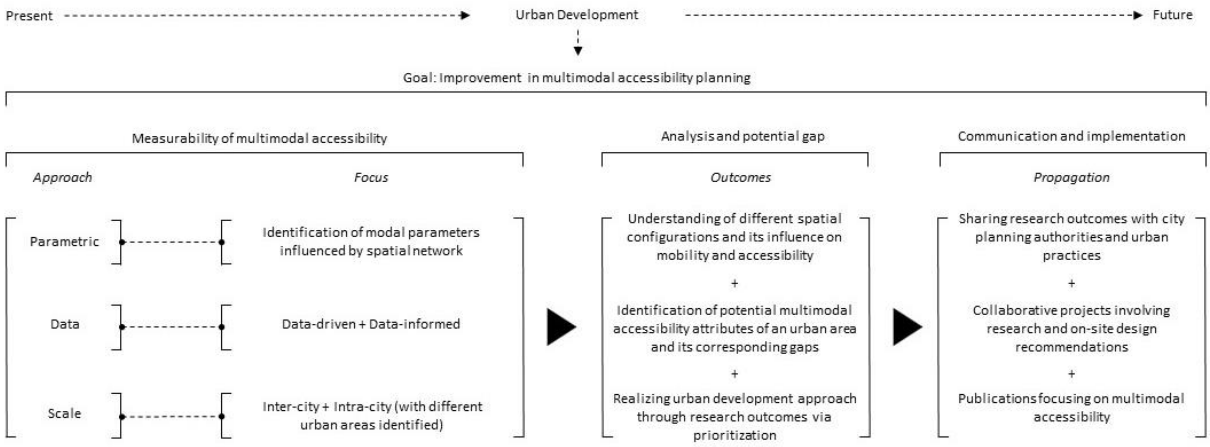

Figure 1: Conceptual framework of the research

Prioritizing urban agglomeration for the research study, with a group of cities emphasizing on the strategic vision towards obtaining a common objective of enhanced mobility, helps in initiating a comparative study which investigates the accessibility phenomenon whilst detecting similarities and (or) differences. In European context, Frankfurt Rhein-Main metropolitan area is one of the major regions in Germany, where the strategic vision (of the 2030 vision) of the urban agglomeration involves planning for an environment-friendly mobility region as one of its main objectives (Regional Authority FrankfurtRheinMain 2020). The Frankfurt Rhein-Main metropolitan region includes independent cities of Frankfurt am Main, Offenbach am Main, Wiesbaden, Mainz, Worms, Darmstadt, and Aschaffenburg, along with other regional districts. The cities lend the region its metropolitan character, a polycentral city system held together with a strong network system, where Frankfurt am Main acts as one of the strong nuclei of commuter flows in the region.

1.2 Research aims and scope

The research primarily aims on developing a reliable and effective methodology to assess accessibility of multimodal system in urban agglomerations. The research design and the outcomes will enable a systematic approach to enhance mobility of a city and its districts, by aiming to:

Evans, G. (2009), Accessibility, Urban Design, and the Whole Journey Environment, Built Environment, 35 (3), pp. 366-385. DOI: https://doi.org/10.2148/benv.35.3.366
Regional Authority FrankfurtRheinMain (2020), FrankfurtRheinMain on the move A Sustainable Urban Mobility Plan (SUMP) for the Region, Frankfurt am Main. Retrieved from www.region-frankfurt.de

- Contribute towards better understanding of accessibility in an urban mobility context, including identification of parameters influenced by different spatial configurations within a city or a group of cities forming an urban agglomeration.

- Understand the gap between the potential accessibility characteristic of an urban area and its present utilization of the network of spaces, within an urban agglomeration comprising of cities of different sizes. This includes identification and understanding of different pre-defined urban development strategies (or approaches) planned for a city and its identified districts.

- Address subjective evaluation via public perception into the overall assessment of urban areas, to include a data-informed approach along with data-driven approach, which contributes towards better understanding of a mobility culture.

Following the research aims, the overall design narrows down its scope of study to essential landmarks within a travel chain, which influences the commuter flow in the urban agglomeration with selection of urban areas which are distinct or prioritized within a city's urban development plan for the future. The urban areas included within the study of a city would be limited to the observation radius corresponding to the identified parameters. These urban areas include city centres and other landmarks areas. The scope of the study restricts to the identified clusters of urban areas including city centres. These include central business districts, which is an area likely to be more concentrated with public transport and pedestrian traffic. Normally, it is the urban area's chief focus of transportation and tends to be more accessible as compared to the other parts of the city (Murphy 2017). Studying the area surrounding city centres would help in understanding different aspects of accessibility and setting benchmarks for the same (unless there are other urban areas having better multimodal accessibility characteristic). Following the city centres, there are other areas which are important for a travel chain within a configuration of urban spaces, involving origin and destination of a travel route. Depending upon the trip generations and transits towards the city centre, the characteristic urban areas may include main transit stations, residential areas, educational spaces, recreational areas, or other urban landmarks. The selected urban areas would include at least one major transportation hub (e.g. railway stations, if not within the city centre), responsible for transport to the proximal cities, which play an important role in maintaining mobility within the urban agglomeration. While the research tries to have a holistic approach to put measurability into accessibility through different modes of mobility, it does not consider all possible variables of modes of transport. The multimodal accessibility within the research mainly focuses upon the mobility sequence for people, within the aspect of short distance mobility, utilizing pedestrian pathways (including users with reduced mobility but does not specifically focus on the entire spectrum of Persons with disabilities), public transport (bus/trams/trains), and mobility modes which may be region specific. The research study does not include modes involving air or water transport.

The travel chain and modes of transport have been evolving over the years, and there can be seen a shift in the choice of mobility by the commuters within the urban agglomerations including Frankfurt Rhein-Main region. The shift to more 'active' means of mobility, was observed with walking, bicycle usage and public transport gaining more priority. From 2002 to 2017, there was an overall increase in pedestrian walks, bicycle utility and public transportation (Regional Authority FrankfurtRheinMain

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Murphy, R. E. (2017), The Central Business District: A study in urban geography, Routledge, New York, pp 9-21. DOI: https://doi.org/10.4324/9781315131153

Regional Authority FrankfurtRheinMain (2018), Regionales Monitoring 2018 Daten und Fakten - Metropolregion FrankfurtRheinMain, Frankfurt am Main, Retrieved from www.region-frankfurt.de

2018). In order to maintain and improve the present quality of life within the mobile environment of the urban agglomeration, it should be a priority to reduce the burden of motorized traffic, with other available options of mobility choices, to satisfy the economic and social needs. With the onset of population growth and increase in mobility demands, access and priority of mobility modes in urban areas have to be taken into consideration. The research study assesses and compares identified accessibility parameters through different identified urban areas within cities of different sizes forming an urban agglomeration.

1.3 Research Questions and Hypothesis

The research framework presents an opportunity to initiate the approach of addressing multimodal accessibility encouraging urban development by answering the following research questions and their corresponding hypothesis:

- What are the various domains of accessibility factors supporting multimodal travel behaviour in urban agglomerations? Are there certain measures which correspond to urban design?

  It is difficult to measure accessibility and majority of the existing approaches have led to a compromise resulting in a huge gap between the understanding and the simplicity of the accessibility measure. This makes it crucial to identify aspects (or attributes) of multimodal accessibility. Many accessibility measures have been previously categorized into different typologies which include Cumulative opportunities measure (addressing the frequency of opportunities that can be reached within a particular distance or time), and Gravity-based measure (where the opportunities are weighted based on distance, time or cost) (Handy & Clifton (2001) and Duranton and Guerra (2016)). This leads to the identification of new measures and methodologies that can influence the location of certain multimodal opportunities (e.g. cycling lanes, transit stops etc.) catering to urban design. These measures would also help in better understanding of an area's accessibility characteristic for different urban stakeholders.

- How does the spatial configuration of certain urban areas support better degree of accessibility as compared to others with respect to inter-city and intra-city perspective? To what extent?

  While a city's or an urban agglomeration's modal split data helps in determining 'how' people move in regards to their prioritized mode of mobility, analysing the spatial configuration of urban areas which influence different parameters of mobility and accessibility (Evans 2019) would help in addressing 'why' people move or utilize an urban area close to or away from its potential accessibility characteristic. Different urban areas have at times shown different accessibility characteristics. For instance, city centres tend to be more accessible (Murphy 2017) than other land uses (including residential, industrial, transport and open areas) with respect to walking and cycling (Wang et.al. 2019). The layout of routes also influences how different user-groups move, as cyclists prefer and dominate direct routes (CROW 2007,

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Wang, Z., Han, Q., & Vries, B. (2019), Land Use/Land Cover and Accessibility: Implications of the Correlations for Land Use and Transport Planning, Applied Spatial Analysis and Planning, pp. 923-940.
CROW (2007), Design Manual for Bicycle Traffic, Utrecht, Netherlands.

Goeverden et al. 2015) in an urban network than indirect routes, which in turn may encourage higher cycling commuter flow (Aultman-Hall et al. 1997). In regards to different city sizes and urban areas, access to public transport has shown to be more concentrated around central nodes of the urban cores (Bok & Kwon 2016), with access levels in larger cities higher than comparatively smaller sized cities (Poelman and Dijkstra 2015). These studies encourage to further check whether a city size influences a particular accessibility attribute or whether an urban area, say city centre, has a higher degree of accessibility in comparison to other urban areas in the city.

- How can the identified parameters for assessing accessibility, be utilized and prioritized, in order to improve the present degree of accessibility supporting multimodal travel? How does the subjective priority via public perception differ from the objective priority of accessibility parameters?

  Promoting accessibility through different stages of urbanization is crucial and a should be a key component in urban policy, design, planning and development (United Nations 2016). This involves inclusion of public opinion, considering the subjective characteristic of a space, which is crucial for policy implications for improving an urban area (Cummins 2000; Liao 2009). The subjective perception of an urban area has previously shown to differ from its objective characteristics in comparative studies (von Wirth et al. 2015; McCrea et al. 2006). This can lead to a different set of hierarchy of urban areas based on their corresponding objective multimodal accessibility attributes, involving data-informed approach via public perception. Utilizing identified parameters for on-site improvement of urban areas also generates a conundrum of whether there are ways to mediate between an urban area's accessibility potential and certain implementations by the urban planning authorities. While different approaches towards understanding accessibility and incorporating it within the urban development plans may vary, a certain focus and prioritization can support urban planning in identifying different urban clusters requiring improvement or meeting its potential accessibility characteristic.

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Goeverden, K. V., Nielsen, T. S., Harder, H., and Nes, R. V. (2015), Interventions in Bicycle Infrastructure, Lessons from Dutch and Danish Cases, Transportation Research Procedia, 10, pp. 403-412. DOI: https://doi.org/10.1016/j.trpro.2015.09.090
Bok, J. & Kwon, Y. (2016), *Comparable Measures of Accessibility to Public Transport Using the General Transit Feed Specification*, Sustainability, 8, 224, pp 1-13.
Aultman-Hall, L., Hall, F. L., and Baetz, B. B. (1997), Analysis of Bicycle Commuter Routes Using Geographic Information Systems: Implications for Bicycle Planning, Transportation Research Record, 1578(1):102-110. DOI:10.3141/1578-13
Poelman, H. & Dijkstra, L. (2015), Measuring access to public transport in European cities, Regional and Urban Policy, European Commission, pp. 2-20.
United Nations (2016), Good practices of accessible urban development Making urban environments inclusive and fully accessible to ALL, Department of Economic and Social Affairs, pp. 6-14.
Cummins, R. A. (2000), Objective and subjective quality of life: An interactive model. Social Indicators Research, 52 (1), pp. 55-72. DOI: 10.1023/a:10070278225
Liao, P. S. (2009). Parallels between objective indicators and subjective perceptions of quality of life: A study of metropolitan and county areas in Taiwan, Social Indicators Research, 91(1), pp. 99-114. DOI:10.1007/sl 1205-008-9327-3
von Wirth, T., Grêt-Regamey, A., & Stauffacher, M. (2015), Mediating Effects Between Objective and Subjective Indicators of Urban Quality of Life: Testing Specific Models for Safety and Access, Social Indicators Research, 122(1), pp. 189–210.
McCrea, R., Shyy, T.-K., & Stimson, R. (2006). What is the strength of the link between objective and subjective indicators of urban quality of life?, Applied Research in Quality of Life, 1 (1), pp. 79-96. DOI: 10.1007/sl 1482-006-9002-2.

1.4 Research Methodology

The research is divided into three phases in continuum, applying research methods with respect to the desired output in each phase. The initial desk-based approach involves literature study which includes understanding of accessibility and mobility in an urban scenario along with the identification and study of various assessment measures for a large city-wide scale and small-scale acupuncture studies, through understanding from best practices. The output of the study would reflect towards varied ways of assessing and measuring accessibility through different criteria and modes of mobility. It would also include the study of selected urban areas and their city's urban development plans for the future involving mobility and accessibility as a subject.

The intermediate phase involves utilizing and improving assessing tools post the literature review. During this phase, the selected urban areas would be initially assessed through the reconnaissance studies, involving on-site visits which helps in better understanding of the area and structuring future data-collection procedures. These urban areas would be mainly selected based on the diverse environment they relate to, including retail high street spaces, residential spaces, areas pertaining major hub for inter-city transportation within the selected urban agglomeration and their identification within their corresponding city's urban development plans for the future. For this purpose, the cluster of three urban areas were selected for each city addressing the intra-city and inter-city spatial analysis, which include:

- City centres: These areas are the central landmarks of the urban core of a city, which is usually concentrated with dense mobility traffic involving pedestrians, public transport, and other user-groups. They include high street areas and attract many economic opportunities making it as one of the important destinations within a travel chain.

- Transit areas: The area surrounding main transit stations responsible for inter-city travel within the urban agglomeration represents an important node with a travel chain, and is also favoured for transit-oriented development involving dense land-use in close relation with public transport services.

- Residential areas: These urban areas are dominated by residential land-use, with least influence from the city centres, industrial areas or main railway stations (like Hauptbahnhof), which act as an origin for majority of travel routes. Unlike city centres or main transit stations, a city does not have a unique residential area, therefore within the scope of the research study residential areas which are identified within the city's urban development plans for the future and fall within the large-scale observational limits of the identified parameters are selected.

The assessment of the selected urban areas initiates with a pilot study within one of the cities forming the urban agglomeration (see Fig. 2). The preliminary outcomes through pilot studies (utilizing identified accessibility parameters) in a city within the Rhein-Main agglomeration, assist in understanding, improving and utilizing the accessibility assessment measures in future, which helps in realizing which urban area pertains to better medium of multimodal accessible environment. This initiates the accessibility assessment within the Rhine Main area including the urban core of city centres with respect to the modes. This includes gaining and analysing data on the built environment

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Hillier, B., and Hanson, J. (1984), The Social Logic of Space, Cambridge University Press, Cambridge, DOI: 10.1017/CBO9780511597237 (for e.g. utilizing attributes influenced by spatial configuration, GIS application and more). For instance, Space Syntax (Hillier and Hanson 1984) as a theory has shown its practical utility through understanding of an urban environment as a network of different elements or units which include streets, open plazas, buildings, bridges, etc. which are linked together directly or indirectly and form a relationship between them. With different user-groups, the multimodal accessibility as a measure for an urban area would vary along with diverse modes of mobility. The overall assessment would be primarily based on the mobility and the accessibility aspect, though corresponding parameters (which may compliment the two aspects) can be assessed based on the iterations in the preliminary pilot case studies. For the pilot study, prior to the diagnosis stage involving accessibility assessment of cities within the Rhein-Main Region, city of Darmstadt is considered to initiate the assessment, based on the overall commuter flows and population growth within the Rhein-Main region (which includes the city of Frankfurt am Main and Offenbach am Main).

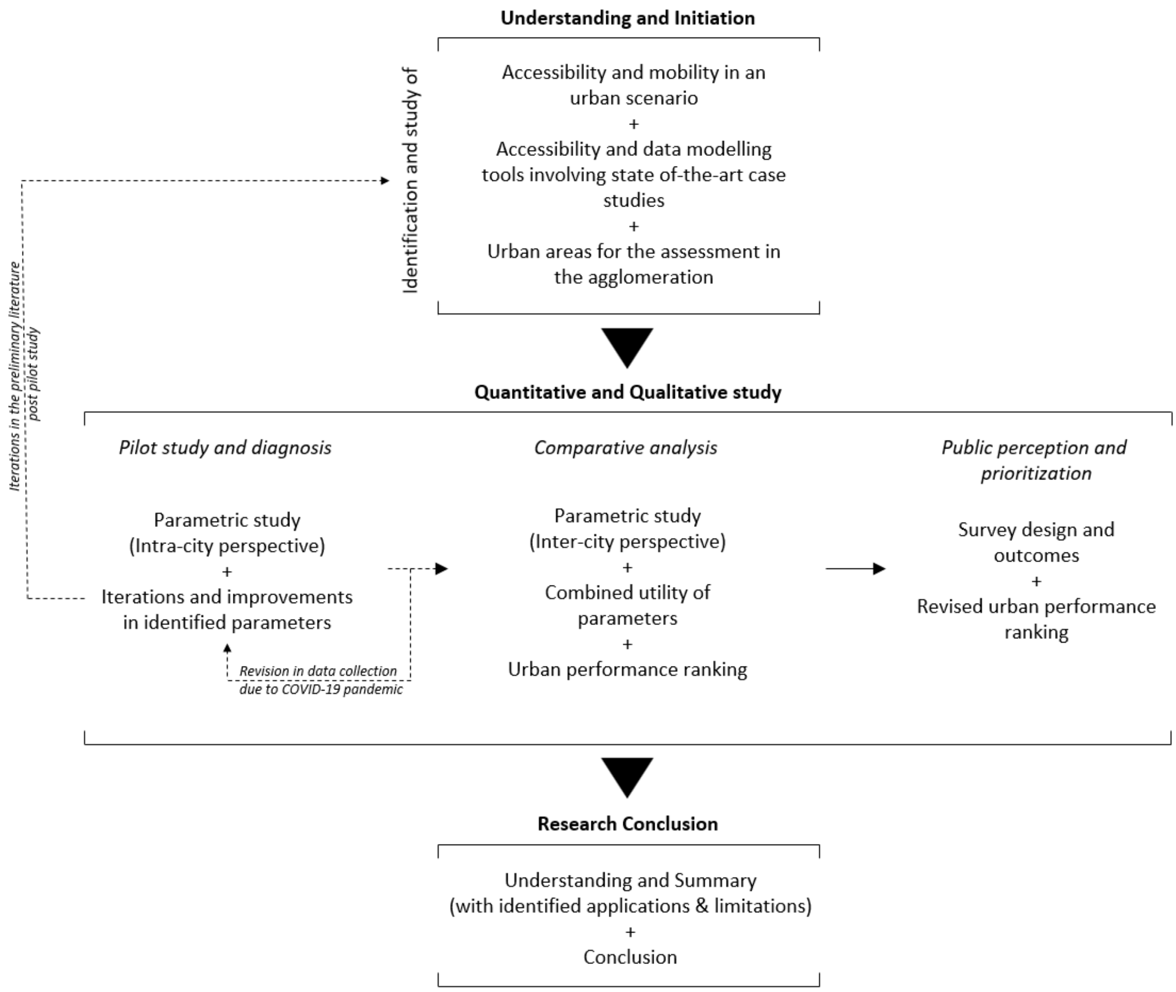

Figure 2: Research methodology flowchart

The assessment of selected urban areas would be mostly based on parameters which are influenced by spatial configurations and would produce a qualitative outcome through quantitative measures. This includes mapping the selected urban areas based on principles corresponding to the identified parameters, leading to a spatial analysis along with other quantitative indexes. Post data collection and analysis, a comparative study for the inter-city perspective provides a data-driven approach where similar urban areas and their hierarchy based on the multimodal accessibility parameters is revealed.

Adjacent to the inter-city perspective, the application of identified parameters through urban intervention projects (e.g. road closure in Frankfurt Mainkai riverfront) is carried forward. This helps in applying and propagating urban research through collaboration with city planning authorities and practices (contributing to the research framework in Fig. 1), fostering different aspects of multimodal accessibility on-site.

Following the comparative study, the public perception of priority focusing towards different aspects of multimodal accessibility is realized with survey outcomes and a revised hierarchy of urban areas and relative priority towards different parameters is generated. With the onset of COVID-19 pandemic in 2020-2021, the urban assessment relating to the data collected prior to the urban lockdown scenario was revised (Fig. 2) in order to have a fair comparison of parameters in different cities and urban areas within similar environmental conditions. Based on the comparison study and the individual parametric characteristics of identified urban areas, a more concrete conclusion and results focusing on identified issues were drawn.

1.5 Structure of the Dissertation

The dissertation is divided into three sections, where the theoretical background and literature help in the initiation of the research (i.e. section 1), followed by the set of parametric pilot studies and analysis through quantitative and qualitative approach which includes comparative analysis and public perception (i.e. section 2), eventually leading to research summary and conclusion (i.e. section 3). Within these three sections, there are overall seven chapters described in summary as follows:

- Chapter 1: Introduction
  The first chapter introduces the research problem and focus with its conceptual framework, along with the research aim, scope, questions, and research methodology.

- Chapter 2: Mobility and Accessibility
  The second chapter provides a background towards the understanding of mobility and accessibility in an urban scenario while defining multimodal behaviour and urban agglomerations. It introduces active mobility, with trends supporting changes in an urban mobility environment, including neighbourhood approach, pedestrianisation and alternate modes of transport. Consideration of accessibility as a measure for an urban area, through utility of different state-of-the-art studies, narrows down the domain of accessibility within the scope of the research. The chapter also looks into the urban mobility in European context and culminates through discussion on different measures influencing mobility within Germany and the mobility vision within the Rhein-Main urban agglomeration.

- Chapter 3: Identification of Parameters and Urban areas
  The chapter deals with the study of various parameters (or performance measures) in order to understand and evaluate diverse urban street networks within the aspect of multimodal accessibility. The identified measures are further evaluated based on their scales of urban perspective, the observation limits, the diversity of transport mediums being taken into consideration through the process, and the state of the art optimum (maximum or minimum) values based on the diverse case studies. Post identification of parameters and urban areas for the study in Rhein-Main urban agglomeration, the understanding of the urban development plans in the three cities of Frankfurt am Main, Darmstadt and Offenbach am

Main assist in narrowing down certain objectives which are related to accessibility, that can be addressed upon through the intra-and inter-city perspectives of the selected multimodal accessibility parameters.

- Chapter 4: Pilot study and spatial diagnosis
  This chapter initiates the spatial study of selected urban areas) through the pilot study in one of the cities forming the urban agglomeration (i.e. Darmstadt). The pilot study assists in understanding the overall timeline for analysing the selected spatial configuration of urban areas through different attributes (or identified parameters). Following the pilot study, the selected urban areas in Frankfurt am Main and Offenbach am Main are analysed through the identified parameters. The spatial analysis is carried through intra-parametric intra-city perspective (with brief inter-city perspective post pilot study) for selected urban areas in different cities.

- Chapter 5: Comparative analysis
  This chapter deals with comparison of urban areas in the selected cities forming the Rhein-Main urban agglomeration through different perspectives including their selected accessibility parameters with corresponding mobility strategies and spatial configurations. The in-depth inter-city comparison of these urban areas helps in assessing different accessibility parameters within geographic boundary limitations based on the literature. This also includes combined use of different identified parameters to understand different objective mobility characteristics of a city or an urban area. Following the inter and intra-city comparison, the identified urban areas in the cities of Darmstadt, Frankfurt am Main and Offenbach am Main are later ranked through a data-driven approach, comparing different urban areas of cities objectively.

- Chapter 6: Public perception and prioritization
  Following the objective performance ranking of selected urban areas, the subjective perception via public opinion on the priority of the selected parameters and urban areas is derived within the Rhein-Main agglomeration. This chapter brings together the quantitative spatial measures and its qualitative outcomes through the perspective of public opinion, and initiates the data-informed approach with a revised urban performance ranking for the overall outcome. This assists in understanding the difference between the subjective and objective priority of urban areas in regards to their multimodal accessibility characteristics.

- Chapter 7: Summary and conclusion
  The chapter summarizes the key takeaways through discussion on the literature and on-site study, and reflects upon the identification of potential utility of the attributes and its link with the current urban development practices through the cities of varying sizes forming the Rhein-Main urban agglomeration. Certain key outtakes from the on-site and on desk research findings are discussed along with future outlook of certain urban areas and limitations which may influence the overall outcome.

The research aims on obtaining identified objectives in continuum throughout the epistemological timeline, involving on-site and on-desk data collection and spatial analysis. It narrows down certain parameters (discussed in Chapters 2 and 3) which connect and integrate different aspects of multimodal accessibility, influencing urban design. This is done primarily through a topological approach of measurability bringing urban research and practice closer to each other. The intra-city (in Chapter 4) and inter-city perspectives (in Chapters 4 and 5), help in understanding how different spatial configurations influence the overall aspect of multimodal accessibility through cities of varying sizes. In addition, experimental urban intervention projects like the one in Frankfurt's Mainkai riverfront (discussed in Chapter 5) provides an opportunity to propagate and implement urban research outcomes (see Fig. 1) more effectively in an urban development timeline. The objective prioritization of aspects (in Chapter 5) and its subjective outlook through public perception (in Chapter 6) reflects the mobility culture which is derived from it. Assessing mobility within an urban agglomeration, where the cities focus on planning for an environment-friendly mobility region, through interdisciplinary means of research methodology, assists in the vision of obtaining an accessible and integrated multimodal urban system.

CHAPTER 2

MOBILITY AND ACCESSIBILITY

Preface

To assess sustainable development of cities and its immediate surroundings, monitoring people's mobility and on-going trends in urban areas is an important factor. Understanding how people move from one point to another helps in estimating future scenarios, which assist in planning for an urban area that is accessible to different user groups in equity. This chapter tries to understand the trends in an urban scenario which culminates with selection of area of study for the research. This chapter introduces and provides a background towards the understanding of mobility and accessibility in an urban scenario while defining multimodal behaviour and urban agglomerations.

2.1 Understanding mobility in an urban scenario

Mobility contributes to quality of life. The ability to move around a city grants a person more access to many opportunities. For an urban area, its mobility and transportation system play a critical role in its overall success to function at its full potential. While transportation in basic terms relates to movement of goods and people, mobility is not a synonym to it. Mobility isn't being limited to one mode of transportation but to have the ability to choose from different mediums of transportation to move to a destination (i.e. school, job, park, shop etc.) for a healthy lifestyle (Fortunati 2018). Cycling, walking, using public transport and other means of mobility within active multimodal system further add to the overall healthy lifestyle of a city in an environmentally friendly way. A better measure of mobility does not necessarily mean high traffic, but can in fact be opposite. This is primarily beneficial for planning authorities which focus on future plans to achieve a region with short-distance mobility through active means of walking and cycling as primary measures. Many cities compete to achieve a better quality of urban environment, where ease of using a mobility service is one of the key factors.

Cars play a dominant role on roads in many cities. With the trend of automobile car sales being expected to double from 70 million in 2010 to 125 million in 2025, majority of the sales are expected to take place in the urban areas (Dargay, J. et al. 2007). The existing urban infrastructure would face difficulty accommodating the rise of private vehicles on road, which has already led to frequent congestions in many urban centres. The traffic congestion timelines around many cities have started to take extraordinary numbers. In Brazil, cities like São Paulo have recorded 340 kilometres long peak

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Fortunati, J. (2018), Mobility doesn't mean the same thing as transportation, Mobility Lab, Virginia, USA. Retrieved from https://mobilitylab.org/2018/07/26/what-is-mobility/

Dargay, J., Gately, D., and Sommer, M. (2007), Vehicle ownership and income growth, worldwide: 1960–2030, *Energy Journal*, Volume 28, Number 4, pp. 143-70.

hour traffic congestions (UOL 2014), while in Europe the hours spent annually in road congestion (see Fig. 3) range from 18 hours in Finland to 46 hours in UK (European Commission 2017).

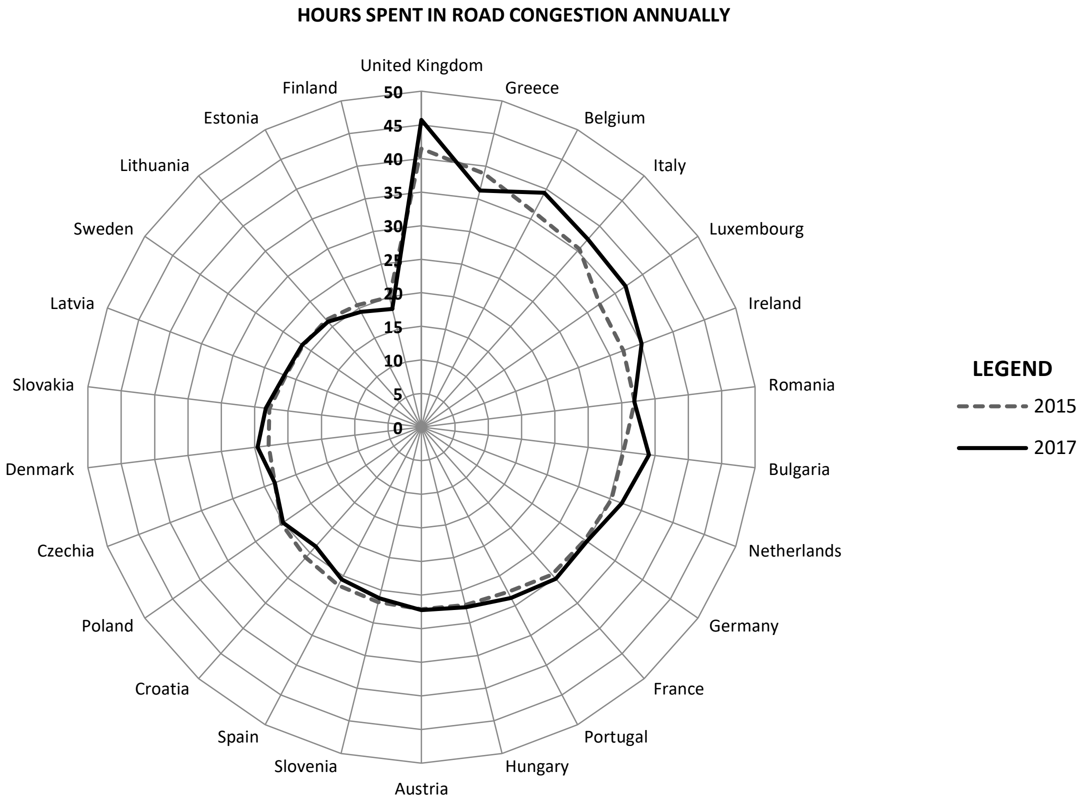

Figure 3: Hours spent by the average driver in Europe through morning and evening peak hours on 220 working days
Source: Graph (graph generated from the available data) - European Commission (2017)

This has in turn resulted in a paradigm shift, where many cities are planning to have better modal share towards active modes of transport which include walking, cycling, and with a recent trend of rise in the utility of electronic scooters in many cities around the globe. Alternative services of bike and car-sharing also compliment these active modes, further assisting in lowering the overall congestion in urban areas especially city centres including central business districts.

2.1.1 Active mobility in urban lifestyle

Active mobility involves walking or cycling for a single trip or a part of trip in combination with public transport, which assists in a promoting health-related benefits in urban lifestyle (Dons, E. et al. 2015). Research has shown active mobility to be associated with better mental health and perceived stress through higher physical activities (Palencia et al. 2017). Physical-activity friendly communities enable and encourage active mobility, which plays an important role in developing physical activity behaviours. With recommended 60 minutes of daily physical activity for children and 150 minutes of weekly physical activity for adults (WHO 2020), creating recreational spaces along with safe walking

UOL Economia (2014), São Paulo sofre engarrafamento recorde de 344 quilômetros, São Paulo. Retrieved from http://economia.uol.com.br/noticias
European Commission (2017), Hours spent in road congestion annually, Energy Union and Innovation, Mobility and Transport, Retrieved from https://ec.europa.eu/transport/facts-fundings/scoreboard/compare/energy-union-innovation/road-congestion_en#2017
Dons, E., Götschi, T., Nieuwenhuijsen, M. *et al.* (2015), Physical Activity through Sustainable Transport Approaches (PASTA): protocol for a multi-centre, longitudinal study. BMC Public Health 15**,** 1126. DOI: https://doi.org/10.1186/s12889-015-2453-3
Palencia, I. A., Panis, L. I., Nazelle, A., Götschi, T., Raser, E., Gaupp-Berghausen, M., Stigell, E., Iacorossi, F., Laeremans, M., Boig, E. A., and Nieuwenhuijsen, M. (2017), 2023 - Active Mobility and Subjective General Health: Roles of Mental Health, Social Support and Physical Activity, Journal of Transport & Health, Volume 5, ISSN 2214-1405.
WHO (2020), WHO guidelines on physical activity and sedentary behaviour, ISBN 978-92-4-001512-8

and cycling pathways, assist in making physical activity functions as part of daily life (WHO 2016). This enables many urban authorities and decision makers to promote active mobility through infrastructure for both physical and mental well-being. In urban areas where mobility is of utmost importance and space is getting scarce, active mobility provides a solution. The physical infrastructure for walking and cycling requires less space (see Fig. 6) when compared to cars and associated infrastructure (e.g. parking areas, on-road occupancy etc.). Many economic benefits have also been associated with active mobility. Cyclists have been seen to spend more overall locally as compared to car drivers, which benefits the local market (Decisio 2017). The study by Rajé F. & Saffrey A. (2016) shows car-centric cities to have 33% higher annual infrastructure costs than less car-oriented cities. It also reflects cycle parking (per square metres) to yield 5 times higher retail than the same area of car parking.

With more than 50% of the trips in the urban area estimated to be less than 10 kilometres (Skougaard, B. 2013), cycling can become one of the important modes of travel. Through policies and infrastructure investments towards cycling in urban areas, study (ITDP and UC Davis 2015) shows the cycle/e-bike share of urban passenger travel to be 11% worldwide by 2030. This would further increase to 14% of urban kilometres of travel by 2050, which has a wide range of potential from 25% in China and Netherlands to 11% in US and Canada. At the same time, move towards cycling in urban cities is also expected to reduce the CO_2 emissions from urban passenger transport by approximately 11% in 2050. This shows how cycling infrastructure can play a major role in cities for personal mobility in future.

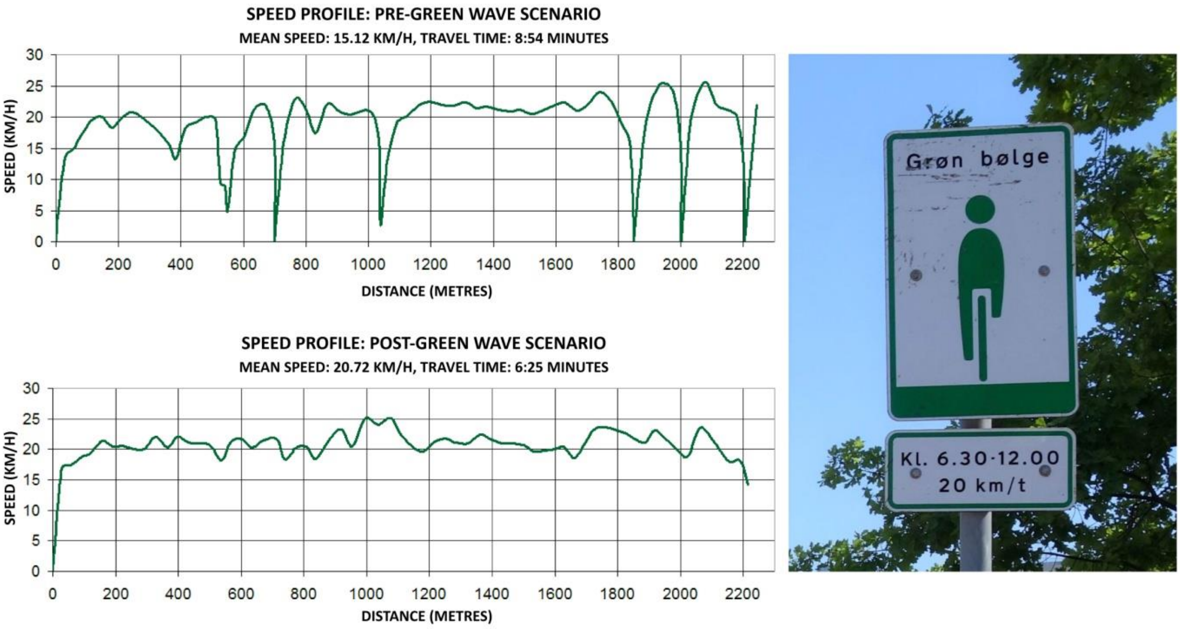

Figure 4: Change in cyclists' speed profile after green wave implementation (left), Green wave signage indicating speed limit (right)
Source: Graph (modified) - Frederiksberg Kommune (2013), Image - Buczynski, A. (2018)

While there are several factors that complement the cycling culture of a city, some need to be prioritized to have a swift shift towards the active mode of mobility. The study by Goeverden et al. (2015) shows that cyclists prefer direct routes with least hindrance to motorized traffic, showing

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WHO (2016), Report of the Commission on Ending Childhood Obesity, Geneva, Switzerland, ISBN 978-92-4-151006-6.
Decisio (2017), Waarderingskengetallen MKBA Fiets: state-of the art [Rating indicators of cycling SCBA: state-of-the-art], Amsterdam.
Rajé, F. and Saffrey, A. (2016), The value of cycling, Department of Transport, Government of UK, UK, pp. 2-36.
Skougaard, B. (2013), Denmark National Travel Survey, 16, pp. 191-194.
ITDP and UC Davis (2015), A Global High Shift Cycling Scenario: The potential for dramatically increasing bicycle and e-bike use in cities around the world, with estimated energy, CO_2, and cost impacts, pp. 5-8
Frederiksberg Kommune (2013), Evaluering af grønne bølger for cyklister i Københavns Kommune In: Buczynski, A. (2018) Green wave for cyclists, European Cyclists' Federation, Brussels. Retrieved from: https://ecf.com
Goeverden, K. V., Nielsen, T. S., Harder, H., and Nes, R. V. (2015), Interventions in Bicycle Infrastructure, Lessons from Dutch and Danish Cases, Transportation Research Procedia, 10, pp. 403-412, ISSN 2352-1465. DOI: https://doi.org/10.1016/j.trpro.2015.09.090.

priority to good connectivity and widths of bicycle paths covering the bicycle infrastructure. In Copenhagen, where bicycle path widths vary between 1.7 to 4 metres (with 2.5 metres the recommended minimum), certain examples include 'green waves' (see Fig. 4). Green waves basically allow continuous flow of bicycle traffic, given the speed of movement is maintained throughout the designated route of travel. These ensure cyclists to move through the town without stopping, leading to the successful bicycle policy of Copenhagen (Gehl, J. 2010). This can be seen in contrast to some cities like San Francisco in California, US where the city has similar length of cycling lanes as that in Copenhagen, while Copenhagen has a modal share of cycling which is almost 14 times as compared the city of San Francisco (City and County of San Francisco 2022 and City of Copenhagen 2019). This demonstrates the difference in the qualitative aspect of the cycle lanes, as the quantitative attributes are similar. One of the reasons for the low modal share in San Francisco could be the quality of bicycle infrastructure, where protected lane separations are less on site. For example, on Polk Street (which is adjacent to the major public transit lane on Van Ness Street) only one cycle lane has a designated lane for movement while the one in opposite direction shares the space with motorized vehicles (see Fig. 5), which is unprotected.

Figure 5: Two-way cycle lanes on Polk Street in San Francisco, California with one unprotected shared lane between the motorized vehicles and bicycles

Gehl, J. (2010), Cities for People, Island Press, Washington, DC, pp. 182-191.
City and County of San Francisco (2022), Estimated Mode Share in San Francisco, San Francisco. Retrieved from https://sfgov.org/scorecards/transportation/non-private-auto-mode-share
City of Copenhagen (2019), The Bicycle Account 2018 Copenhagen City of Cyclists, Copenhagen, Denmark. Retrieved from https://kk.sites.itera.dk/apps/kk_pub2/index.asp?mode=detalje&id=1962

These combined factors put a certain responsibility towards planning authorities to look over this special user group in future, as they, i.e. cyclists, merge the perspectives of two diverse users i.e. car drivers and pedestrians (Cromwell 2013), where they can move fast like automobiles but at the same time experience their immediate urban environment like pedestrians.

Walking, on the other hand, offers a high degree of freedom to move around a city's urban landscape, with it being most healthy, clean and efficient mode of movement. It is an essential part of travel chain, which comprises of many modes of travel to reach majority of destinations in an urban area. Walking as a mode includes many landuse benefits through social, economic and environmental perspectives (Litman 2004). In terms of economic benefits, it provides more access to people who cannot drive leading to reduction in transportation costs. From the social perspective, it serves as a medium for people in neighbourhoods to interact in a healthy lifestyle with access to better opportunities. With less infrastructure required for walking (see Fig. 6) and its reduced energy consumption, it serves as a sustainable medium for short-distance mobility in urban environment.

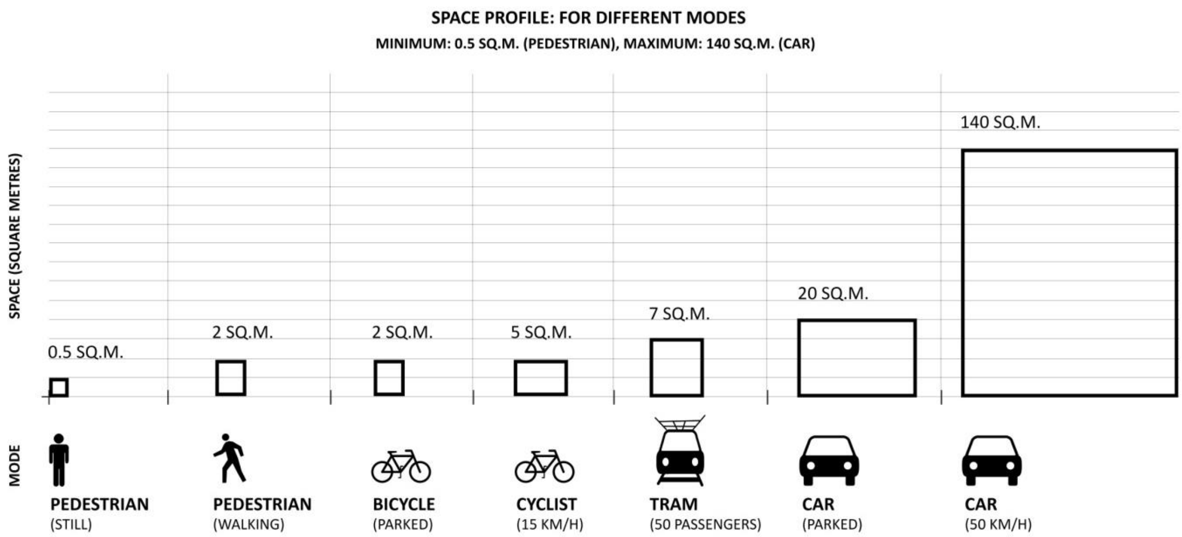

Figure 6: Varied occupied spaces by different travel modes (in square metres)
Source: Image (modified based on data) – Harms and Kansen (2017)

In cities where car traffic is high, pedestrian pathways (or sidewalks) play a significant role for people to walk, which otherwise would force them on roads, reducing their overall safety. With regards to high walkable neighbourhoods, the attributes including residential density, land-use mix and street connectivity play a major role (Leslie et al. 2005). Proximity to destinations, good weather conditions and safety also assist towards a better perception of walking environment (Ariffin and Zahari 2013). Adding to these factors, block lengths (i.e. perceived lengths of streets or corridor) and edge conditions also contribute to streets being more walkable (Singh 2016). This indicates how a good network of streets is important for a walkable neighbourhood in an urban scenario.

Cromwell, P. (2013), Designing for the social experience of bicycling, Gehl Blog, Retrieved from https://gehlpeople.com/blog/designing-for-the-social-experience-of-bicycling/
Litman, T. (2004), Economic Value of Walkability, World Transport Policy and Practice, 10 (1), pp. 3-11.
Harms, L. and Kansen, M. (2018), Cycling facts Netherlands Institute for Transport Policy Analysis I KiM, Ministry of Infrastructure and Water Management, The Hague. ISBN: 978-90-8902-183-0
Leslie, E., Saelens, B., Frank, L., Owen, N., Bauman, A., Coffee, N., and Hugo, G. (2005), Residents' perceptions of walkability attributes in objectively different neighbourhoods: a pilot study, Health & Place, 11 (3), pp. 227-236. DOI: https://doi.org/10.1016/j.healthplace.2004.05.005
Ariffin, R. N. R. and Zahari R. K. (2013), Perceptions of the Urban Walking Environments, Procedia - Social and Behavioral Sciences, 105, pp. 589 -597.
Singh, R. (2016), Factors Affecting Walkability of Neighborhoods, Procedia - Social and Behavioral Sciences, 216, pp. 643-654, ISSN 1877-0428.

For longer distances covering different urban areas within a city, public transport combined with walking and cycling plays an integral role in active mobility. Availability of public transport has shown to be one of the important aspects of urban mobility in many cities (Knupfer et al. 2018). With increasing urbanization and growth of the cities, public transportation as a mode has the potential to find balance and contribute towards the sustainable system of urban movement.

It also plays an important role in connecting the urban to rural areas at the peripherals of the city, ensuring mobility in urban agglomerations. The public transit options such as metro, trams, rails, and buses provide an efficient medium for moving large number of people within a city. Especially in large urban centres, high share of population has higher access to public transport as compared to medium-sized urban centres (Poelman & Dijkstra 2015). Within the study, high access relates to the ability of people to have ease of movement to walk to a nearby transit station having a frequency of more than 10 departures per hour (with low access corresponding to less than four departures per hour). The lower access in medium-sized cities was mainly due to lack of diverse transport modes (e.g. Metros) as compared to larger cities in urban centres. While the access to public transport can be improved through addition of more stops or increased frequencies, it might not be financially sustainable in areas with lower population density, though it can have a long-term impact through people shifting away from private vehicles leading to lower vehicular emissions and car-traffic.

Many people in cities travel by walking or cycling, yet often the car-centric approach to urban development sees its negative impact on walking environment and cycling infrastructure. While the strategies to increase active mobility varies between the disciplines of urban planning, transport planning and urban health authorities, their objectives to promote active mobility are often seen to overlap (Koszowski, C. et al. 2019). With varying approaches to improve the mobility environment in cities, the understanding of the potential for different travel modes assists in identifying the potential of an urban street network in a city (or an urban area).

2.1.2 Multimodal and intermodal mobility as a travel behaviour

In an urban scale, the travel behaviour of an individual has an influence on the mobility environment of the city. The terms ‘multimodal’ and ‘intermodal’ have been used in the transportation sector of goods, which differ in its interpretation for an individual’s way of travelling in an urban area. While the two terms, in the transportation industry, refer to the type of contract and logistics involved of how goods move from an origin to the destination, they vary in their definitions on an urban scale for a person’s mobility. With respect to the urban perspective of an individual’s mobility, terms ‘multimodal travelling’ and ‘intermodal travelling’ have been used by Zumkeller et al. (2005) which puts the significance on the route aspect of one’s movement. While ‘intermodal travel’ focuses on different modes of transport on one route, ‘multimodal travel’ focuses on use of different modes of transport on different routes (see Fig. 7). For example, if a person cycles to a transit station to use a tram or a train to reach a destination, it relates to intermodal behaviour of travel; while cycling to the destination and coming back in the return trip through public transport would be a multimodal travel behaviour.

Knupfer, S. M., Pokotilo, V. and Woetzel, J. (2018), Elements of success: Urban transportation systems of 24 global cities, Mckinsey Center for Future Mobility, pp. 6-69.
Poelman, H. and Dijkstra, L. (2015), Measuring access to public transport in European cities, Regional and Urban Policy, European Commission, pp. 4-20.
Koszowski C., Gerike R., Hubrich S., Götschi T., Pohle M., Wittwer R. (2019), Active Mobility: Bringing Together Transport Planning, Urban Planning, and Public Health. In: Müller B., Meyer G. (eds) Towards User-Centric Transport in Europe, Lecture Notes in Mobility, Springer.
Zumkeller, D., Manz, W., Last, J., & Chlond, B. (2005), Die intermodale Vernetzung von Personenverkehrsmitteln unter Berücksichtigung der Nutzerbedürfnisse (INVERMO), Report, Universität Karlsruhe, Germany In: Jonuschat, H., Stephan, K. and Schelewsky, M. (2015), "Understanding Multimodal and Intermodal Mobility", Sustainable Urban Transport (Transport and Sustainability, Vol. 7), Emerald Group Publishing Limited, Bingley, pp. 149-176. DOI: https://doi.org/10.1108/S2044-994120150000007018

At times, there is also a third term i.e. unimodal mobility which emphasizes on travel by only using one mode of mobility (e.g. using motorized vehicles). Jonushchat et al. (2015) defines multimodal mobility as a mobility behaviour characterized by combination of different mobility modes and its flexible utility based on the situation and availability of the modes, while intermodal mobility is a mobility behaviour which involves combination of transportation modes on one route of travel.

'Intermodality' and 'multimodality' have shown their significance for the future of mobility through some urban development plans involving mobility within and between the cities (Stadtwerke Offenbach 2017). The two terms are defined with respect to the weekly utility of the travel modes by an individual, where multimodality or multimodal transport behaviour refers to using different modes of transport over a course of time (e.g. a week), while intermodality or intermodal transport behaviour includes utilisation of multiple transportation modes in one single trip. In principle, the intermodal transport behaviour is observed more for a longer trip, with public transport playing a major role interacting with other modes of mobility.

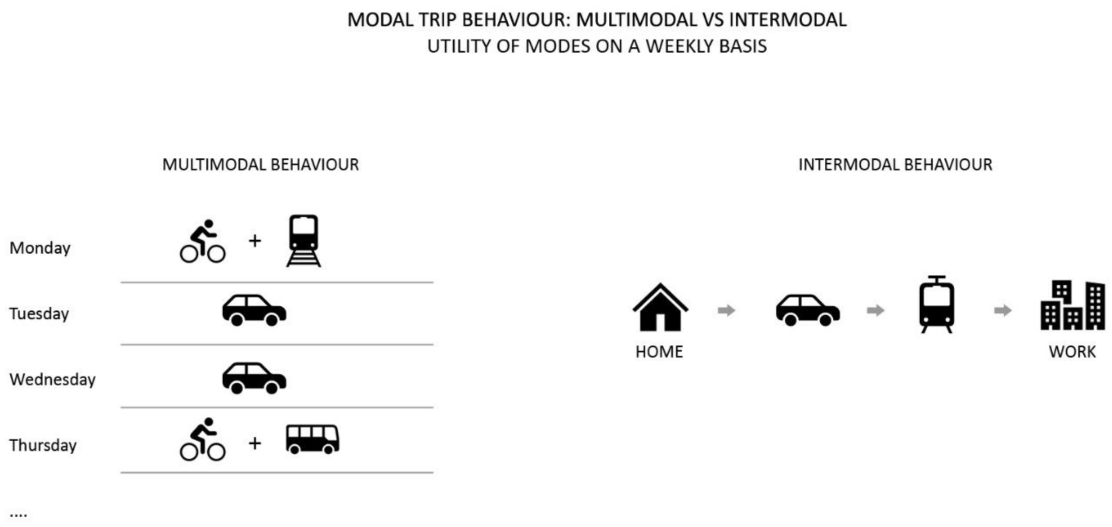

Figure 7: Multimodal vs Intermodal travel behaviour
Source: Image (modified based on data) – TU Dresden (2010) In: Stadtwerke Offenbach (2017)

In the context of mobility services, the European Commission (1997) defines intermodality as the 'characteristic of a transport system that allows at least two different modes to be used in an integrated manner in a door-to-door transport chain'. Though this perspective is based on the freight transport and strategies, it can also be understood through the mobility perspective of an individual in an urban space.

Jonuschat, H., Stephan, K. and Schelewsky, M. (2015), Understanding Multimodal and Intermodal Mobility, Sustainable Urban Transport, Transport and Sustainability, Vol. 7, Emerald Group Publishing Limited, Bingley, pp. 149-176. DOI: https://doi.org/10.1108/S2044-994120150000007018
TU Dresden (2010) Interdependenzen zwischen Fahrrad- und ÖPNV-Nutzung, Analysen, Strategien und Massnahmen einer intergrierten Förderung in Städten, Dresden. In: Stadtwerke Offenbach (2017), Mobilitätsplan für die Stadt Offenbach Fortschreibung Nahverkehrsplan Stadt Offenbach 2018 – 2022, Offenbach am Main, pp. 70-73.
European Commission (1997), Communication from the Commission to the Council, the European Parliament, the Economic and Social Committee and the Committee of the Regions, Intermodality and intermodal freight transport in the European Union, A system's approach to freight transport, Strategies and actions to enhance efficiency, services and sustainability, COM (97) 243 final, Brussels, pp. 1-20.

The important aspect amongst the described mobility behaviours is the freedom of choice for an individual to choose the mode of mobility to travel from the origin to the destination. These can vary from individual, shared and public transport modes. The individual modes would mostly include the ones which an individual can access directly, i.e. car, bicycle, motorcycle etc. The shared transport modes are usually the ones which can neither be categorized as public transport nor individual transport modes, such as car-sharing, bicycle sharing, e-scooter services etc. On the other hand, buses, trams or trains which run on a fixed route available to the public are the public transport modes. The intermodal perspective of mobility involves more interaction between different modes of transport for a person's travel behaviour, while the multimodal perspective focuses more on the individual modal potential in an urban scenario and has comparatively less interaction with other modes of transport. In order to improve a mode's potential on an individual basis, multimodal perspective comes into picture; whereas to improve the interaction between different modes of transport on an urban scale, intermodal perspective is taken into consideration.

2.1.3 Trends surrounding changes in urban mobility

As rapid urbanization takes place in many cities, it also pushes the planning authorities to take steps to accommodate the growing demands in a sustainable manner. These take shape through introduction or change in policies, revisions in master plans and through many alternative mediums to meet their goals year after year. These induce trends in an urban scenario which impact the overall network of mobility in cities.

Neighbourhood approach

Global urban centres like Singapore, Melbourne and Paris have shown their focus on travel time goals, for people to reach their destinations in less time. In Singapore's Land Transport Master Plan 2040 (LTA 2020), all trips (which includes destinations like schools, shops, parks, clinics and other essential services) using active, public or shared mode of transport are planned to be completed within 20 minutes. This is followed by 90% of the peak-period journeys to be done by either active, public or shared mode of transport. It also focuses on short distance travels where 150 kilometres of covered linkways (i.e. covered walking pathways), 1000 kilometres of cycle pathways and better active mobility infrastructure is prioritized by 2040. With respect to long-distance public modes like buses, traffic signal priority and separate lanes are planned in a more barrier-free environment.

In Paris, the concept of 15-minute city (Moreno, C. 2019) has been resurgent where the agenda is to reach workspace, parks, cultural venues, hospitals and essential destinations within a neighbourhood in the specified time. Similarly, in Australia, the city of Melbourne plans to have '20-minute neighbourhoods' with access to safe cycling and local transport (DELWP 2019). While in US, the urban movement towards making walkable neighbourhoods took shape in late 20th century through 'New Urbanism' (Yeung, P. 2021). The concept of reaching major destinations within short period of time has been worked upon in past, including the concept of a 'neighbourhood unit' in 1920s (Perry 1929) before cars dominated the streets.

Land Transport Authority [LTA] (2020), Land Transport Master Plan 2040, Government of Singapore, Singapore
Moreno, C. (2019), The 15 minutes-city: for a new chrono-urbanism, Retrieved from http://www.moreno-web.net
Department of Environment, Land, Water and Planning [DELWP] (2019), Plan Melbourne 2017-2050 Addendum 2019, Victorian Government, Australia.
Perry, C. A. (1929), The neighborhood unit, a scheme of arrangement for the family-life community, Monograph One in Neighborhood and Community Planning, Regional Plan of New York and Its Environs, New York.
Yeung, P. (2021), How '15-minute cities' will change the way we socialise, Worklife, BBC, Retrieved from https://www.bbc.com/worklife

The renewed interest on having an accessible neighbourhood on a global scale lays priority on providing and improving the existing infrastructure for short-distance mobility (e.g. sidewalks or cycling pathways), if not already in place.

Pedestrianization and car-free approach

A move from car-centric planning approach to people-centric planning is gaining momentum in many cities, where pedestrians and people using non-motorized means of transport are given more priority for the future development. Many cities like Paris, Masdar, Copenhagen, Bogota, Dublin and Hyderabad have introduced different ways to reduce car-traffic by implementing several measures which include car-free days, limited parking spaces, and pedestrianization. Cities like Hamburg, Oslo, and Helsinki have announced plans to be private car-free cities in future (Nieuwenhuijsen and Khreis 2016). In Asia, Singapore and Hong Kong have implemented permanent pedestrian streets where access for cars during night time was restricted and made available only to pedestrians, and served as an opportunity to various social activities. These measures would impact the modal-split in future, where the share of people using active modes of transport via walking or cycling, along with public transport would increase.

People have been seen to walk more in pedestrian-friendly city centres. The existence of public transport has also led to more pedestrian streets in many cities. Cities like Nuremberg, having underground rail system, have seen 44% of pedestrians walk more than 2 kilometres on weekdays, increasing to 53% on weekends (Monheim 1995). The study by Hass-Klau C. (2003) has shown cities operating with light rails, including trams, having longer pedestrian streets than cities with buses. Majority of the cities with trams had longer cycling facilities, larger pedestrian areas and greater traffic calmed streets. This shows how public transport impacts the city and its movement lifestyle, assisting in promoting active modes though walking and cycling. One of the earliest successful pedestrianization projects while cars were dominating the streets, was in Copenhagen. It involved the Strøget street as an experimental area in early 1960s. It led to +35% increase in pedestrian volume after first year, contributing to +20% increase in citywide pedestrian volumes (Global Designing City Initiative 2016). It reflects how such measures impact the streets of a city, attracting more people to walk.

While pedestrianizing streets in cities has been successful in many experimental pilot projects, not all have seen a permanent change and eventually have reversed back to earlier conditions. In some cities of North America and Northern Africa, the temporary pedestrianization did not transform successfully due to many reasons which include opposition from residents, retailers, less planning for shifted traffic and lack of institutional and political support (Yassin H. H. 2019). An intermediate way of dealing with opinion of residents towards pedestrianization of streets can be seen via play streets order (London Borough of Hackney 2020). As an example, in Hackney, residents can apply to close a street (except main roads or those on bus route) for three hours per week or month, post consultation from people living in the neighbourhood. Such measures help in assessing the potential of streets to different users-groups and their preferred modes of travel.

Nieuwenhuijsen, J. & Khreis, H. (2016), Car free cities: Pathway to healthy urban living, Environment International, 94, pp. 251-262, ISSN 0160-4120.
Monheim, R. (1995), Mobilität zu Fuss, Eine Bestandsaufnahme des Fussgängerverkehrs, Verkehrsministerium Baden-Württemberg (ed) Fussgängerfreundliche Verkehrs-und Stadtplanung, Tagesband Expertengespräch, Stuttgart, pp. 13-21.
Hass-Klau, C. (2003), 14 - Walking and its relationship to public transport, Sustainable Transport, Woodhead Publishing, pp. 189-199, ISBN 9781855736146.
Global Designing City Initiative (2016), Global Street Design Guide, Island Press, pp. 198-200.
Yassin, H. H. (2019), Livable city: An approach to pedestrianization through tactical urbanism, Alexandria Engineering Journal, 58, 1, pp. 251-259, ISSN 1110-0168.
London Borough of Hackney (2020), Play streets, Roads and Transport, London. Retrieved from https://hackney.gov.uk/play-streets

Alternate modes of transport

Globally, electric scooters (e-scooters) have become a new means of transport for people in urban areas. With its first introduction of sharing system in US in 2017, many countries like Germany have recently made the use of e-scooters legal on main roads since 2019 (Agora Verkehrswende 2019). This took place via Small Electric Vehicles Act (eKFV) which made it mandatory for the e-scooter users to use bicycle infrastructure wherever possible within 20kmph speed limit, excluding its use on pedestrian sidewalks. While the introduction of the e-scooters has been on the rise globally, the transition of the new mode on streets hasn't been swift immediately. A study in Portland, Oregon (PBOT 2019) has shown 39% of e-scooter users using pedestrian sidewalks illegally due to absence of bicycle facilities, which reduces to 21% in the presence of unprotected bike lanes (and 8% in presence of protected bike lanes), further reducing to 0% around bicycle boulevards. It also faced problems in parking, which led to obstruction to pedestrian movement (or transit access), blocked sidewalks, and barrier to disabled access. With e-scooter pricing being significantly expensive as compared to public transportation, these factors are to be dealt with to increase the share of people using e-scooters in a safe and mobile environment.

With more opportunities for people to move efficiently in groups, car-sharing and car-pooling have provided a platform for the same. While the two terms may act as synonyms, they slightly vary in their functionality. While both involve the car being shared by the people to move in a common direction of route, the ownership of the car varies. While the car is owned by a company in car-sharing, the vehicle is owned by an individual in car-pooling (Delhomme & Gheorghiu 2016). Car-pooling has shown 12.5% reduction in number of kilometres travelled (International Energy Agency 2005), which helps in reducing fuel consumption leading to less pollution. As a next step, free-floating car-sharing (FFCS) can be seen as an evolved version of traditional car-sharing approach, which allows users to pick-up and return cars anywhere within the city in specified boundary limits. In a study of 22 cities in North America and Europe (Habibi S. et al 2017), average daily trip lengths of FFCS have shown to fall within a range of 2.5 - 6 kilometres. This range is quite comparable to that of cyclists, as most cycling trips are between 2.5 - 7.5 kilometres in length on regular bicycles, which increases to 15 kilometres on electronic bikes (i.e. e-bikes) (CIVITAS 2016). The similar range of trip lengths reflect the alternate mode choices people have within a city, given the existing infrastructure supports the modal utility services.

2.1.4 Mobility during Coronavirus pandemic

With the outbreak of Coronavirus pandemic (COVID-19) in 2020, many cities around the world have seen changes in their mobility lifestyle. Many people have shifted to walking and cycling through the streets which were once congested by motorized vehicles. This has led to reduction in local air pollution by 60% globally (IQAir 2020). At the same time, the social distancing regulations has led to renewed interest in dedicating more space to people. There have been many examples which include temporary pedestrianization of urban spaces, widening of pedestrian pathways and cycle lanes, and more seating spaces in open unused areas.

Agora Verkehrswende (2019), Shared E-scooters: Paving the Road Ahead, Policy Recommendations for Local Government, Berlin, pp. 5-46.
Portland Bureau of Transportation [PBOT] (2019), 2018 E-Scooter Findings Report, Portland, USA, Retrieved from https://www.portlandoregon.gov/transportation/article/709719
Delhomme, P. and Gheorghiu, A. (2016), Comparing French carpoolers and non-carpoolers: Which factors contribute the most to carpooling? Transportation Research Part D: Transport and Environment, 42, pp. 1-15, ISSN 1361-9209. DOI: https://doi.org/10.1016/j.trd.2015.10.014.
Habibi, S., Sprei, F., Englund, C., Pettersson, S., Voronov, A., Wedlin, J., and Engdahl, H. (2017), Comparison of free-floating car sharing services in cities, ECEEE Summer Study Proceedings, France, pp. 771-778.
CIVITAS (2016), CIVITAS Policy Note: Smart choices for cities. Cycling in the city, Netherlands, Retrieved from https://civitas.eu
IQAir (2020), Report: COVID-19 impact on air quality in 10 major cities, Retrieved from https://www.iqair.com/fr/blog/air-quality

With lockdown measures being eased out gradually in many cities, people perceived the use of public transportation as a risk to avoid close contact and crowds. This led to more cars being back on roads in major cities of China and other countries, with decrease in public transport utility. There was 53% below normal volume in metros from pre-pandemic scenario in Beijing, while Berlin being one of the first European cities to come out of lockdown saw its public transit use down by 61%, followed by 87% lower utility of public transport in Madrid (Bloomberg 2020).

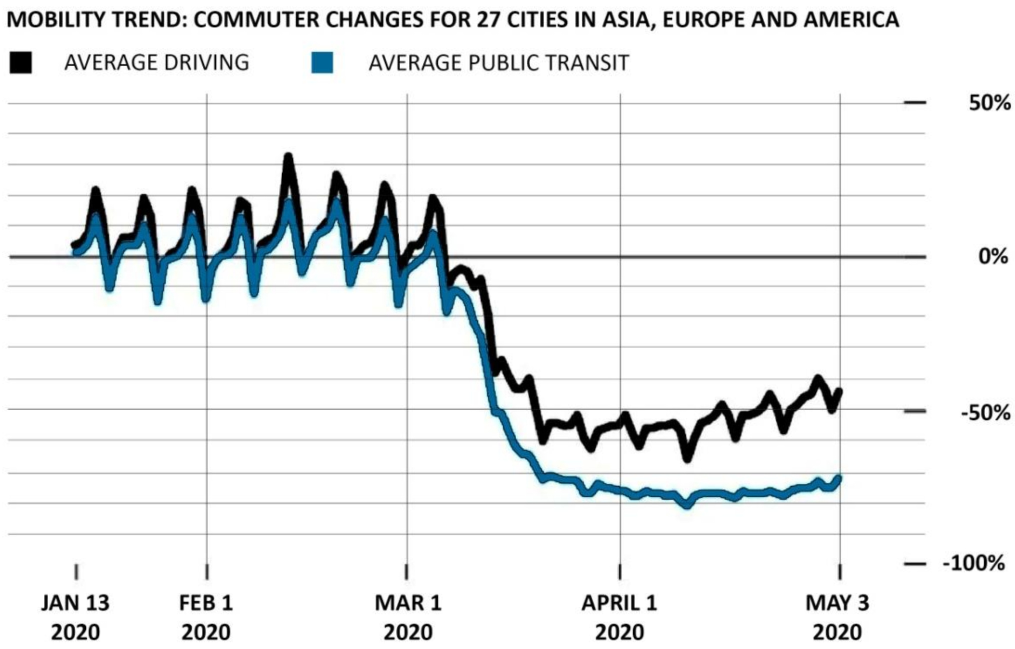

Figure 8: Commuter changes for cities in 2020 showing shift fast recovery of private vehicles over public transport during COVID-19 lockdown measures. Source: Image (modified) - Bloomberg (2020)

The pandemic altered the perception of people towards walking and cycling, with many urban administrations also taking definitive steps. More than 1800 cities took the action to support non-motorized transport through walking and cycling since the start of the COVID-19 pandemic (Goestch, H. & Quiros, T. P. 2020). In order to reduce crowding of people on public transport, many cities have planned to introduce temporary cycle lanes and expand the existing network of cycling. The city of Bogotá planned to open 76 kilometres of cycle lanes, with 22 kilometres of new cycle lanes converted overnight by changing car lanes (Wray, S. 2020). Many German cities have temporarily introduced interventions on the existing network of bike lanes through 'pop-up' cycle lanes and widening of existing cycle lanes for people to maintain social distancing through active modes of transport (Oltermann, P. 2020). With the introduction of 'open roads' in Milan through wide pedestrian pathways and new cycle lanes, the city plans to move towards the path of sustainable mobility by reallocating street space from cars to pedestrians and cyclists (Municipality of Milan 2020). In Paris, since the pandemic took place, more than 50 kilometres of bike lanes known as 'coronapistes' have

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Bloomberg (2020), The car is staging a comeback, spurring oil's recovery, Retrieved from https://www-bloomberg-com.cdn.ampproject.org/c/s/www.bloomberg.com
Goestch, H. and Quiros, T. P. (2020), COVID-19 creates new momentum for cycling and walking. We can't let it go waste, Transport for Development, World Bank, Retrieved from https://blogs.worldbank.org/transport/covid-19-creates-new-momentum-cycling-and-walking-we-cant-let-it-go-waste
Wray, S. (2020), Bogotá expands bike lanes to curb coronavirus spread, SmartCitiesWorld, Retrieved from https://www.smartcitiesworld.net
Oltermann, P. (2020), Pop-up bike lanes help with coronavirus physical distancing in Germany, The Guardian, Berlin, Retrieved from https://www.theguardian.com/world/2020
Municipality of Milan (2020), Quartieri. Con "Strade aperte" nuove aree pedonali, ciclabili, zone 30 e spazi pubblici, Milan, Italy, Retrieved from https://www.comune.milano.it

been introduced in the city (Yeung, P. 2021). In a major group of cities on a global platform, C40 cities are focusing on giving streets back to the people, especially by creating 15-minute cities where people could reach their destinations for essential needs by walking or cycling on a larger network (C40 2020). These steps propagate shift towards active modes by providing more safety and allow people in their respective cities to follow social distancing measures with added space of movement.

2.2 Understanding accessibility in an urban scenario

Accessibility as a term has varied and diverse definitions and understandings, and links itself to different fields of study. It is important to understand as to what the term 'accessibility' means and how it is perceived with respect to the urban context. Accessibility refers to the ease to arrive to facilities, activities or goals, which could be appointed in general as opportunities. In addition, accessibility could be defined as the intensity of the possibility of 'interaction' (Hansen, 1959) and 'exchange' (Engwicht, 1993). With respect to the perspective of Hansen, accessibility deals as a function of service towards an individual's 'opportunities', which in turn leads to generation of needs, and associated activities towards it. Interaction within the system, leads to an enhanced accessible environment. Further exchange of services, act as an interim part of the opportunities and services, which also play an integral role in order to access the same.

Various disciplines analyse accessibility, but their perspective is often varied. Transport planners generally focus on mobility, particularly vehicle travel while land use planners focus on geographic accessibility. The geographic accessibility usually limits to distances between different activities. Communications experts focus on telecommunication quality as a measure of accessibility, which includes providing portion of households with access to telephone, cable and Internet services. Social service planners focus on accessibility options for specific groups to specific services (such as disabled people’s ability to reach medical clinics and recreation centres) (Litman, 2016). In order to analyse accessibility, Litman defines the term through diverse perspectives of the individuals based on their profession and their respective focal points, which in other terms can be regarded as the 'activities or goals' based on the definition by Hansen and Engwicht. With respect to a space, an accessible public space is one where many different people can come, and also where many different people can do different things: it is an accessible node, but also an accessible place (Bertolini and Dijst, 2003). With the adjacent perspective, Bertolini and Dijst place public space as their central node and define the access to the space. Access deals with the ability of diverse user-groups who can access the space, and at the same time are able to interact with their immediate environment and the surrounding elements don't act as barriers. The statement also defines that the focal point acts as a node, in other words there are other nodes which act as spaces which are not necessarily public spaces but other elements like pedestrian junctions, public transportation service stops, etc. The notion of defining accessibility for an area is usually place-based, i.e. it is understood as a measure of accessing or reaching a place from the point of origin.

In an urban environment, the parameters of accessibility and mobility have been seen to be dictated by the design and layout of the buildings and the immediate road infrastructure (Evans, G. 2009). The network of roads (or streets) is influenced by the layout of buildings and vice versa, which impacts the

C40 (2020), C40 Mayors' Agenda for a Green and Just Recovery, USA, pp. 2-43. Retrieved from https://www.c40.org/other/agenda-for-a-green-and-just-recovery
Hansen, W. G. (1959), 'How accessibility shapes land use', Journal of American Institute of Town Planners, pp 73-76.
Engwicht, D. (1993), 'Reclaiming our cities and Towns: Better Living with Less Traffic, New Society Publishers. Retrieved from www.newsociety.com
Litman, T. (2016), 'Evaluating Accessibility for Transportation Planning: Measuring People's Ability to Reach desired Goods and Activities', Victoria Transport Policy Institute, pp 3-9.
Bertolini, L. and Dijst, M. (2003), Mobility Environments and Network Cities, Journal of Urban Design, 8:1, pp. 27-43. DOI: 10.1080/1357480032000064755

physical distances and routes an individual takes to reach their destination. Once these layouts are established in an urban setting, they become the identity of the neighbourhood, of the city, which is permanent in nature with temporary changes in its structure from time to time.

2.2.1 Accessibility as a measure

Within an urban environment, accessibility plays an important role in assessing many areas. Many locations are easier to reach by different modes of transport including walking, bicycling or a combination with public transport. Accessibility as a parameter is often utilized to measure the potential of an urban area through various attributes which have been majorly distance or time based. Some studies take the distance factor to analyse different service accessibilities including job accessibility (Cheng and Bertolini 2013), spatial accessibility to hospitals (Zheng et al. 2019), accessibility to retail and services (Scott and Horner 2008), and many other opportunities (or destinations). Location plays an important role in the study of accessibility, and it shows how the degree of accessibility varies i.e. some locations have higher quality of accessibility while some have a lower figure. There has been a good relation between accessibility and urban development, with accessibility playing a crucial link between land-use and transportation (Hansen 2009). In US, accessibility is utilized as a measure to improve the existing infrastructure impacting pedestrians, cyclists and transit (Duranton and Guerra 2016).

ACCESSIBILITY MEASURE: SPACE SYNTAX ANALYSIS (INTEGRATION)

ACCESS TO DIFFERENT PUBLIC SPACES IN GRANADA, SPAIN

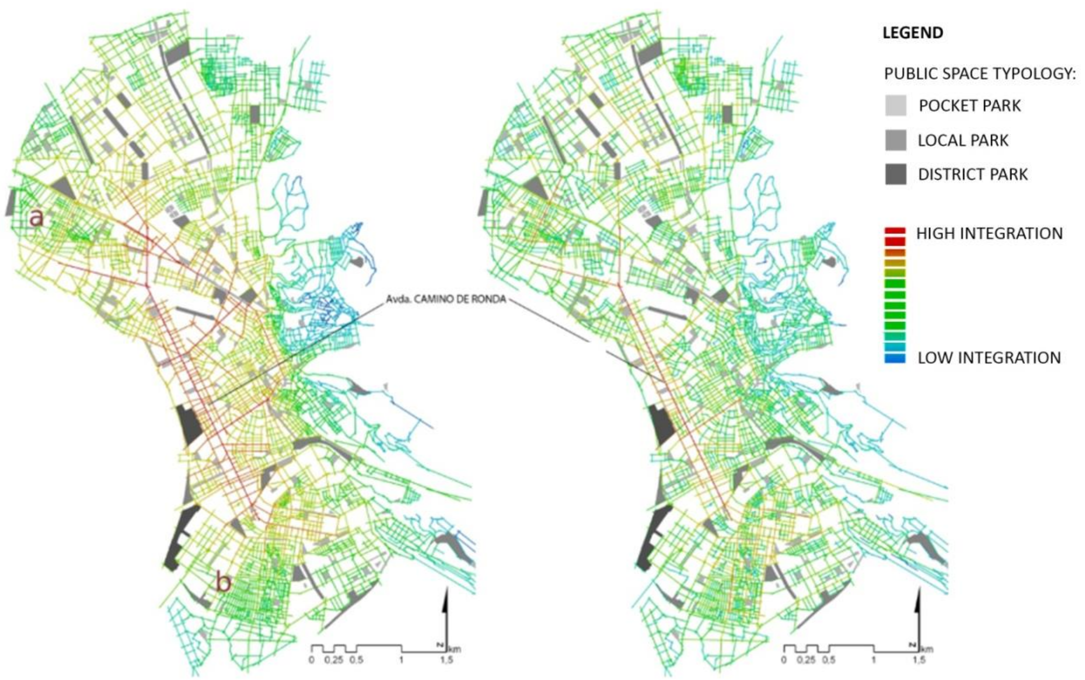

Figure 9: Global integration (left) and local integration (right) of selected urban area in Granada showing access to public spaces
Source: Image (modified) - Era R. (2012) Note: a and b are two areas with low global integration values, excluding the eastern area.

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Cheng, J. & Bertolini, L. (2013), Measuring urban job accessibility with distance decay, competition and diversity, Journal of Transport Geography, 30, pp. 100-109, ISSN 0966-6923.
Zheng, Z. et al. (2019), Spatial accessibility to hospitals based on Web Mapping API: An Empirical Study in Kaifeng, China, Sustainability, 11 (4):1160.
Scott, D., & Horner, M. (2008), The role of urban form in shaping access to opportunities: An exploratory spatial data analysis, Journal of Transport and Land Use, 1(2), pp. 89-119.
Hansen, H. S. (2009), Analysing the role of accessibility in contemporary urban development, Computational Science and its Applications, International Conference on Computational Science and its Applications, 5592, Heidelberg, pp 385-396. DOI: https://doi.org/10.1007/978-3-642-02454-2_27

With different user groups, accessibility as a measure for an urban space varies along with diverse modes of mobility. Space Syntax (Hillier and Hanson 1984) as a theory has shown its practical utility through understanding spaces in an urban environment as a network of different elements or units (i.e. streets, open plazas, buildings etc) which are linked together and form a relation between them. With each unit having its own degree of accessibility, Space Syntax analysis has opened a new way of understanding these relationships through different perspectives of users including pedestrians, automobiles, and cyclists through different parameters (for e.g. integration, connectivity etc.). Studies including Penn A. et al. (1998), Monokrousou and Giannopoulou (2016), and many more showcase the ability of the Space Syntax analysis to predict human movement in urban spaces. Era R. (2012) utilizes Space Syntax to improve the pedestrian accessibility to public spaces in Granada (see Fig. 9) through different measures (including integration). In the analysis, the integration values mainly comply with two different user groups based on their movement. While global integration takes all the units (i.e. streets for the particular study) to address the access to automobiles, local integration restricts to limited units to showcase the access to pedestrian movement. The analysis indicates how some public spaces closer to highly integrated streets have more access and provide more freedom of choice for people to move, as compared to parks which have low frequency of highly integrated streets in its periphery. This helps in prioritizing certain streets which are crucial to link other spaces in the urban network and assist local authorities in their urban planning and development process. One key element which distinguishes the Space Syntax analysis from other accessibility measures, is its ability to define relationships within the network of streets through the human-eye perspective, which portrays a unique way of assessing accessibility.

ACCESSIBILITY MEASURE: PUBLIC TRANSPORT ACCESSIBILITY LEVEL (PTAL)

ACCESSIBILITY LEVELS OF DIFFERENT ZONES TO PUBLIC TRANSPORT IN LONDON

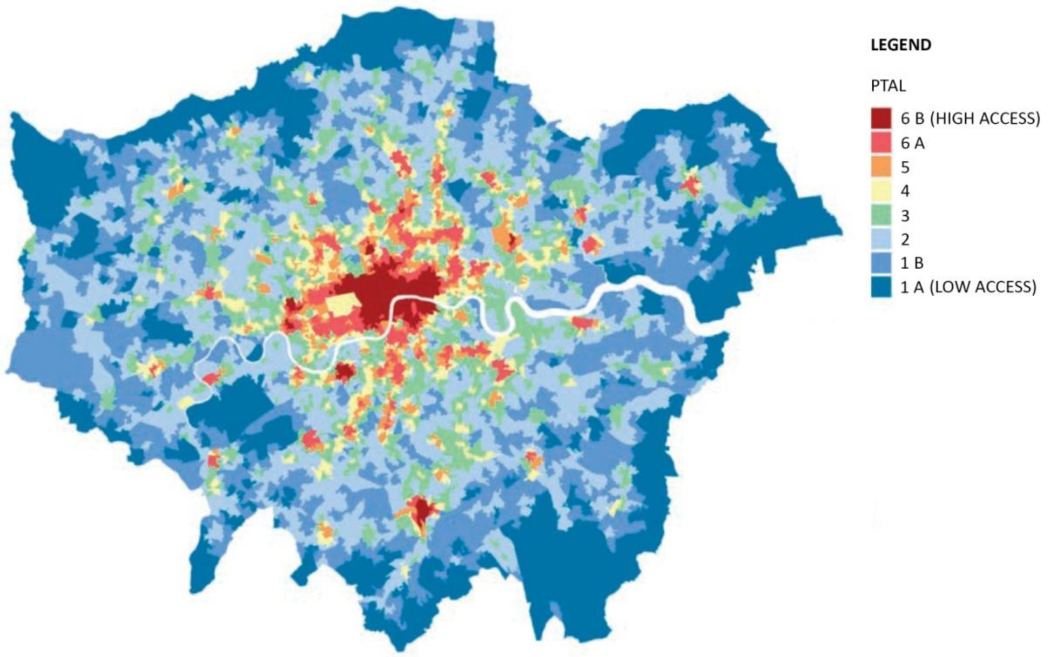

Figure 10: Accessibility levels based on PTAL index in London
Source: Image (modified) - TFL (2015)

Penn A, Hillier B, Banister D, Xu J. (1998), Configurational Modelling of Urban Movement Networks, Environment and Planning B: Planning and Design, 25(1), pp. 59-84.
Monokrousou, K. and Giannopoulou, M. (2016), Interpreting and Predicting Pedestrian Movement in Public Space through Space Syntax Analysis, Procedia - Social and Behavioral Sciences, 223, pp. 509-514, ISSN 1877-0428. DOI: https://doi.org/10.1016/j.sbspro.2016.05.312.
Era, R. (2012), Improving pedestrian accessibility to public space through space syntax analysis, Proceedings: Eighth International Space Syntax Symposium, Santiago, pp. 1-16.
Transport for London [TFL] (2015), Assessing transport connectivity in London, London, Retrieved from tfl.gov.uk

Apart from private vehicles and other individual modes of mobility, public transport allows different user-groups to move through diverse spaces within an urban area. Access to public transport services is usually characterized by its proximity to an origin or destination, along with other factors which include service frequency, cost of travel, diversity of modes, and more. Murray et al. (1998) defines access as the opportunity of the system use with respect to the proximity of the service and its cost. A mode of public transit is underutilized if the barriers or distances to reach the service station are greater at the point of origin or destination. There are many measures which try to produce a level of accessibility for public transit through the measure of distance and time. One such measure which is utilized by the local authorities includes Public Transport Accessibility Level i.e. PTAL (Transport for London 2015). The measure assesses accessibility for an urban space based on its proximity to the transit station along with the peak hour frequency of the services with pre-defined observation boundaries (see Fig. 10). These boundaries are based on human movement and by determining the accessibility of urban spaces, the index helps in supporting many urban planning processes.

Some of these include determining housing densities (which is based on the principle that urban areas with good access to transit services favour intense development), provision for parking spaces (e.g. providing less parking space for areas with more access to transit services to encourage use of public transport), establishing new service links for less accessible urban spaces and many more. Studies by Yang et al. (2019), Adhvaryu et al. (2019), and many others utilize the index in different urban environments demonstrating its ability to represent different access levels, which helps in prioritizing the areas with low levels of access to public transport. Similar to PTAL, there are other indicators such as closeness centrality or network coverage under the SNAMUTS tool (Curtis and Scheurer 2015), assessing the accessibility perspectives which include more complex cumulative-opportunity or gravity-based measures of accessibility (Makri and Folkesson 1999). While the cumulative-opportunity based measure of accessibility is usually utilized to indicate the frequency of opportunities which is accessible within a particular distance or time from the point of origin, gravity-based measure (Hanson 1959, as mentioned in Makri and Folkesson 1999) adds weightage to the opportunities. Through PTAL, with different catchment radii for different modes of travel, the index assists in communicating the accessibility perspective with different disciplines through its simplicity and accessible data driven approach. Different measures of accessibility have been utilized to address different aspects to determine accessibility as a factor to improve the present level of access in urban areas. While most of the measures utilize distance (or time) as parameter, others combine accessibility-related aspects to examine an urban area as a whole. A prerequisite knowledge of these measures assists in choosing different parameters (and to further improve them) to address and prioritize different aspects for planning and policy decision making.

2.3 Urban mobility in European context

With urban mobility in focus, the European Commission (2020) has set several goals for a sustainable

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Murray, A., Davis, R., Stimson, R. J., and Ferreira, L. (1998), Public Transportation Access, Transportation Research Part D: Transport and Environment, 3(5), pp. 319-328. DOI: https://doi.org/10.1016/S1361-9209(98)00010-8.
Yang, R., Liu, Y., Liu, Y., Liu, H., and Gan, W. (2019), Comprehensive Public Transport Service Accessibility Index-A New Approach based on Degree Centrality and Gravity Model, Sustainability, 11(20):5634. DOI: https://doi.org/10.3390/su11205634
Adhvaryu, B., Chopde, A., and Dashora, L. (2019), Mapping public transport accessibility levels (PTAL) in India and its applications: A case study of Surat, Case Studies on Transport Policy, 7(2), pp. 293-300, ISSN 2213-624X. DOI: https://doi.org/10.1016/j.cstp.2019.03.004
Curtis, C., and Scheurer, J. (2015), Performance measures for public transport accessibility: Learning from international practice, Journal of Transport and Land Use, 10(1).
Makri, M.-C., and Folkesson, C. (1999), Accessibility measures for analyses of land use and travelling with geographical information systems, Department of Technology and Society, Lund Institute of Technology, Lund, Sweden.
European Commission (2020), Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions Sustainable and Smart Mobility Strategy - putting European transport on track for the future, Brussels. Retrieved from https://ec.europa.eu/transport/themes/mobilitystrategy_en

and resilient transportation system in future. It focuses on 100 European cities to be climate neutral, with 30 million zero-emission vehicles to be operational by 2030. With respect to other modes of long-distance transport, zero-emission aircrafts are planned to be operational by 2035, followed by cars, buses, along with heavy duty vehicles to be zero emission vehicles by 2050. It focuses on a sustainable and healthy interurban and urban mobility system through measures which include the high-speed rail traffic to double, along with better infrastructure for cycling in next ten years. An accessible multimodal system for people would establish a resilient transport system through many practices.

Aligning walking and cycling measures to overall mobility strategy for cities has led to dedicated short-term and long-term plans being executed. In large-sized cities like Paris, the introduction of 10-hectare car-free space for cycling and walking alongside river Seine has resulted in decongestion by cars which helps with the execution of investments in bicycle infrastructure and different zones based on speeds (i.e. 30 kmph or 20 kmph 'meeting zones' and pedestrian areas) (Köhler et al. 2019). With respect to medium-sized cities, similar approaches have been observed to move towards an accessible multimodal system. Implementing sustainable mobility through their plan, the city of Vitoria-Gasteiz proposed a superblocks model where the utility of public spaces was divided according to the mobility typology (CIVITAS 2013). This resulted in 68 superblocks where the use of private cars and public transport would be prohibited. The introduction of 'slow-speed streets' allowed vehicles to adjust their speed of movement to that of pedestrians and cyclists. Street elements like planters and flower boxes, assisted in reducing the vehicular speed. The overall outcome of the plan led to increase in the proportion of pedestrian surface from 45% to 74%, along with reduction in urban noise levels as the space for cars was transformed for pedestrians. While the plan led to introduction of 17 superblocks (including 47 streets) overall in practice, the limitation in funds led to further works to be implemented through light (and cheap) measures.

In Europe, different cities have shown different mobility characteristics. The modal share of urban movement in major European cities (see Table 1) shows how different cities function with one mode dominating over the other. The cycling cities of Amsterdam and Copenhagen have had high modal share of cyclists moving around the city, which is even beyond the modal share by public transport. With respect to Copenhagen, the city plans to further reduce the modal share of cars to 25% by 2025 based on their CPH 2025 Climate Plan (City of Copenhagen 2019). The modal share is often representative of the amount of street space each mode is allowed in an urban area. A shift in the modal share from one mode to another, would influence the amount of street space available for different user-groups in their daily travel behaviour, be it multimodal or intermodal. In Amsterdam, with many busy streets being too narrow for all modes to share the space, the planning authorities through their mobility implementation plans (Municipality of Amsterdam 2015) suggested three ways of providing more street space. The first includes provision of garage spaces to reduce on-street parking space by cars. With 40% of space already occupied by car-related infrastructure, the relocation of parking space from busy streets would provide an opportunity for other modes to have more space for their movement. The second measure includes sharing of street lanes between public transport i.e. trams and cars, where it is possible. The shared space approach would minimize the infrastructure for the two modes of travel and offer more space for other user-groups. The third measure for providing more street space includes introduction of 30km/h zones, especially on streets where cyclists are

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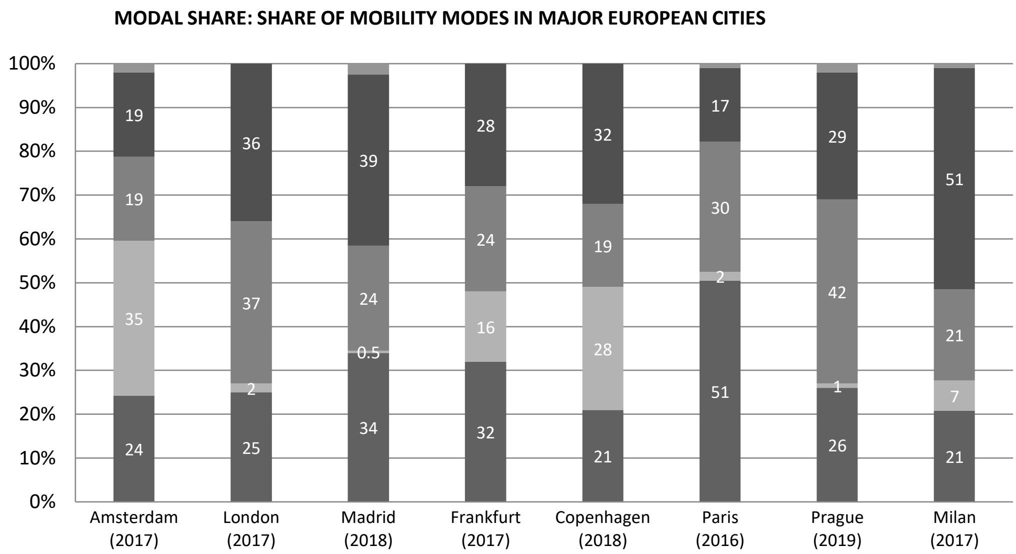
Köhler, D., Németh, B., Mourey, T., and Caballero, J. (2019), Manual Including Thematic Guidelines and Handbook for Local Campaigners, European Mobility Week 2019, European Commission. Retrieved from https://mobilityweek.eu
CIVITAS (2013), Case Study Streets designed for sustainable mobility Demand Management Strategies, ICLEI, Freiburg, Germany. Retrieved from https://civitas.eu/measure/superblocks-model
City of Copenhagen (2019), The Bicycle Account 2018 Copenhagen City of Cyclists, Copenhagen, Denmark. Retrieved from https://kk.sites.itera.dk/apps/kk_pub2/index.asp?mode=detalje&id=1962
Municipality of Amsterdam (2015), Uitvoeringsagenda Mobiliteit, Amsterdam. Retrieved from amsterdam.nl/parkeren-verkeer/uitvoeringsagenda

predominant. This would invite car and motor traffic as guests eventually shifting the fast-traffic to other streets.

Private modes of transport have been prevalent in cities like Milan, Madrid and London, although with respect to London, the city has the network of public transport dominating the private transport on modal share. This showcases the choice of public transport as a mode being preferred over the private modes, which is also observed through the cities of Paris and Prague. With respect to the city of Madrid, vast majority of the trips are being made by private vehicles, followed by walking and public transport. Other modes including cycling, taxis etc. represent only 3 percent of the total modal share. From late 1990s, the modal share of public transport in Madrid has reduced by 8%, while that of private vehicles has increased by 11%. One of the reasons for the change is attributed to the relocation of activity and residence areas towards the peripheral areas of the city (Consorcio Regional de Transportes de Madrid 2019). This shows how the interventions on the land-use planning impacts the overall urban mobility system, which in the case of Madrid reduced the overall modal share of public transport.



	Amsterdam (2017)	London (2017)	Madrid (2018)	Frankfurt (2017)	Copenhagen (2018)	Paris (2016)	Prague (2019)	Milan (2017)
Others	2	0	2.5	0	0	1	2	1
Private Transport / Cars	19	36	39	28	32	17	29	51
Public Transport	19	37	24	24	19	30	42	21
Cycling	35	2	0.5	16	28	2	1	7
Walking	24	25	34	32	21	51	26	21

■ Walking ■ Cycling ■ Public Transport ■ Private Transport / Cars ■ Others

Table 1: Modal split in different European cities showing varied characteristics Note: Figures may have slight differences due to rounding off Data Source: Amsterdam (Municipality of Amsterdam 2019), London (Transport for London 2018), Madrid (Consorcio Regional de Transportes de Madrid 2019), Frankfurt (Bundesministeriums für Verkehr und digitale Infrastruktur 2020), Copenhagen (City of Copenhagen 2019), Paris (Mairie de Paris 2016), Prague (Techniká Správa Komunikací Hlavního Města Prahy 2020), Milan (CNR-IIA and Kyoto Club 2019).

Many cities progress on the modal share trend for their future plans, working towards a sustainable and efficient mobility system. With the share of active and sustainable modes of transport (i.e. walking, cycling and public transport) being around 64% in 2017, the city of London aims to increase the share

Consorcio Regional de Transportes de Madrid (2019), Encuesta de Movilidad de La Comunidad de Madrid 2018, Madrid, Spain. Retrieved from https://www.crtm.es to 80% by 2041. This builds up from the trend of how the people in the city have shifted towards the public mode of transport, as the modal share was less than half of private mode share in early 1990s (Transport for London 2018). The high modal share of public transport in Prague reflects upon its measures of prioritizing the public transport vehicles in order to maintain the positive ratio of people moving through public transit system as compared to private transport. Some of these measures involve the traffic light system in the city favouring the network of trams and buses with zero to less delay in travel, along with dedicated lanes for buses and trams. While the city has a high share of people using public transport for their daily mobility, the proportion of cyclists on the other end is low. The low modal share of cyclists in Prague can be attributed to weak integrated system, where the cycles aren't allowed to use majority of buses along with limited tram access (TSK 2020). Such barriers prevent the potential of successful multimodal integration in the mobility system of urban areas. On the contrary, the cities of Copenhagen and Frankfurt show a more balanced distribution of modal share of different modes as compared to other cities. While Milan deals with high share of vehicular traffic with respect to modal split, its future plans focus on reducing the share through measures which include allocating more pedestrian space and cycle pathways in the city. These measures have seen rapid implementation, especially during the pandemic in 2020, where the focus on the present scenario of urban mobility is prioritized (Laker 2020). With cities moving towards reducing share of private vehicles in the overall modal share, a trend on moving towards active mobility can be observed with mobility based on short-distance being of utmost importance. This has also been positively corresponded by the choice of people who prefer car-free urban planning, especially in Germany (BMUB and UBA 2017). The ability to move around the city where people depend less on cars but can walk on foot, cycle or use public transport as a medium of transport has been widely accepted by the people in Germany.

2.3.1 Shift towards short-distance mobility system in Germany

Based on a public survey, majority of the people believe to have a better life if there is less car dependency, with many favouring urban developments that focuses on an alternative as compared to car-centric approach for their city or community in Germany (BMUB and UBA 2017). To support and improve active mobility, national pedestrian and cycling strategies have been put to force to be adopted by the federal government through diverse action plans. With initiatives like National Cycling Plan 2020 (Federal Ministry of Transport, Building and Urban Transport 2012), the promotion of cycling along with walking and public transport (comprising together as eco-mobility) have been put into action. Some of the plan's main priorities include:

- Promotion of cycling as a main mode of mobility in both urban and rural areas.
- Creation of bicycle infrastructure along with pilot projects and supportive measures.
- Importance of cycling with the integrated transport system which includes linking it with the objectives in fields comprising of urban development, health and other social subjects.

Transport for London (2018), Travel in London Report 11, London, UK. Retrieved from http://content.tfl.gov.uk/travel-in-london-report-11.pdf
Techniká Správa Komunikací Hlavního Města Prahy [TSK] (2020), Prague Transportation Yearbook 2019, Prague, Retrieved from http://www.tsk-praha.cz
Laker L. (2020), Milan announces ambitious scheme to reduce car use after lockdown, The Guardian, Retrieved from https://www.theguardian.com/world/2020/apr/21/milan-seeks-to-prevent-post-crisis-return-of-traffic-pollution
BMUB and UBA (2017), Umweltbewusstsein in Deutschland 2016 Ergebnisse einer repräsentativen Bevölkerungsum-frage, Online Edition, Germany. Retrieved from https://www.umweltbundesamt.de
Federal Ministry of Transport, Building and Urban Development (2012), National Cycling Plan 2020 Joining Forces to evolve cycling, Second Edition, Berlin, Germany. Retrieved from https://repository.difu.de/jspui/handle/difu/232116

- and emphasis on safety through campaigns and recommendations for states and local authorities.

Geht Doch! is another example of the programme launched by the Federal Environment Agency in Germany (Umweltbundesamt 2018) which lays groundwork for nationwide walking strategy through its seven goal criteria. It acknowledges pedestrian traffic to be insufficiently researched and reported in topics related to transport. One of the questions it tackles includes finding ways to record foot traffic adequately, with focus on state-of-the-art alternatives supporting and expanding pedestrian pathways in cities. Within the Geht Doch! framework, some of the goals for basic concept of pedestrian traffic includes:

- Increasing proportion of walking as a medium: The share of people walking would increase from 27% to 41% in core urban areas and from an average of 24% to 35% in rural areas.

- Improving the safety of walking: This includes reduction in pedestrian accidents with long-term prevention of fatal accidents to zero.

- More active lifestyle: This involves promotion of healthy activities expanding to more than 30 minutes a day.

- Independent movement for users with restricted mobility: People with restricted mobility i.e. ones using wheelchairs, canes etc. would be able to move with less assistance from others.

- Making walking more attractive in cities and towns: Through the model of compact and mixed-function city in urban development, the objective is to reduce the walking path by 8 kilometres per route.

In order to summarize the overall mobility scenario in Germany, the Mobilität in Deutschland (MiD) reports in past two decades have assisted in showcasing the share of modes being utilized through 'modal split' (or modal share) in states and cities. The term relates to the share of mode over the transport volume and overall trips being made. While the earlier reports list the use of private vehicles as a separate mode, the latest report (i.e. 2017) further segregates the mode into private vehicle drivers and passengers. While slight growth has been observed amongst cycling and using public transport as a travel mode, the proportion of trips travelled on foot have reduced slightly over the years. These characteristics vary through different states within Germany, where the city states of Berlin, Hamburg and Bremen produce higher share of public transport and cycling being used as a mode to travel. Overall urban regions in metropolis and large cities have shown higher proportion of active means of transport (see Table 2) i.e. walking, cycling and public transport (62% in metropolis and 50% in large cities) in modal share as compared to medium and small-sized cities (39% in medium-sized cities and 33% in small cities). This shows how the share of modal choice varies among cities based on their sizes, where private vehicles show more dominance in medium and small cities in Germany. While the urban areas in large cities and metropolis show high dependence on active mobility system, the medium and small cities show more dependence on private motor vehicles. In the discussion regarding modal split in Germany, it is important to differentiate between the definition of large and medium-sized cities, where large cities are areas having 100000 inhabitants and more, while medium-sized cities have inhabitants ranging between 20000 and 100000. Following this definition, it would put cities like Frankfurt, Berlin, Offenbach, Darmstadt and many others in one

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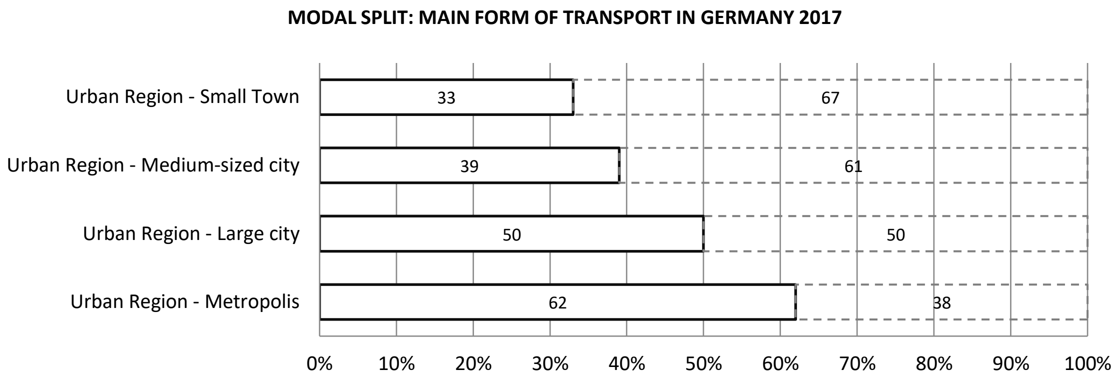
Umweltbundesamt (2018), Geht Doch! Grundzüge einer bundesweiten Fußverkehrsstrategie, Online Edition, Dessau-Roßlau, Germany. Retrieved from https://www.umweltbundesamt.de/publikationen/geht-doch
Bundesministeriums für Verkehr und digitale Infrastruktur [BMVI] (2020), Mobilität in Deutschland - MiD Regionalbericht Hessen, Bonn. Retrieved from https://wirtschaft.hessen.de/sites/default/files/media/hmwvl/infas_mid2017_regionalbericht_hessen.pdf

group. Irrespective of the range categorization, the trend shows inhabitants in larger cities generally being more dependent on active mobility modes as compared to smaller cities.



	Urban Region - Metropolis	Urban Region - Large city	Urban Region - Medium-sized city	Urban Region - Small Town
Active Modes	62	50	39	33
Private Modes	38	50	61	67

Table 2: Modal split in urban areas of cities based on their size in Germany
Data Source: Follmer, R. and Gruschwitz, D. (2019)

Urban planning principles influencing short-distance mobility

In Germany, the guiding urban planning principles of *Innenentwicklung vor Aussenentwicklung* (i.e. internal development before external development), *Doppelte Innenentwicklung* (i.e. double internal development) and more have an influence on how the mobility behavior takes shape for a network of urban areas. The German Building Code (i.e. Baugesetzbuch) defines the concept of *Innenentwicklung* as a development plan for making areas usable again through densification and other internal development measures in an accelerated procedure. The 2013 amendment to the German Building Code formulated the principle of giving priority to internal development as a general objective of urban land use planning. Against the backdrop of the current high demand for additional living space in integrated urban locations, this principle has come into particular focus (UBA 2014). This makes the planning authorities under obligation to look for possibilities for internal (or inner) development prior to any agricultural or forest land being converted for the purpose. This falls within the brownfield redevelopment project category, where the revitalization contributes towards sustainable urban development. This contributes towards the development of a 'city of short routes' and reduces traffic volume and congestion (Kälberer 2005). The benefits of 'internal development before external development' (i.e. Innenentwicklung vor Aussenentwicklung) lie in the avoidance of landscape encroachment, which addresses towards a sustainable approach of living in urban areas where there is a possibility of using existing infrastructure or making better use of its potential. Identifying potential housing construction in the inner area can result from very different urban development situations. These include, for example, the filling of empty gaps between buildings, the addition of extensions and floors to existing buildings, the redensification of old multi-story housing estates, etc. This also includes the conversion of building infrastructure which were previously not used for residential purposes.

Follmer, R. and Gruschwitz, D. (2019), Mobility in Germany - short report, Federal Ministry of Transport and Digital Infrastructure (BMVI), Bonn. Retrieved from www.mobilitaet-in-deustchland.de

Kälberer, A. (2005), The Future lies on Brownfields, Federal Environmental Agency, Dessau, Germany, pp. 5-8.

UBA (2014), Brownfield redevelopment and inner urban development, Germany. Retrieved from https://www.umweltbundesamt.de/en/print/23715 15-08-22

While the *Innenentwicklung vor Aussenentwicklung* concept would lead to less distances between existing infrastructure and opportunities within a city (which in turn influences the mode of mobility a person uses to move around for intra-city travel) along with less expenditure on mobility infrastructure, there would be many obstacles to initiate the process. These include owners not willing to invest or sell their properties within the inner-city limits for the brownfield project, difficult spatial layouts for new construction, resistance from residents living in the neighborhood, differences in the priorities from diverse stakeholders and more. In addition to densification principles, *Doppelte Innenentwicklung* focuses on internal development which considers structural as well as green development. Preservation and development of urban greenery along with densification of urban areas in the inner parts of the city is the main basis of *Doppelte Innenentwicklung* (Kühnau et al. 2017). The guiding principle assists in tackling conflicting goals between structural and open-space development, which are often at the expense of open green spaces. The viewpoint of the two-way internal development makes the network of spaces more attractive which in turn influences the distance of active movement for a person (Gruen 1964). While there are studies which suggest stress-relieving potential of green exposures (Barton and Petty 2010, Woo et al. 2009), which influences walking in an urban environment, study by Zhang et al. (2020) showcases the size and distribution of green spaces like parks having less influence when walking to park destinations than it is on route choice for the commute (with crowding or congestion being one of the plausible reasons). Overall, principles of densification of urban areas through brownfield urban development approach support the short-distance mobility system where the existing potential of urban areas is utilized, and greenfield urban developments at a distant-peripheral boundary of a city are discouraged, which reduces the overall distance-time frame of reaching different destinations with better accessibility.

2.3.2 Rhein-Main urban agglomeration and its urban mobility vision

2.3.2.1 Defining urban agglomeration

Urban agglomeration as a term has seen many definitions over the years, where some planners, practitioners and planning authorities relate the term being equivalent to town clusters, conurbations, cluster of cities, urbanized areas which are within daily commutable radius, metropolis belt, urban expansion area, and many more (Fang & Yu 2017). Many of these definitions refer to metropolitan region as their basis, which tends to include one or more central cores and other cities in peripheral area that are linked to each other economically, socially or both. In addition to core cities, an urban agglomeration includes small and medium-sized cities, which interact together in a healthy competitive environment for a better overall growth.

Though many definitions have similarities in their approach, they at times differ on the basis of quantitative measures. Based on quantitative definitions of urban agglomerations, the population criteria range from an overall value being at least 2.5 million (Gottman 1957) to 30 million inhabitants (Yao et al. 2001). Fang & Yu (2017) summarize the agglomeration term as a process that evolves in

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Kühnau, C., Böhm, J., Reinke, M., Böhme, C. and Bunzel, A. (2017), Doppelte Innenentwicklung – Perspektiven für das urbane Grün Empfehlungen für Kommunen, Bundesamt für Naturschutz, Bonn, pp. 6-9.
Gruen, V. (1964), The heart of our cities: The urban crisis: diagnosis and cure, Simon and Schuster, New York In: Wiśniewski, L. S. (2020), Urban Distances. Dimensions of Urban Units and Distribution of Functions in the City in context of Walking, Cycling and Public Transport Distances, Space & Form, 46, pp. 211-238. DOI: 10.21005/pif.2021.46.C-08
Barton, J. and Pretty, J. (2010), What is the best dose of nature and green exercise for improving mental health? A multi-study analysis, Environmental Science & Technology, 44(10), pp. 3947–3955.
Woo, J., Tang, N., Suen, E., et al. (2009), Green space, psychological restoration, and telomere length, The Lancet 373(9660), pp. 299–300.
Zhang X, Melbourne S, Sarkar C, Chiaradia A, Webster C. (2020), Effects of green space on walking: Does size, shape and density matter? Urban Studies, 57(16), pp. 3402-3420. DOI: 10.1177/0042098020902739
Fang, C. and Yu, D. (2017), Urban agglomeration: An evolving concept of an emerging phenomenon, Landscape and Urban Planning, Volume 162, ISSN 0169-2046, pp. 126-136.
Gottmann, J. (1957), Megalopolis, or the urbanization of the North-eastern seaboard, Economic Geography, 33(7), pp. 189-200.
Yao, S., Zhu, Y. & Chen, Z. (2001), China's urban agglomeration, University of Science and Technology of China Press, Hefei.

stages. This initiates from a city with its first expansion to immediate peripheral areas leading to a population of 5-10 million, i.e. a metropolitan area with a single core (i.e. a central or a major city) at its structure. This expands to large metropolitan belts and megalopolis areas, which can have a population of 30 million with poly-central cores where many cities form an integrated system, which function as an international growth centre. In regards to overall Gross Domestic Product (GDP), their study signifies minimum 10,000 US dollars per capita within the urban agglomeration region, which assists in putting the economic perspective in definition.

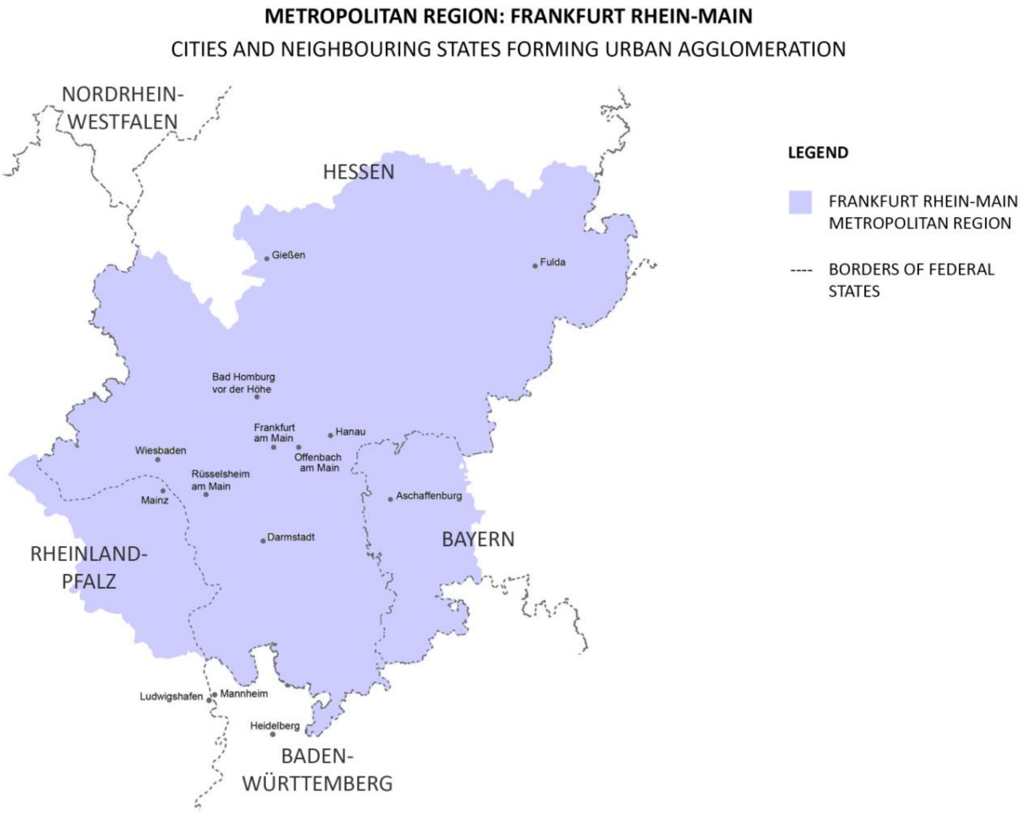

Figure 11: Metropolitan region of Frankfurt Rhein-Main
Source: Image (modified) - Regional Authority FrankfurtRheinMain (2018)

In Germany, with the resolution of Ministerial Conference of Spatial Planning in 2005, eleven German regions were designated as metropolitan regions. The largest metropolitan region in Germany is that of Rhein-Ruhr region with Köln and Bonn as their major cities with an overall population above 11.6 million inhabitants. These regions are concentrated with scientific and socio-cultural opportunities along with major political and decision-making organizations (e.g. government bodies, headquarters etc.). Overall, two-third of the German population live and work in these metropolitan regions. Frankfurt Rhein-Main metropolitan region (see Fig. 11) is one of the major regions in Europe and is fourth largest in the country. The expanding metropolitan region of Rhein-Main includes major cities such as Frankfurt, Offenbach am Main, Darmstadt, Wiesbaden, Darmstadt, Mainz and many more. As the name suggests, the polycentric region includes the two rivers of Rhein and Main flowing through different cities forming the agglomeration. With an area of approximately 14,750 square kilometres,

Regional Authority FrankfurtRheinMain (2018), Regionales Monitoring 2018 Daten und Fakten - Metropolregion FrankfurtRheinMain, Frankfurt am Main, Retrieved from www.region-frankfurt.de the Rhein-Main region includes 5.8 million inhabitants with Gross domestic product per capita being around 46,000 Euros (Regional Authority FrankfurtRheinMain 2020); which assists in denoting the area as an agglomeration quantitatively.

Over the years, the Frankfurt Rhein-Main region has seen a positive growth in its overall population with major growth rates (above 5%) being observed in the cities of Frankfurt (10.3%), Offenbach (9.8%) and Darmstadt (9.7%). The region also accounts for 16% of the population being from foreign countries. Regarding the transport infrastructure, the region has large network of highways along with busy railway routes including long-distance trains (e.g. ICE and IC) and regional trains (e.g. S-Bahn and RB/RE). The main railway station in Frankfurt i.e. Frankfurt Hauptbahnhof is one of the busiest transit stations in Germany with numerous long-distance trains to other countries which leads to daily commuter flow of 450,000 approximately. This is followed by 40-60,000 daily commuter flow through other major railway stations in Mainz, Wiesbaden and Darmstadt. Regarding airways, Frankfurt/Main airport has the highest passenger volume in Germany with daily commuter flow of around 167,000 passengers which has shown its peak to 215,000 passengers (Regional Authority FrankfurtRheinMain 2018). These figures and characteristics of the urban agglomeration signify the amount of commuter exchange taking place on local and global levels, which amounts to high interaction and overall social and economic growth of the region.

2.3.2.2 Mobility in Rhein-Main region

The Rhein-Main urban agglomeration includes cities from other federal states, with different administrative boundaries for the regional authority to look over their tasks. It mostly covers major cities and districts within the southern section of the federal state of Hessen. In 2018, the Regional Authority FrankfurtRheinMain initiated the master plan with emphasis on mobility in the region.

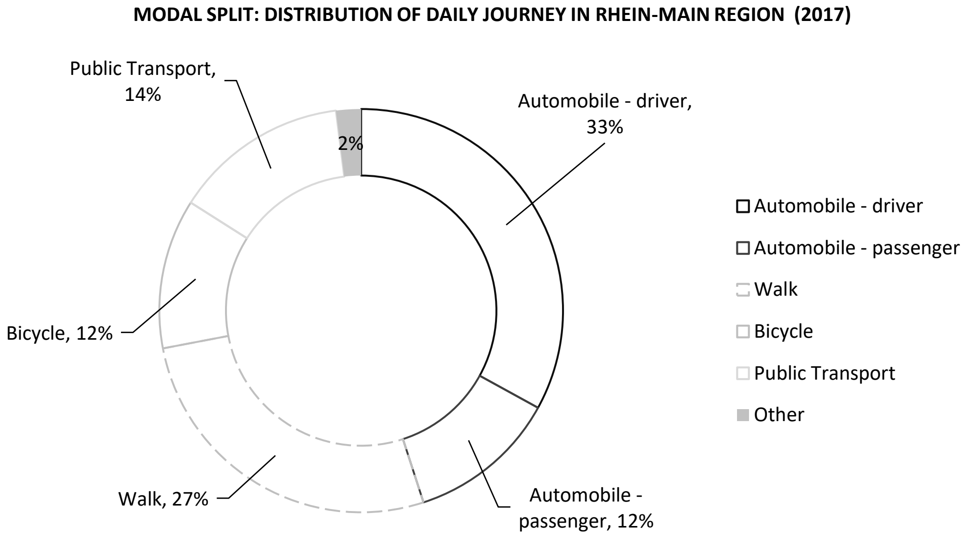

Figure 12: Modal split in Frankfurt Rhein-Main region
Source (data): MiD (2017), In- Regional Authority FrankfurtRheinMain (2020)
Note: The modal-split distribution caters to the administrative Rhein-Main region which does not include cities from neighbouring states (e.g. Mainz or Aschaffenburg) and limits itself to 75 municipalities within the regional authority.

Regional Authority FrankfurtRheinMain (2020), FrankfurtRheinMain on the move A Sustainable Urban Mobility Plan (SUMP) for the Region, Frankfurt am Main, Retrieved from www.region-frankfurt.de

One of the major tasks within the plan was to improve public transport and current state of mobility. The Sustainable Urban Mobility Plan (SUMP) region for the master plan was introduced, which does not include cities from other states i.e. Mainz or Aschaffenburg, and also has a reduced size within the metropolitan region for its administrative purposes. As discussed before, modal split plays an important role in portraying the mobility behaviour in different urban areas, which showcases proportion of daily journeys made through different modes of travel. In the Rhein-Main region this distribution (see Fig. 12) takes place with cars dominating almost half of the daily journeys (i.e. 45%), followed by walking (i.e. 27%). The public transport and cycling modes account to 14% and 12% respectively. Compared to the MiD report in 2008, the share of automobiles accounted to 37% (self) and 14% (passenger), followed by 11% via public transport, 9% via cycling and 27% through walking. This shows a decrease in the share of automobiles by 6%, which contributes to increase in active mode share including public transport.

Considering the perspective of active modes of travel, the modes are almost on par with the private motorized vehicles for daily travel needs. The current mobility scenario in the region sees cars dominating the roads, which often leads to congestion problems. In order to overcome the problem, the mobility plan needs to focus on improving alternate modes of transport for better dispersion of modal shares for daily commute. This sustainable perspective is reflected through the objectives of the Regional Authority where it focuses on increasing the overall share of sustainable modes (i.e., by walking, cycling and public transport) from 55% in 2017 to 65% by 2030. In order to achieve this goal, several measures mostly focusing on short-distance mobility through active modes play a crucial role in the future years. In line with the transport transition towards a sustainable mobility system in Rhein-Main urban agglomeration, the regional authority has set several measures (23 in total) which are categorized into seven major themes. Some of these measures include:

- Establishing integrated cycling network, which involves inter-city cycle highways as one of the measures;
- Enabling pedestrian traffic with more space and reduced walking times (which is similar to the neighbourhood concept);
- Developing accessible multimodal mobility hubs, which are available in public spaces and can complement existing mobility services with additional services based on the demand;
- Rail-centred land-use planning, where new development areas are prioritized in proximity to the rail service station;
- Improved network of public transport, involving expansion of route networks; and more.

The measure of building cycle highways between cities has already been on the way with one of the first being Frankfurt-Darmstadt cycle highway (i.e. FRM 1). These prioritized routes have the potential to provide less barrier to cyclists while commuting, enabling more safety by having a dedicated lane not being shared (on major parts) with other modes. These connections will expand leading to a large network of high-speed bicycle lanes in the metropolitan region. With respect to the rail-centred land-use planning, emphasis is being paid on building settlements which are in close proximity to the existing railway lines. This involves maximum distance from the rail service station being 2000 metres, which enables people to use these services more efficiently with higher degree of access to the mode. The measure also involves exploring options for the expansion of existing rail lines to further settlements through new stops in order to increase its access in a sustainable medium. These set of measures enable in understanding the approach towards future mobility scenarios in the Rhein-Main region and would reflect the acquired mobility behaviour, which shall influence the modal split of different cities based on their *mobility culture* and depend on its potential multimodal accessibility characteristics.

Different mobility lifestyles or culture in different cities of varying sizes can be clustered through urban form, socio-economic characteristics, transport infrastructure, travel behaviour and mobility-related perceptions (Klinger et al. 2013). In their study, Klinger et al. (2013) categorize 44 large German cities (i.e. cities with more than 100 thousand inhabitants), including some cities forming Rhein-Main agglomeration, based on the mobility culture. The study is based on understanding indicators of urban mobility culture, where urban form (which caters to population size, settlement density and housing, and less towards to the spatial layout of the built environment) and transport infrastructure act as cultural priorities assisting in understanding different preferences and mobility lifestyle represented by a city's population. Within the identified clusters, the cities of Offenbach am Main and Wiesbaden were identified as 'auto-oriented cities', while Darmstadt and Frankfurt am Main were identified as 'walking cities with multimodal potential'. While auto-oriented cities showed higher modal share of motorized vehicles, walking cities with multimodal potential showed higher modal share of walking trips along with low car trips. The later cluster of cities also included potential for cycling, more public transport trips. This assists in having an overview of cities based on their mobility perspective, and with further understanding of the urban areas through accessibility measures it would add to narrative of addressing multimodal accessibility planning within the urban development framework of a city or a group of cities.

In addition to the mobility vision through the regional authority of Rhein-Main urban agglomeration, another linked initiative from the state of Hessen through Mobiles Hessen 2035 (Hessisches Ministerium für Wirtschaft, Energie, Verkehr und Landesentwicklung 2018) focuses on improving the present state of mobility. One of the focus fields within its strategies is the local mobility, with pedestrians and cyclists being major focus groups. The infrastructure for pedestrian and bicycle traffic would be continuous and comprehensive, i.e. they would not be bound within the boundaries of a municipality but emphasis would be on merging the neighbouring network of the infrastructure to maintain the local network with better reach. With the share of cycling increasing gradually in urban areas, dedicated lanes and shared space concepts in traffic calmed areas or pedestrianized spaces are becoming more popular. Especially with the outcome of pandemic in 2020-21, more experimental spaces for short-distance mobility were observed within the region to provide more space and follow social-distancing. In 2020, pop-up experimental cycle lanes were installed in certain parts of the city in Darmstadt to strengthen cycling. During the corona-lockdown conditions, as the density of car traffic reduced on certain roads, the city planned on establishing experimental pop-up cycle lanes on roads which were less used. The short-term experimental lanes were utilized for a specific period, with successful outcomes leading to long-term implementations. One of the objectives of the decision was to connect the eastern parts of the city, along with the city centre, to the main railway station in the west (Kabel, C. 2020). Similar initiatives were observed in Frankfurt am Main, where an 800m length of Mainkai street was closed to vehicular traffic in 2019 for a year, inviting pedestrians and cyclists to the new shared open space. Initiatives like these assists in providing an accessible network for active modes with improved safety conditions on a long-term basis. Overall, while there are urban planning principles and mobility measures which guide a city's approach towards its urban development focusing directly or indirectly on mobility and accessibility aspects, there is a need to identify the

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Klinger, T., Kenworthy, J. R., and Lanzendorf, M. (2013), Dimensions of urban mobility cultures – a comparison of German cities, Journal of Transport Geography, Volume 31, pp. 18-29. DOI: https://doi.org/10.1016/j.jtrangeo.2013.05.002

Hessisches Ministerium für Wirtschaft, Energie, Verkehr und Landesentwicklung (2018), Hessenstrategie Mobilität 2035, Hessen wird Vorreiter der Verkehrswende, Wiesbaden. Retrieved from https://www.mobileshessen2030.de/hessenstrategie_mobilitaet_2035

Kabel C. (2020), Pop-up -Wege im Test, Frankfurter Rundschau, Rhein-Main, Darmstadt. Retrieved from https://www.fr.de/rhein-main/darmstadt/radverkehr-in-darmstadt-pop-up-wege-im-test-90021116.html potential of urban areas in regards to its multimodal accessibility to prioritize and implement the identified measures accurately and efficiently.

2.4 Summary

The chapter introduces mobility in an urban scenario through multimodal and intermodal aspect, active mobility trends surrounding changes in urban mobility (which include neighbourhood approach, pedestrianization approach, and alternate modes of transport) along with the immediate impact of Coronavirus pandemic on the mobility environment. Different approaches towards enhancing mobility in different cities, along with the impact of modal choice on the mobility infrastructure and vice versa, reflect the diversity of planned, pilot (or experimental), and implemented urban projects within the subject area. The relation of distance to certain travel modes assist in understanding certain boundary limits for modal choices within the urban areas. For example, majority of cycling trips cover a minimum distance length of 2.5 kilometres within cities (CIVITAS 2016), which also corresponds to the minimum travel kilometres by car (FFCS in particular) for intra-city travel in many countries.

The understanding of accessibility as an aspect within an urban scenario assists in reflecting certain attributes of accessibility which when utilized in combination with the aspect of mobility caters towards the multimodal accessibility planning. The multimodal accessibility as a term relates to the ease of accessing a space through movement by different modes which involve streets as one of the primary medium. The large-scale perspective of accessibility combined with mobility, focuses on streets, open spaces and urban configuration of spaces (dictated by the layout of buildings and the built environment) which characterizes an urban area within a city. The impact of urban planning policies focusing on densification (for e.g. *Innenentwicklung vor Aussenentwicklung* or *Doppelte Innenentwicklung*) showcases the short-distance mobility approach in Germany. In addition, while micro-climate conditions from green spaces add towards making an urban area attractive to walk through (Gruen 1964), density of retail spaces and public transport are more strongly associated with walking density (Zhang et al. 2020). With congestion and crowding of spaces being one of the attributes influencing walking (at times also leading to less significant association between density of green spaces and walking density), the aspect of space availability should be addressed for assessing accessibility of an urban area prior to addressing cumulative opportunities of spaces (like green areas). With accessibility being regarded as a measure (time or distance based) for an urban area, it varies based on the mode of mobility a person uses. It also varies for urban areas or cities of different sizes, with a derived assumption of larger cities having better accessibility than comparatively smaller cities.

The research study would contribute to understand accessibility characteristics of different urban areas belonging to cities of different sizes within an urban agglomeration. It will also cater to understanding how the mobility culture (where clusters of cities are identified such as ‘walking cities with multimodal potential’ or ‘auto-oriented cities’) relates to the identified accessibility aspects. In regards to state of the art accessibility measures, utility of Space Syntax (as one of the measures) has shown its application to improve urban spaces covering different user-groups, along with other measures (such as PTAL) being utilized by the city authorities focusing on accessibility through public transportation. These measures ensure the application of certain state-of-the-art research methodologies which are being utilized on a large-scale city level to improve its present level of multimodal accessibility. The urban mobility in European context showcases different urban policies and measures by city authorities which impact the overall modal split, and assists in understanding how different cities function with certain barriers. With a group of neighbouring cities functioning within an urban agglomeration, the inter-city and the intra-city characteristics through certain attributes (or parameters) would enable realization of the potential areas for improvement via urban development.

CHAPTER 3

IDENTIFICATION OF PARAMETERS AND URBAN AREAS

Preface

Regarding urban mobility, urban designers and transportation planners often provide different expertise and techniques in planning due to differences in priorities (Binder et al. 2020). This requires a need to identify research tools which are universal in nature. The chapter deals with the study of various parameters in order to understand and evaluate diverse urban street networks within the aspect of multimodal accessibility. The chapter tries to answer whether there is a particular category of accessibility measures which can be utilized to understand the impact of urban configurations on movement. The identified measures are further evaluated based on their scales of urban perspective, the observation limits, the diversity of mobility mediums being taken into consideration through the process, and the state of the art optimum (maximum or minimum) values based on the diverse case studies. The observation scale ranges from micro-scale which may be related to human-eye scale, to the macro-scale representing a bird's eye view. Following the identification of accessibility measures to be utilized (and improved), the urban areas within an agglomeration for the on-site study are selected, along with the discussion on mobility and urban development strategies.

3.1 Identification and selection of parameters

The modal split (as discussed in the previous chapter) in major European cities included user-groups who preferred walking, cycling, using public transport or utilizing a motorized vehicle for their movement. The accessibility parameters which are associated with these modes of mobility, at times also supporting multiple modes of travel, are introduced and selected based on their universal application and understanding. Certain applications or methodology is required to address the data-informed approach, where the outcome includes a human factor for the prioritization of factors. With certain measures of the multimodal accessibility selected and later compared through different criteria, accessibility parameters were identified into certain categories and narrowed down to the ones relating to the identified principles of urban design of streets, and travel demand and trip generation.

Accessibility measures have been previously grouped into different categories which mainly include distance-based, cumulative opportunities, gravity-based (Bhat et al. 2002), topological or

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Binder, R. B., Tobey, M. B., Jittrapirom, P., Steidl, P. J., Yamagata, Y., Yang, P. P. J. (2020), Chapter 5 - Integrating urban mobility in urban design, Urban Systems Design, pp. 125-162. DOI: 10.1016/B978-0-12-816055-8.00005-1
Bhat, C., Handy, S., Kockelman, K., Mahmassani, H., Gopal, A., Srour, I. and Weston, L. (2002), Development of an Urban Accessibility Index: Formulations, Aggregation, and Application, Research Report Number 4938-4, Conducted for the Texas Department of Transportation, The University of Texas, Austin.

infrastructure based (Vale et al. 2016), geometric and more (Tu & Hua 2014). Distance-based measure is one of the simplest measures where spatial separation plays an important role, i.e. distance is utilized as a proximity measure where higher separation or longer distance relates to lower accessibility. Distances play an important role for measuring accessibility, and are especially sensitive to the type of distances which are being used. Some distances are based on shortest network distance, time, Manhattan distance (Craw 2017), Euclidean distance (i.e. straight line between two points) and more. Distance-based measures find their utility once the opportunities (or destinations) are perfect for e.g. emergency health services, public transport stops, etc. where the closest point of access is the prioritized destination. One of the recent accessibility measures which falls under distance-based accessibility measure would be the Public Transport Accessibility Level (Transport for London 2015). It utilizes distance as a measure of access time through a normal human walking speed to the nearest public transport station. The gravity-based measures find their utility when the opportunities (or destinations) are less-perfect and more complimentary in nature. These include green spaces, jobs, commercial spaces or shops, where higher frequency of opportunities represents higher accessibility. Vale et al. (2016) in their study regards cumulative opportunities measure as a sub-domain or a particular case of gravity-based measure. Lin et al. (2018) in their study utilize relative space access index through the gravity model to calculate access to health-care facilities by bus and cars. While following the measure, there were certain gaps in the research outcomes due to inaccuracy caused by domain of data availability.

Following the distance- and gravity-based measures, topological measures can be utilized to understand and analyse the impact of street networks on the movement and overall accessibility. These do not evaluate existing opportunities, but have the potential to be utilized as planning tools, either to identify intervention priorities or to identify impacts of the urban development proposals (Vale et al. 2016). Usually these measures take no account of origins or destinations in the urban area and focus on the network characteristics, including density of intersections (Cervero & Radisch 1996), link to node ratio (Ewing 1996), density of street segments (Transport for London 2014, Tresidder 2005 and Dill 2004), or immediate built environment characteristics through the evaluation of infrastructure including the Level of Service (LOS) such as Cycling Level of Service (Transport for London 2014), Level of Traffic Stress (Maaza et al. 2012), BiWET i.e. Bikeability and Walkability Evaluation Table (Hoedl et al. 2010), Pedestrian Footway Comfort Assessment (Finch 2010) and similar measures (see Table 3).

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Tu, M. and Hua, X. (2014), The Construction of Open Space System Integrated with Rainwater Management In: Cavallo, R., Komossa, S., Marzot, N., Pont, M. B., and Kuijper, J. (2014), New Urban Configurations, IOS Press, pp. 963-968. DOI: 10.3233/978-1-61499-365-0-968

Craw, S. (2017). Manhattan Distance. In: Sammut, C., Webb, G.I. (eds) Encyclopedia of Machine Learning and Data Mining, Springer, Boston, MA. DOI: https://doi.org/10.1007/978-1-4899-7687-1_511

Lin, Y., Wan, N., Sheets, S. et al. (2018), A multi-modal relative spatial access assessment approach to measure spatial accessibility to primary care providers, International Journal of Health Geographics 17, 33, pp. 1-22. DOI: https://doi.org/10.1186/s12942-018-0153-9

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Ewing, R. (1996), Best Development Practices: Doing the Right Thing and Making Money at the Same Time, American Planning Association, Chicago, IL, pp 12-22.

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Tresidder, M. (2005), Using GIS to Measure Connectivity: An Exploration of Issues, School of Urban Studies and Planning in Portland State University, Portland, OR, USA.

Dill, J. (2004), Measuring Network Connectivity for Bicycling and Walking In: Proceedings of the 83rd Annual Meeting of Transportation Research Board, Washington, DC, USA, pp. 11–15.

Maaza, M., Furth, P. G., and Nixon, H. (2012), Low-Stress Bicycling and Network Connectivity, Mineta Transportation Institute, San Jose, CA.

Hoedl, S., Titze, S., and Oja, P. (2010), The Bikeability and Walkability Evaluation Table: Reliability and Application, American Journal of Preventive Medicine, Volume 39, Issue 5, pp. 457-459. DOI: https://doi.org/10.1016/j.amepre.2010.07.005.

Finch, E. (2010), Pedestrian Comfort Guidance for London Guidance Document, Transport for London, London. Retrieved from www.tfl.gov.uk/walking

Measure Typology	Topological measure								Distance measure		Geometry + Topological measure			Gravity / Gravity + Topological measure		
	Macro-scale perspective				Micro-scale perspective				Macro-scale perspective		Macro-scale perspective			Macro-scale perspective		
Name of measure	Intersection Density	Mesh Density Analysis	Link-Node Ratio	Street Density	Pedestrian Footway Comfort Assessment	Level of Traffic Stress	NALP	BiWET	Public Transport Accessibility Level	Neighbourhood Pedestrian Accessibility	Intelligibility (Space Syntax)	Bicycle Route Directness	SNAMUTS	Walk Score®	National Walkability Index	Relative Spatial Access
Author	Cervero & Radisch 1996	TfL 2014	Ewing 1996	Tresidde-r 2005/ Dill 2004	E. Finch 2010	Maaza et. al 2012	Gauvin et. al 2005	Hoedl et. al 2010	TfL 2015	Aultman-Hall et. al 1997	Hillier B. 1984	Nordstorm T. and Manum B. 2015	Curtis C. and Scheurer J. 2015	Redfin 2022	EPA 2021	Lin et al. 2018
Measurement Transport medium																
- Bicycle		X			X	X	X	X				X				
- Bus									X	X			X		X	X
- Tram									X				X		X	
- Rail									X				X		X	
- Walk	X		X	X	X		X	X	X	X	X		X	X	X	
- Wheelchair					X		X									
- Automobiles	X		X	X							X					X
Area of observation	Network intersection	Bicycle lane	Network link & intersection	Networ-k link	Pedestrian street	Bicycle lanes	Street segments	Street segments	Public transport and street network	Walkways	Axial network	Bicycle lane	Public transport and street network	Street routes / network	Block group	Street network
Origin / Destination based	No	No	No	No	No	No	No	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observation limits	per network area	1km x 1km	per network area	per network area	6m length / footway	per lane segmen-t	min. 60m of street segment	10m street intervals	640m radius - Bus/tram 960m radius - Rail	per neighbourhood	320m radius min. (for integration based on case studies)	600 segments min.	Per network area	30-minute walking distance	Block groups (different sizes in urban & rural area)	Catchment size: 30 min. (cars), 60 min. (bus)
Preferred measure	Values above 0.70 preferred (max 1)	Min: 4km of cycle lane	1.4 minimum for a walkable area	-	3 persons per metre per minute (ppmm)	LTS 1 (based on index system)	10 (as per the three dimensions including activity friendliness)	-	60+ index level	400m min. walking distance	Slope 45° with +ve degree of correlation	1.5-1.6 (as per selected case studies)	Minimum inter-peak period service frequency of 20 minutes (for weekends)	90-100 (based on Walk Score®)	15.26-20 (as per the final National Walkability Index scores)	3.00+ (SPAI for cars) and 0.25+ (SPAI for buses) as per case studies
Scale of measure	Macro	Macro	Macro	Macro	Micro	Micro	Micro	Micro	Macro	Macro	Macro	Macro	Macro	Macro	Macro	Macro

Table 3: Comparison of diverse performance measures through different criteria

Some accessibility measures utilize a combination of two or more categorized groups. For instance, the Walk Score® (www.walkscore.com) or National Walkability Index (EPA 2021) utilizes gravity-based measure of spatial accessibility through cumulative opportunities and topological measure of street intersections and related measures. While these measures have focused on measuring potential walkability characteristics, i.e. the built environment's ability to support walking (Hirsch et al. 2013), of an urban area, they fail to address the street conditions or the available width of space available for a person's movement. This is addressed better by the crowding and movement restriction aspect, which addresses the availability of space for movement (indirectly evaluating the built environment similar to BiWET), covered within the Pedestrian Footway Comfort Assessment (Finch 2010). Similar to walkability, a built environment's ability to support cycling would be termed as bikeability and it would vary for different modes of mobility. The bicycle route directness approach by Nordström and Manum (2015) focuses on the movement potential of cyclists through streets utilizing Space Syntax theory. This addresses a new perspective of addressing routes for cycling, where the evaluation of the built environment can be undertaken on potential routes, once identified. In regards to Space Syntax, there has been a growing interest in measuring accessibility of an urban space through its spatial attributes (Karimi 2017). In contrast to gravity-based measures, Space Syntax utilizes different attributes including integration, connectivity, intelligibility and more to measure accessibility through the network of axial lines (Tu and Hua 2014). Space syntax measures consider topological distances and caters towards geometric accessibility, in comparison to gravity-based or distance-based measures. It can be grouped into a geometric-topological measure. SNAMUTS as an accessibility measure, having its core methodology inspired from the Space Syntax theory, addresses public transport accessibility similar to PTAL. With respect to the gap between data collection and data availability, PTAL provides a better approach with less gap in comparison though SNAMUTS focuses on diverse outcomes relating to different indicators. Overall, how a street network, part of the built environment, influences movement can be mostly addressed through the topological-based accessibility measurement approach (Vale et al. 2016). Addressing multimodal accessibility also involves certain modes of mobility to be addressed, along with urban design principles.

Urban design for streets

Some of the identified measures (or attributes) relate to the six principles of inclusive urban design for streets (Burton and Mitchell 2006). The principles were developed to cover streets, open spaces, and buildings on a neighbourhood scale, from studies involving older people (with dementia). These principles include familiarity, legibility, distinctiveness, accessibility, comfort and safety. While the perspective of accessibility i.e. to access (or reach) a particular destination is one of the important factors for all the five performance measures in the research study, other principles also share some common characteristics. The aspect of 'comfort' is the dominant factor in the performance measure of 'crowding and movement restriction' where the availability of space for movement determines the resistance faced by a person using a particular street. The higher crowding and movement restriction

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Gauvin, L., Richard, L., Craig, C. L., Spivock, M. et al. (2005), From Walkability to Active Living Potential An ''Ecometric'' Validation Study, American Journal of Preventive Medicine, 28 (2S2), pp. 126-133. DOI: 10.1016/j.amepre.2004.10.029

Aultman-Hall, L., Roorda, M., Baetz, B. W. (1997), Using GIS for Evaluation of Neighborhood Pedestrian Accessibility, Journal of Urban Planning and Development, 123 (1), pp. 10-17.

Redfin (2022), Walk Score®, Retrieved from www.walkscore.com

EPA (2021), National Walkability Index Methodology and User Guide, USA. Retrieved from https://www.epa.gov

Hirsch, J. A., Moore, K. A., Evenson, K. R., Rodriguez, D. A., and Roux, A. D. (2013), Walk Score® and Transit Score® and Walking in the Multi-Ethnic Study of Atherosclerosis, American Journal of Preventive Medicine, Volume 42 (2), pp. 158-166. DOI: https://doi.org/10.1016/j.amepre.2013.03.018

Nordström, T. and Manum, B. (2015), Measuring bikeability: Space syntax based methods applied in planning for improved conditions for bicycling in Oslo, Proceedings of the 10th International Space Syntax Symposium, University College London, London.

Karimi, K. (2017), Space Syntax: consolidation and transformation of an urban research field, Journal of Urban Design, 23:1, pp. 1-4. DOI: 10.1080/13574809.2018.1403177

Burton, E. and Mitchell. L. (2006), Inclusive Urban Design: Streets for Life, Architectural Press, Oxford, pp. 52-128.

a particular street will have during its peak hours of utility, the lower would be the aspect of comfort. The principle of 'safety' can be indirectly observed through the identified potential of streets through 'normalisation of angular choice'. With direct routes for cycling being identified on a city-wide scale, the prioritisation of having a separate bicycle pathway on these streets would enable a safe and direct movement of the user-groups through the overall network of street hierarchies. Safety is also reflected through the crowding attribute, where streets with more movement restriction and conflicts would be unsafe and have higher probability of colliding with other user-groups using same space.

The low 'connectivity' of streets with more cul-de-sacs also links with the aspect of safety. While cul-de-sac neighbourhoods often lead to privacy and safety (Southworth and Joseph 2004), the higher frequency of cul-de-sacs would also lead to the area being disconnected. The aspect of 'legibility' shares similar characteristics with 'intelligibility' where the attributes addresses upon the ability for a person to pin-point their location in an urban configuration of open spaces. The more intelligible a space is, easier it is for a person to navigate and understand the network of streets from their location within. The urban configuration of spaces would determine the intelligibility of an urban area, which can be influenced by the associated block lengths in the area. The principle of 'distinctiveness' (i.e. reflecting a particular characteristic of an area) can also be understood based on the diversity and typology of urban areas through their peak hour timelines of movement, which is based on how the streets are classified (e.g. whether they are high streets, transport interchange areas etc.). The inability to distinguish a street, would either be a result of combination of many typologies or lack of a distinct characteristic. 'Familiarity' can be a result of specific routes taken to reach a destination, based on a person's chain of travel events. This can be indirectly linked to the shortest route for accessing a public transit station through 'public transport accessibility level', which utilises the aspect. This also links to the 'intelligibility' characteristic of an urban area, which would support a person to navigate through the area. The aspect of 'familiarity' and 'distinctiveness' can be utilized inversely to improve the 'intelligibility' of a network of low integrated streets, through added landmarks, distinct design, colours, or skyline (Lynch 1960).

Travel demand and trip generation

With the perspective of travel demand and trip generation within the built environment, Ewing and Cervero (2010) utilize the aspect of 5Ds which would influence the former characteristic. The five Ds were developed through the previous 'three Ds' which included diversity, density and design (Cervero and Kockelman 1997). The five variables of diversity of land use, density of destinations, destination accessibility, distance to transit, and design of urban space also share some common traits with the five identified performance measures in the study. The high diversity of land use in an area leads to greater choice for destinations, which could increase the on-street peak hour frequency of user-groups (observed in the pedestrian crowding performance measure). The high peak hour frequency of the people using the streets could also reflect towards the destination (or the origin) having diverse land use, or having multiple spaces acting as destinations, good access to transit, or design of the urban space. The PTAL addresses the variable of 'distance to transit' and 'destination accessibility'. The access walk time within the performance measure of PTAL utilises the shortest distance to reach a transit service station, and the multiple destinations based on the different routes and transport modes reflect towards the destination accessibility with more opportunities to choose from.

Southworth, M. and Ben-Joseph, E. (2004), Reconsidering the cul-de-sac, Access, 24, pp. 28-33.
Lynch, K. (1960), The Image of the City, The MIT Press, Cambridge, pp. 46-181.
Ewing, R. and Cervero, R. (2010), Travel and the Built Environment, Journal of the American Planning Association, 76:3, pp. 265-294. DOI: 10.1080/01944361003766766
Cervero, R. and Kockelman, K. (1997), Travel demand and the 3Ds: Density, diversity, and design, Transportation Research D, 2(3), pp. 199–219.

The ‘design of urban space’ influences the way people use their immediate spaces through the configuration of open space network. While the macro-scale perspective of connectivity (i.e. link-node ratio), intelligibility, PTAL, route directness and micro-scale perspective of crowding is influenced by the design of urban space, the performance measure of crowding links closely to the direct influence of the urban design variable on-street (as it includes the architectural aspect of street-elements and street-widths in its measure). The design of a node or a space, influences different performance measures. For example, an accessible transit station as a transport node junction would focus on different aspects involving distance from other areas, modes of transport, travel time, interaction with other modes and more; as compared to a street or a network of streets as a space which would focus on its connectivity with other streets, its comfort for different user-groups, legibility and other aspects. Connectivity index with its link-node ratio along with the density of links (i.e. streets) and nodes (i.e. intersections), caters towards the street-network characteristics within the area.

The analysis of the built environment by Ewing and Cevero (2010) concluded that walking strongly relates to factors including land use diversity, density of nodes (or intersections) and the number of destinations within the specific walking distance. The proximity to the transit service station and the street network design relate to the use of public transportation modes i.e. buses and trains. The study also showcased population density to have a weak association with travel behaviour. Considering the identified performance measures, the factor of connectivity, along with added attribute of crowding and movement restriction further assist in understanding an urban area’s walkability potential. While, the Public Transport Accessibility Level (PTAL) portrays the perspective of accessing public transport service stations through the access time, with added aspect of peak hour frequency of the different public transport modes within a city (or an urban area). Diverse urban areas, based on landuse, or typology of categorization, and their relative influence on the performance measures assist in comparing accessibility attributes. With respect to the diverse transport modes, the Public Transport Accessibility Level (PTAL) addresses the majority of the modes including tram, rail and bus through the medium of walking. The micro-scale of the index makes it possible to address separate service stations within the surrounding boundary from the origin. The measure is origin-destination based, excluding footway assessment (or crowding and movement restriction methodology), but including local and global integration involving intelligibility and directness of routes via NACH, i.e. Normalisation of Angular Choice (Nordström and Manum 2015). The accessibility perspective within the domains of short-distance mobility through the performance measures, influences or utilizes walking as a medium, directly or indirectly, to create a benchmarking system. In order to assess diverse urban areas, the link-node ratio through the urban network assists in understanding how walkable a particular network is. It gives a general macro-scale perspective prior to the further distinct analysis of selective parameters, through the micro-scale perspective.

In addition, the measures which provided a particular range of desired values, assisting in overall assessment of multimodal accessibility, were selected. With respect to the Level of Traffic Stress, Pedestrian Footway Comfort assessment is prioritized with the inclusion of diverse user-groups including cyclists in order to understand the movement restrictions, and correlating the data with other attributes, say, the directness of bicycle routes (via NACH). The utilization of Space Syntax analysis through diverse sub-parameters of angular choice and integrations on local and global levels, lead towards the application of Intelligibility and directness of bicycle routes (which in-turn utilizes NACH). The two measures assist in projecting how the human eye perspective in transition towards a macro scale perspective can be perceived, and understood through both graphic and numeric representations. The performance measures selected are based on constant transition between the micro and macro scale perspectives in order to understand different view-points of multimodal accessibility in the urban scenario. With respect to the performance measures, majority of the attributes included the objective of obtaining higher values, excluding pedestrian footway assessment and level of traffic stress, where lower values correlated with higher degree of accessibility.

Selected parameters

The urban network of streets is the major focal area of observation within the performance measures studied, in order to understand how the urban configuration influences the accessibility parameter. Based on the identified categories of accessibility measures and their corresponding attributes which relates to the urban design principles (Burton and Mitchell 2006) and travel aspects of built environment (Ewing and Cervero 2010), the accessibility measures involving street network characteristics comprising of link-node ratio and intersection density (through connectivity), Space Syntax measures of accessibility including intelligibility (through integration) and route directness (through NACH), public transport accessibility through PTAL, and crowding and movement restriction aspect are taken into consideration. This addresses the first research question. Majority of the measures relate to a topological-based measure of accessibility directly or indirectly, which would be utilized (individually or in combination) and improved, to analyse the impact of street networks on the movement and overall accessibility. These measures will also have less gap between the data collection and data availability for the spatial analysis involving quantitative techniques putting measurability into accessibility, leading towards a qualitative outcome.

The observation boundaries of the selected five measures of multimodal accessibility differ from each other, with majority (four out of five) having an outcome showcasing a macro-scale perspective (see Fig. 13). These range from the micro-scale perspective of 'crowding and movement restriction', which focuses on the selected street widths in an urban space, to the 'route directness' which utilizes the Space Syntax attribute of NACH focusing on a macro-scale of a city-wide perspective (or a bird's eye view). The diversity in the range of the observation area is a result of diverse modes of mobility considered within the spatial analysis and the parameters being utilized to analyse the accessibility attribute corresponding to a configuration of open spaces. In regards to a compact urban area representing a certain typology of space, certain minimum boundaries are fixed for a macro-level spatial analysis. Application of the selected accessibility measures, with potential improvements and combination of certain measures to analyse and understand different mobility behaviour pertaining to a selected urban area or a city adds towards the existing literature where urban infrastructure-related accessibility measures are utilized as planning tools. This assists in identifying the potential of an urban area in regards to its multimodal accessibility characteristic, the intervention priorities improving the existing level of accessibility or the impacts of the urban development proposals. In addition, while including diverse methodologies cannot be considered as a negative approach to address and bring measurability into accessibility (as it reflects towards the research efforts to annotate the complexity of understanding accessibility through a holistic approach), it poses a risk to address different aspects and perspectives using similar principles or approach to measure accessibility. This adds to the present complexity of understanding accessibility, and therefore requires a priority of identifying distinct attributes which are well-defined with less uncertainty in their definitions. This also helps in further conveying the research outcomes through distinct aspects of multimodal accessibility to diverse stakeholders, ranging from urban design and planning professionals to a resident occupying a space in an urban area, playing a crucial role in an urban development timeline from planning to execution in continuum.

Following the study of state-of-the-art measures through different perspectives and viewpoints, the in-depth understanding of the selected accessibility parameters is addressed as follows:

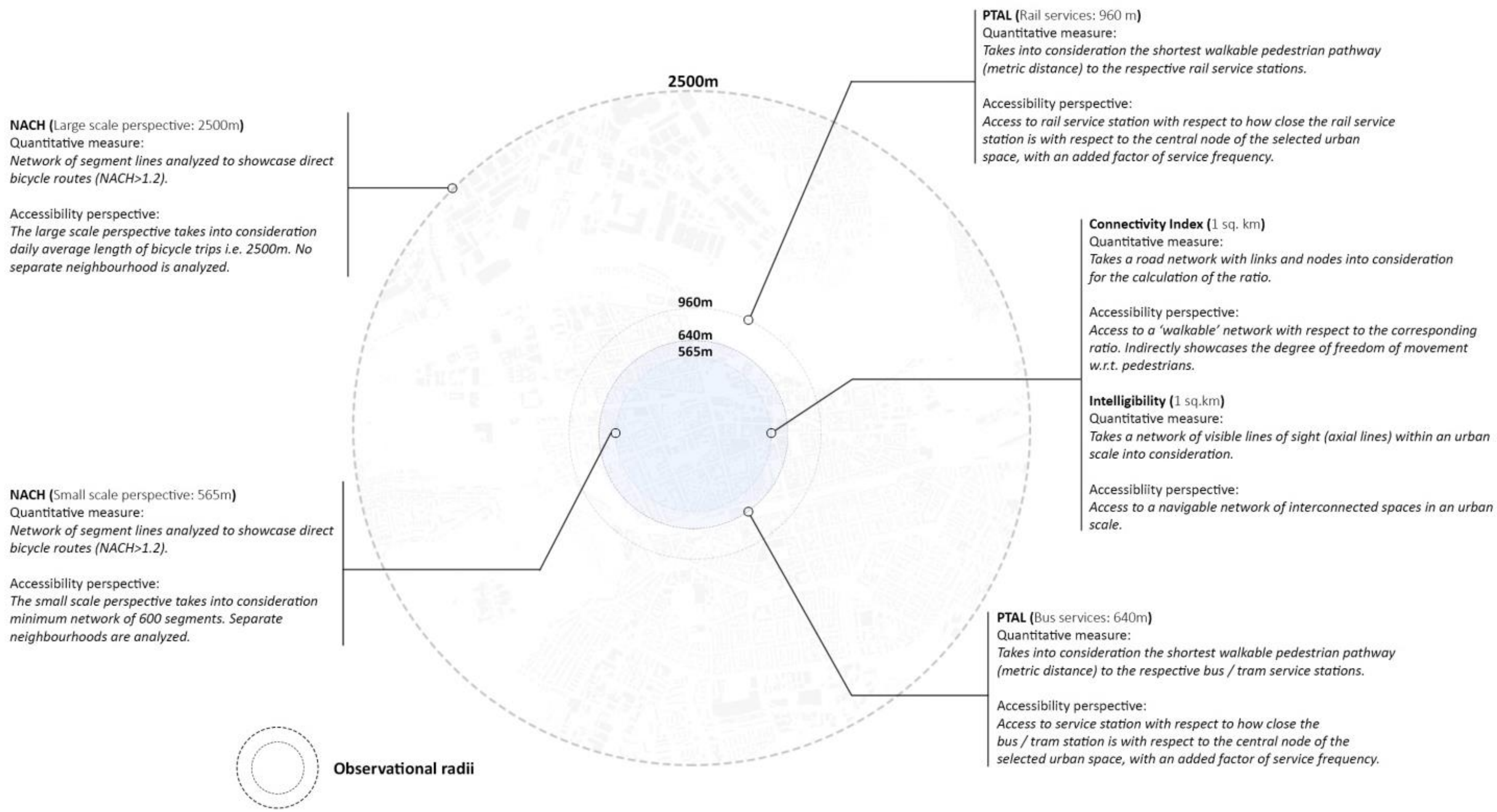
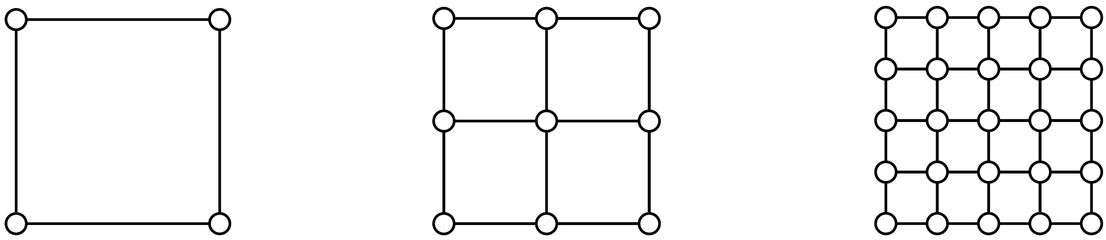


Figure 13: Accessibility perspectives and observation boundaries within selected parameters
Note: Crowding and movement restriction is a micro-scale attribute on a street level, which is mainly covered within 1sq.km. area

3.1.1 Connectivity index

With street network being one of the primary mediums for diverse mobility modes to access different parts of the city, a good connectivity influences the accessibility characteristic of the immediate urban area. For the quantitative evaluation, a connectivity index, which evaluates how well a roadway network connects destinations (Ewing 1996), is utilized. It is computed by dividing the frequency of network links by the frequency of network nodes. Links are the street segments between intersections, and the node are the intersections themselves. Cul-de-sacs in a street network count the same as any other link end point. Some studies have analysed connectivity index (or link-node ratio) of street networks to understand the effect of connectivity on travel behaviour, which includes pedestrian activity and travel mode choice. A study in New York showcased the importance of street connectivity to understand pedestrian activity (Hajrasouliha and Yin 2015), which culminated in it having a positive impact on pedestrian volume. Street connectivity was seen as a fundamental street network characteristic, along with street network density and patterns, to influence an individual's choice of movement i.e. by walking, cycling, driving or using a public transport system (Marshall and Garrick 2010). An increased nodal density (or intersection density within a street network) and connectivity showed its association with active modes of mobility i.e. walking and cycling, along with use of public transit services. The index can be calculated for pedestrian and cycling access, considering connections and links for non-motorized travel, such as a path that connects the ends of two cul-de-sacs. This encourages urban practitioners to understand the urban street geometry, which can assist in creating a pedestrian-friendly urban space.



Links (L) = 4
Nodes (n) = 4
Connectivity Index (L/n) = **1**

Links (L) = 12
Nodes (n) = 9
Connectivity Index (L/n) = **1.33**

Links (L) = 40
Nodes (n) = 25
Connectivity Index (L/n) = **1.6**

Figure 14: Different hypothetical street networks showing connectivity index with varying links (or street segments) and nodes (or intersections)

The higher the value of the index is, larger is the choice parameter for the pedestrian users regarding the routes, which in-turn leads to more degree of freedom with directions, between the origin and destination points within the street network. The presence of cul-de-sacs (or dead ends), on the contrary, diminishes the connectivity index value of the street network. Ewing (1996) suggests an index value of at least 1.4 is required for a walkable community. Based on the examples, higher frequency of links and low frequency of cul-de-sacs would entertain a better walkable network with better connectivity.

In the following figures, the Connectivity Index reduces by 0.08 with the introduction of 3 Cul-de-sacs

Ewing, R. (1996), Best Development Practices: Doing the Right Thing and Making Money at the Same Time, American Planning Association, Chicago, IL, pp 12-22.
Hajrasouliha A. and Yin L. (2015), The impact of street network connectivity on pedestrian volume, Urban Studies, 52(13):2483-2497. DOI:10.1177/0042098014544763
Marshall, W.E. and Garrick NW (2010), Effect of Street Network Design on Walking and Biking, Transportation Research Record, 2198(1), pp. 103-115. DOI:10.3141/2198-12

on the original nodal points whereas it decreases by 0.13 on the new nodal points (Fig. 15). The linking of the cul-de-sac in the network affects differently based on its connectivity with respect to the overall network system. In summary, the cul-de-sacs or the dead-end streets reduce the overall connectivity index of a network.

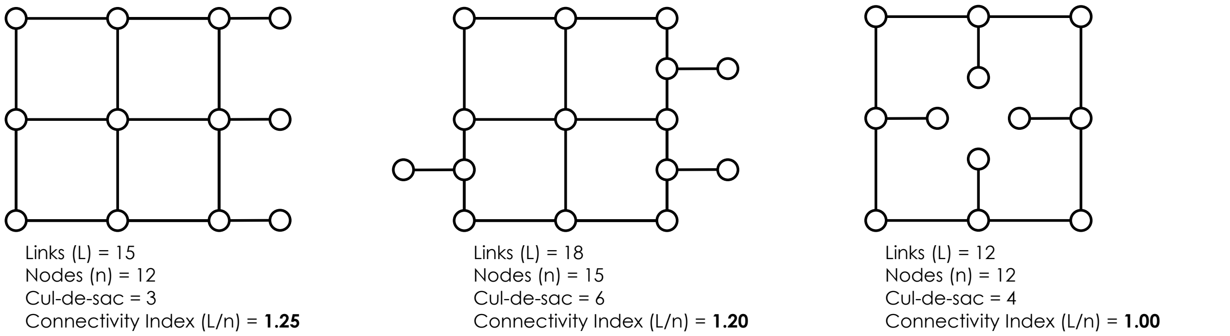


Figure 15: Different street networks showing connectivity index with introduction of cul-de-sacs on the hypothetical street networks

The Connected Node Ratio (CNR) is measured by dividing the number of street intersections i.e. nodes by the combined added sum of intersections i.e. nodes (n) and cul-de-sacs (c) (or dead ends of the street network) (see Fig. 16). The maximum value is 1.0. Higher numbers indicate that there are relatively few cul-de-sacs and, theoretically, a higher level of connectivity. CNR values of 0.7 or higher are favoured (Criterion Planners Engineers, 2001). The cul-de-sacs in the link-node ratio are not distinguished as a separate element but is regarded as a regular link in the system but in the Connected Node Ratio, the cul-de-sacs are distinguished in defining the ratio for the measure and therefore identifies the dead ends as the means of measure to relate with the outcome.

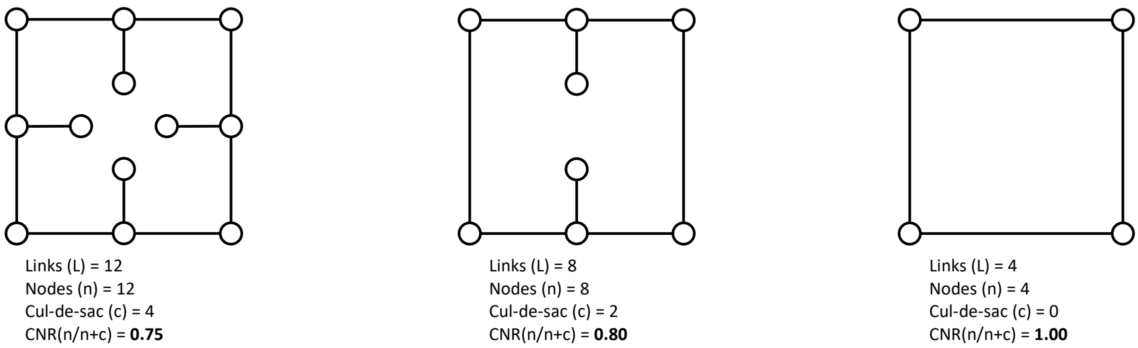


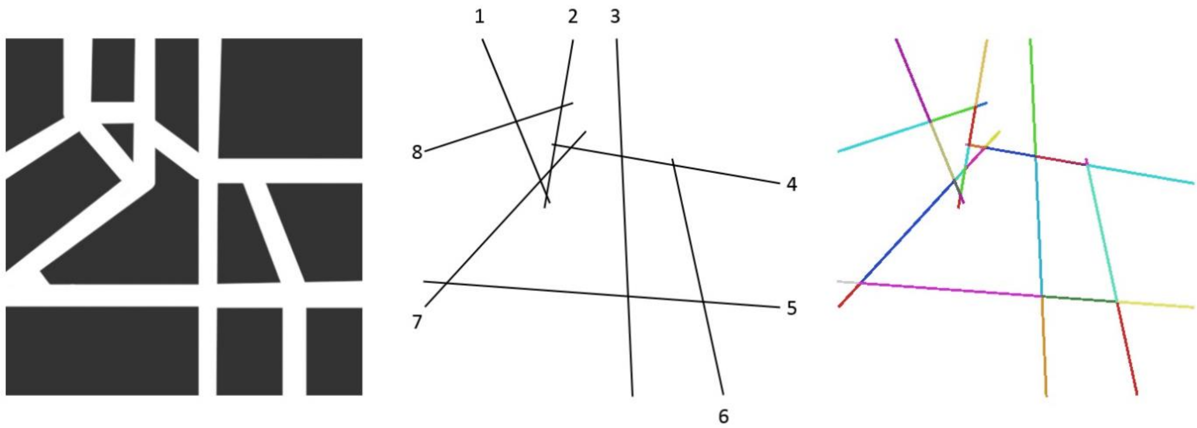
Figure 16: Different street networks showing their corresponding Connected Node Ratio (CNR)

The understanding of street geometry through different urban areas assist in a comparative approach of prioritizing which areas require improvement in regards to their street network through connectivity standards. Different aspects like block sizes, typology of the urban area dictating the street network and more attributes impact the overall frequency of intersections and links within the network of streets. The influence of intersection density and cul-de-sacs on the overall connectivity of the street network determines the mobility approach by the people and different user-groups utilizing the immediate space.

Criterion Planners Engineers (2001) INDEX PlanBuilder Users Guide, Portland, OR

3.1.2 Space Syntax attributes

Space Syntax is becoming a flourishing platform for spatial studies, increasingly well integrated with other approaches and expanding its scope and scale of investigation. The real test of theory and method is its application in the real world of projects and development. The Space Syntax theory originated in the late 1970s, which was proposed by Bill Hillier and his counterparts. The theory finds its application in understanding spatial configurations in urban areas through a set of defined attributes. A set of applications on a large urban scale include modelling pedestrian movement in urban transportation planning (Lerman et al. 2014) and urban public spaces (Van Nes and Yamu 2021), understanding spatial connectivity of routes (Navastara et al. 2018), evaluating new road connections (van Nes 2007), densification strategies of the city (De Koning et al. 2017), and more. For the analysis of street networks in accordance to the Space Syntax theory, the streets are represented by either axial lines or segment lines (which are different from the central street lines in common practice). An axial line is the longest straight line of vision, as experienced by a human in an open space, while a segment line is a part of the axial line between adjacent intersections (Hillier and Hanson 1984). Figure 17 showcases a hypothetical urban configuration of spaces through figure-ground map, which is represented by a network of long axial lines through open spaces or streets (8 in total), followed by a map of segment lines (32 in total). The '1' axial line disintegrates into 4 segment lines, while '6' segment line disintegrates into 3 segment lines. Similar set of axial and segment maps, when mapped manually for different urban areas, have been used for studying different attributes within the Space Syntax theory, including Intelligibility.



(a) (b) (c)

Figure 17: Figure ground map for an urban configuration in (a), represented by a set of axial lines in (b), and segment lines in (c)

3.1.2.1 Intelligibility

The intelligibility parameter is based on the Space Syntax theory of spaces, where spaces are treated

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Lerman, Y., Rofè, Y. and Omer, I. (2014), Using Space Syntax in Transportation Planning, Geographical Analysis, 46: 392-410. DOI: 10.1111/gean.12063

Van Nes, A. and Yamu, C. (2021), Space Syntax Applied in Urban Practice. In: Introduction to Space Syntax in Urban Studies, Springer, Cham. DOI: 10.1007/978-3-030-59140-3_7

Navastara, A. M., Yusuf, M., and Navitas, P. (2018), Application of space syntax method to measure spatial connectivity in campus of Institut Teknologi Sepuluh Nopember (ITS), IOP Conference Series: Earth and Environmental Science, Vol. 202 012015, Indonesia.

Van Nes, A. (2007), Centrality and economic development in the Rijnland region, Social and spatial concepts of centrality, Proceedings space syntax, 6th international symposium, Istanbul.

De Koning, R.E., A. van Nes, Y. Ye, and H.J. Roald (2017), Strategies for integrated densification with urban qualities, Combining space syntax with building density, land usage, public transport and property rights in Bergen city, Proceedings of the 11th international space syntax symposium, University of Lisbon, Lisbon.

Hillier, B. and Hanson, J. (1984), The Social Logic of Space, Cambridge University Press, Cambridge, pp. 17- 91.

as voids. These spaces (or voids) differ in diverse scales based on the degree of measurement i.e. ranging from street networks or a public plaza on a large urban scale, to a small architectural scale involving network of rooms on a floor inside a building. The characteristic of a space to be intelligible, is to signify the ease of understanding a space and navigate through the configuration of voids (or open spaces) with less difficulties. Regarding intelligibility, the attribute utilizes integration, that involves axial lines through the large urban scale of street network (Hillier 2007). The attribute of integration introduces accessibility through a 'to-movement' characteristic, where approaching an open space based on its relationship with other open spaces in the urban network is the main focus.

Hillier explains the integration (or global integration) attribute by analysing how deep or shallow each axial line is from one another in the urban configuration. Analysing how deep or shallow each line is from other lines up to three steps away is termed as radius-3 integration (or local integration), which has a close relation to determine pedestrian movements (Hillier et al. 1993) and also acts as a good predictor of a place being relaxing to pedestrians in open public spaces as opposed to global integration (Knöll et al. 2017). Limiting the radius to 1, is termed as connectivity (within the Space Syntax theory), which in simple terms determines how many immediate axial lines a particular line is connected to. In Space Syntax, Intelligibility is a property which is based on the correlation of connectivity and global integration. A strong positive correlation determines a space to be intelligible, which is a quality of network of spaces to be easily navigable. A scatter plot of an intelligible and unintelligible space (see Fig. 18) shows how the points around the regression line exhibit less deviation for an intelligible space whereas they segregate and show weak correlation for an unintelligible space.

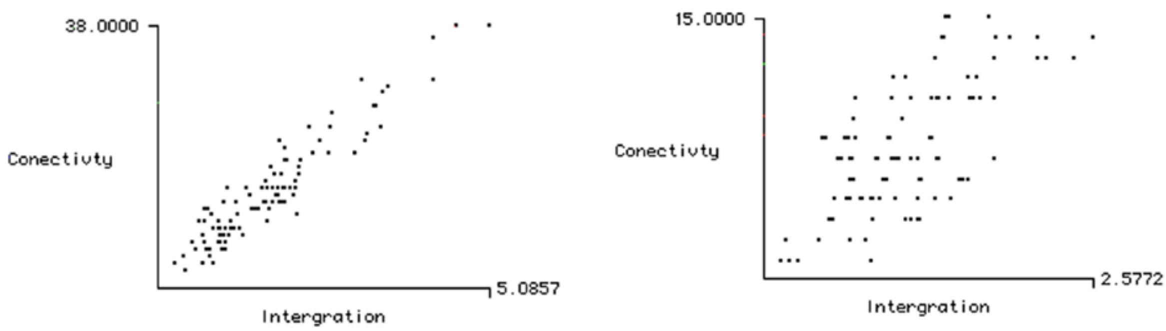

Figure 18: Spatial layout with strong intelligibility (left) and weak intelligibility (right) (Source: Hillier 2007)

This approach by Space Syntax assists in quantifying a qualitative characteristic of a network of open spaces to determine how navigable the existing environment is. It also assists in identifying the potential of wayfinding through an urban area, with focus on weakly (and strongly) connected and integrated axial streets in the urban network. Haq and Girotto (2003) in their study conclude intelligibility as an important measure which is predictive of wayfinding and environmental cognition, while it acknowledges the possibility of different layouts (based on their geometries and shapes) to have similar intelligibility characteristic.

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Hillier, B. (2007), Space is the Machine Bill Hillier A configurational theory of architecture, Space Syntax, London, pp. 93–103.

Hillier, B., Penn, A., Hanson, J., Grajewski, T. & Xu, J. (1993), Natural movement: or, configuration and attraction in urban pedestrian movement, Environment and Planning B: Planning and Design, 20, pp. 29–66.

Knöll, M., Neuheuser, K., Cleff, T. and Rudolph-Cleff, A. (2017), A tool to predict perceived urban stress in open public spaces, Environment and Planning B: Urban Analytics and City Science, 45(4), pp. 797–813.

Haq, S. and Girotto, S. (2003), Ability and intelligibility: Wayfinding and environmental cognition in the designed environment, Proceedings of the 4th International Space Syntax Symposium, London.

3.1.2.2 Normalisation of Angular Choice (NACH)

Accessibility on bicycle can be described as the possibility for people to reach their main destinations along direct routes (Nordström and Manum 2015). In order to capture the movement potential of cyclists, the measure to be utilized would vary as compared to the measures used for the pedestrian movements, as there is a difference in the character of the mobility. An understanding of the fact that the angle of movement plays an important role for moving cyclists, where sharp turns or connectivity of the streets through acute angles is considered to be a disadvantage towards the route directness (or the potential of the particular street section to attract bicycles), is taken into consideration. Intelligibility parameter uses the correlation of two factors involving integration in accordance to Space Syntax theory, which showcases a to-movement potential, whereas the NACH utilizes the factor of 'choice' (in Space syntax theory), which relates to the through-movement potential of the network system. While integration is destination-based measure, choice is the potential route-based measure to reach the desired destination. The normalisation of angular choice (NACH) (Hillier et al. 2012), has been used to compare directness of the routes in the selected urban spaces in the city. The following measure is applied in order to calculate the Normalised Angular Choice of a street segment:

$$NACH = \log(CH+1)/\log(TD+3) \quad (1)$$

The choice measure (CH) is normalized through the Total Depth measure (TD). Within the Space Syntax theory, 'choice' refers to the street segment being passed through on the shortest routes within the predetermined radius of observation (Hillier et al. 1987); while 'total depth' is the topological depth (or steps) between the selected segment and all other segments in the network (Hillier and Hanson 1984). In the study by Hillier et al. (2012), the cities and several parts within the cities with minimum 600 segments were taken into consideration with maximum segments ranging to 250000. Through the correlation of the diverse case studies, no strong correlation was discovered between the mean NACH values and the size of the city. This led to a universal approach for the measure on varying scales i.e. the measure could be used to study various scales of urban networks irrespective of its direct influence on the normalized choice measure. The mean NACH values showed a better correlation with predicting movements in diverse cities and individual areas as compared to 'choice' measures.

The parameter measures the deviation from a regular grid, with maximum NACH values ranging between 1.5 to 1.6 (or even more) and mean NACH values ranging between 0.7 to 1.2 in real cities. The NACH measurements, would be undertaken within a minimum radius of 565m (catering to 1 sq.km. area of observation) where the selected urban spaces focus more on short-distance mobility in the selected urban areas. Catering to the urban development plans, within the short-distance mobility aspect of active mobility, and the long-term perspective of the mobility environment, the average bicycle trip length of 2.5 kilometres (Parkin 2012 & CIVITAS 2016) is taken into consideration. The large scale and small-scale perspective of the NACH routes would assist in determining the potential of the existing street networks, which would assist the urban planning authorities to prioritize certain routes based on their cycling potential and accessibility. The routes with high NACH values, would reflect the directness for cyclists having least angular deviation in their movement. Nordström and Manum (2015) in their study concluded on the potential of these routes contributing towards better cycling

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Nordström, T. and Manum, B. (2015), Measuring bikeability: Space syntax based methods applied in planning for improved conditions for bicycling in Oslo, Proceedings of the 10th International Space Syntax Symposium, University College London, London.

Hillier, B., Yang, T., and Turner, A. (2012), Normalising least angle choice in Depthmap, The Journal of Space Syntax, Vol 5 (2), pp.155-193.

Hillier, B., Burdett, R., Peponis, J., and Penn, A. (1987), Creating Life: Or, Does Architecture Determine Anything? Architecture et Comportement/Architecture and Behaviour, 3 (3) 233 – 250, pp.237.

Parkin, J. (2012), Cycling and Sustainability, Transport and Sustainability, Volume 1, Emerald Group Publishing Limited, United Kingdom, pp. 111-131.

CIVITAS (2016), Policy Note Smart Choices for the City: Cycling in the City, Online Edition, pp. 16-17.

environment, given the cycling infrastructure supported the movement of the user-groups. While NACH segment analysis caters to the direct routes, the slope of the street network is not taken into consideration for the study. With potential routes being identified in the street network analysis, the street segments favouring accessible slope should be prioritized in order to establish new cycling infrastructure unless already functional on-site.

Overall the two varying observation areas for the NACH network of street segments, corresponding to 565m radius and 2500m radius, would be utilized for the small-scale and the city-wide perspective respectively. The minimum observation area of 1 sq.km. (often similar to the size of many city centres) relates to the urban acupuncture study as a tool for studying public spaces (Gehl and Svarre 2013), in order to understand the multimodal attributes of the urban street network. The assessment of representative areas through acupuncture studies assist in understanding the smaller scale of street networks, which is part of a larger city-wide configuration of streets.

3.1.3 Public Transport Accessibility Level (PTAL)

Provision of public transport in an urban network adds another degree of freedom for the users to move, based on different modes of public transport and their desired destinations, and to make the origin-destination linkages more accessible. With respect to the short distance mobility, accessing various public transport service stations is dependent upon how accessible the immediate network surrounding the service station is to its immediate users i.e. pedestrians. In order to assess the degree of accessibility of diverse modes of public transport services, the Public Transport Accessibility Level (Transport for London 2015) index is utilized to understand the different urban spaces within the timeline of the research study. The index is one of the mediums to link the service accessibility of the transport modes through the perspective of pedestrian users. It does not take into consideration the ease of boarding or alighting the transport service, but emphasizes on the closeness of the stations with respect to the selected origin points, with destinations being the service stations located in the service network. The boundaries of observation vary with respect to each mode of transport, which in-turn are based on the human walking speeds.

The methodological index was developed in 1992 by the London Borough of Hammersmith and Fulham. The PTAL index has been utilized in urban studies for guiding planners in enhancing the urban plans by integrating the two aspects of urban transport and land-use planning, improving and identifying residential locations, understanding of mobility needs and more (Adhvaryu et al. 2019). With the identification of PTAL characteristic of certain urban areas, the prioritization of improving their access to public transport could be initiated with urban development plans of cities and their corresponding districts.

The PTAL index takes into consideration the walk access times (i.e. the time taken to reach a destination by walking) and the service availability of the transportation modes during the morning peak hours within a pre-defined zone from a point of interest (poi). Walk times are calculated from specified points of interest to all public transport service access points i.e. bus stops, rail stations, underground stations and tram stations. For the calculation of the walk access time, assumed average human walking speed

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Gehl, J. and Svarre, B. (2013), How To Study Public Life, Island Press, Washington, DC. DOI: https://doi.org/10.5822/978-1-61091-525-0_6
Transport for London (2015), Assessing transport connectivity in London, London. Retrieved from tfl.gov.uk
Adhvaryu, B., Chopde, A., and Dashora, L. (2019), Mapping public transport accessibility levels (PTAL) in India and its applications: A case study of Surat, Case Studies on Transport Policy, Volume 7, Issue 2, pp. 293-300. DOI: https://doi.org/10.1016/j.cstp.2019.03.004

of 4.8 kmph is taken into consideration with respect to the shortest accessible pathway. The walk access time (T_{wat}) along with the average waiting time (T_{awt}) for the service, adds together resulting in the total access time (T_{tat}). This ensures the frequency of the public transport service is taken into consideration for the overall access time for a service station. The total access time is later converted into Equivalent Doorstep Frequency (EDF), which determines a measure as if the transport service was available at the doorstep. With respect to the maximum frequency of the service, the weightage of 1 is given to the corresponding route, while the other routes are given a weightage of 0.5 for the index (in Equation 5). The overall process is summed up as follows:

$$T_{tat} = T_{wat} + T_{awt} \quad (2)$$

$$T_{awt} = [0.5 \times (60/f)] + r \quad (3)$$

$$EDF = 30/T_{tat} \quad (4)$$

$$I_{mode} = EDF_{max} + EDF_{others} \times 0.5 \quad (5)$$

$$I_{poi} = \sum I_{modes} \quad (6)$$

The time measure is calculated in minutes for the PTAL index (I), with ƒ denoting the morning peak hour service frequency and r being the reliability factor with respect to late services. The reliability factor for bus services is 2 minutes while it is 0.75 minutes for rail services (Transport for London 2015). Overall the cumulative index for each public transport mode is calculated in order to achieve an overall index (I_{poi}) value catering to all public transport modes. The index is further grouped into six categories (excluding the group 0) based on the cumulative PTAL value (see Table 4). Group 1 (including 1a and 1b) is the PTAL group with lowest level of accessibility to public transport, where the PTAL index value below 5.01 falls within group 1b. Group 6 (including 6a and 6b) is the PTAL group with the highest level of accessibility to public transport, where the PTAL index value beyond 40.00 falls within group 6b.

Range of Public Transport Accessibility Level (PTAL)

PTAL Group	**Accessibility Index (I_{poi})**
0 (worst)	0
1a	0.01 – 2.50
1b	2.51 – 5.00
2	5.01 – 10.00
3	10.01 – 15.00
4	15.01 – 20.00
5	20.01 – 25.00
6a	25.01 – 40.00
6b (best)	40.01 +

Table 4: PTAL group corresponding to the accessibility index of public transport modes
Note: The table is based on the data by Transport for London (2015)

The PTAL measure of a particular point of interest focuses towards the accessibility of public transport through individual modes and through the combination of the available modes within the observation area. With the time being the major factor of accessibility of these services, the physical barriers (for e.g. absence of pedestrian pathways, non-availability of shortest routes etc.) may lead to increased access time, which in turn would reduce the overall PTAL of the area. The index utilizes average human speed of walking for its calculation of access time, which would not relate to the perspective of users with reduced mobility (or persons with disability). While prioritizing urban areas with less PTAL index values would be necessary for improving the overall access to public transport services, an alternative perspective for diverse user-groups should be taken into consideration catering to barrier-free approach of accessibility.

3.1.4 Crowding and movement restriction

Within an urban scenario, the provision of a footway (or a pedestrian pathway) provides a medium to initiate one of the most common modes of active mobility i.e. walking, which in-turn leads to added pedestrian accessibility to many urban destinations. The freedom of space each footway provides along with the pedestrian density, determines the ease of movement with their corresponding barriers. Based on these factors, the pedestrian footway comfort index was developed by Finch E. (2010) which identifies various characteristic environments that are appropriate based on the users utilizing the immediate space. The index is developed to evaluate different areas based on categories which include high streets, office, residential, tourist and transport interchange areas. High streets are defined as areas being dominated by shopping and retail spaces, and restaurants; while office areas usually include more commercial or (and) government office buildings. The residential areas are usually characterized by the houses (or privately-owned properties) directly facing the streets; areas with high influx of tourists (e.g. areas with historical importance, museums etc.) are designated as tourist areas; and transit stations like rail stations or bus stops are transport interchange areas. The index of crowding is utilized within the research study, for different urban areas, along with further diversification within the user groups based on their speed of movement.

Prior to the data collection, the site is categorized and based on the typology, certain peak timelines are selected with respect to each category. For example, the index addresses morning peak hours between 8:00 and 10:00 for transport interchange areas, while it recommends afternoon peak hours between 14:00 and 18:00 for high street areas. The areas are identified within the site which include dominant pedestrian flows, through reconnaissance studies. These studies can be assisted through the Space Syntax analysis, in order to identify predominant areas with high pedestrian flows through local integration (Hillier 1996), which predicts pedestrian densities in the axial street network. In order to obtain the peak hour pedestrian frequency, control gateways (see Fig. 19) are identified around the observation area. A control gateway is defined as the imaginary line, across the width of the selected street, through which the pedestrians cross. In addition to the on-site counting, the user-groups are categorized based on their pace of movement as follows:

1. Pedestrians: These include all pedestrians crossing the control gateway line (e.g. People walking, persons with baby strollers, kids, and users with reduced mobility).

2. Cyclists: These are persons riding a bicycle crossing the gateways, and usually have high speed of movement in comparison to pedestrians.

3.E-scooters: Persons using the electric scooters (or boards) as a medium of their mobility.

Finch, E. (2010), Pedestrian Comfort Guidance for London Guidance Document, Transport for London, London. Retrieved from www.tfl.gov.uk/walking
Hillier, B. (1996), Cities as movement economics In: Space is the Machine, Cambridge University Press, Cambridge, pp.110-137.

4. URM (Users with reduced mobility): These include wheelchair users, users with cane, walkers etc.

5. Baby strollers: These are persons with a baby stroller, who usually have slow speed of movement.

6. Two-wheelers: These are on-street motorized two-wheeled vehicles (e.g. motorcycles, scooters etc.).

7: Four-wheelers: These are on-street motorized vehicles, with minimum four wheels (e.g. cars, taxis etc.).

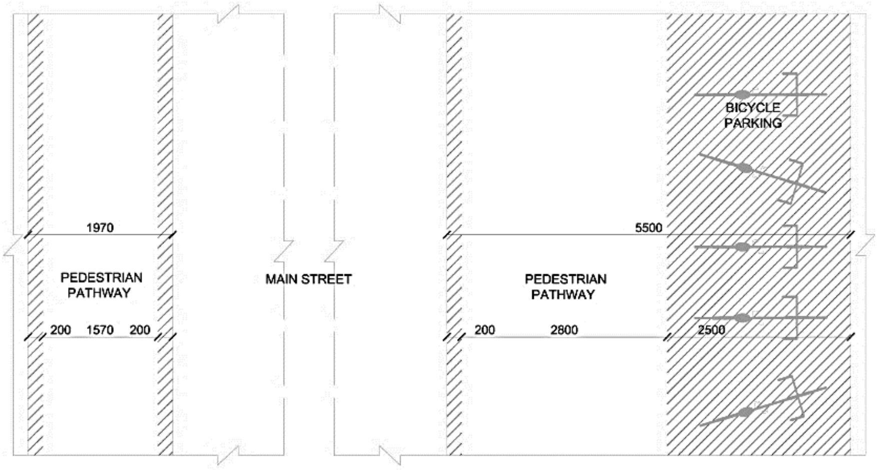

Figure 19: A control gateway across the street with pedestrian pathways and buffer widths (e.g. along street and building edges of 200mm width and bicycle parking)

The diverse user-groups can be further classified into slow-paced and fast-paced user-groups, where slow-paced groups include people walking, URM, baby strollers and kids, whereas the rest fall within fast-paced user-groups. The movement pace of a group of people is often determined by the pace of its slowest member within the group. With the on-site visit, the selected control gateways are first measured with their respective street widths including street elements which may act as a barrier to the pedestrian movement (in Appendix). The buffer widths are identified based on the index description, which usually explains the movement behavior of people with the street elements. It is the approximate space left between the street element and a person while moving. For example, a standard buffer width of 200mm is identified for a building edge or a street edge. With the available footway widths, obtained after the buffer spaces with respect to the street elements are deducted, the peak hour pedestrian frequency data is collected on-site and a measure of pedestrian crowding is calculated, as follows:

$$\text{Pedestrian crowding} = (P_f / W) / t \qquad (7)$$

In equation 7, the P_f is the peak hour frequency of people moving on a control gateway, W is the available footway width for movement in meters, and t is the time of observation i.e. 60 minutes. The overall pedestrian crowding is calculated as persons per meter per minute (i.e. ppmm). With respect to the available pedestrian crowding, the index is categorized with respect to several movement restrictions, ranging from A+ level with <3ppmm denoting a minimum 3% movement restriction to E with >35ppmm with 100% movement restriction. Areas with crowding above 12ppmm and 41% movement restriction, often lead to frequent conflicts resulting in reduced speed of movement, which may influence pedestrians to avoid taking a particular street. Selective areas with dominant vehicular traffic are also taken into consideration, in order to relate the active modes of mobility with the traffic.

3.2 Selection of urban areas for the study

With selected accessibility performance measures in place with respect to their varying observational radii, selection of urban areas within different cities forming the urban agglomeration of Frankfurt Rhein-Main helps in a comparative study which acknowledges the potential and present level of accessibility. As discussed in the previous chapter, in recent years, the region has seen a 5% increase in its population with major cities being Frankfurt (10.3%), Offenbach (9.8%) and Darmstadt (9.7%). These cities also showcase high commuter flows within the region with respect to the Office for Statistics and Urban Research (Amt für Statistik und Stadtforschung 2020). Since 2009, Offenbach has shown most increase in the out-flow of commuters (+60%) within the Rhein-Main region compared to other cities, while Darmstadt (on par with Frankfurt) has shown most in-flow of commuters within the urban agglomeration.

On the basis of growing urban population and commuter flows within the expanding metropolitan region of Frankfurt Rhein-Main, three cities giving a poly-central characteristic were selected for the research study which include Frankfurt, Darmstadt and Offenbach. The next step within the hierarchy of selecting urban spaces is to represent spaces where people gather or disperse in large or small scale (Gehl, J. & Svarre, B. 2013). This leads to urban acupuncture study, where urban areas (minimum 1 sq. km.) are selected to carry forward the accessibility studies leading to a comparative learning through the epistemological timeline. The main emphasis of selecting the urban areas is to locate spaces where people commute to and from, which makes it a part of the urban mobility system. It would be based on the diverse environment they relate to, including retail high street spaces, residential spaces, areas pertaining major hub for inter-city transportation within the selected urban agglomeration and their identification within their corresponding city's urban development plans for the future. For this purpose, the cluster of three urban areas were selected for each city addressing the intra-city and inter-city spatial analysis, which include:

- City centres: These areas are the central landmarks of the urban core of a city, which is usually concentrated with dense mobility traffic involving pedestrians, public transport, and other user-groups. They include high street areas and attract many economic opportunities making it as one of the important destinations within a travel chain.

- Transit areas: The area surrounding main transit stations responsible for inter-city travel within the urban agglomeration represents an important node with a travel chain, and is also favoured for transit-oriented development involving dense land-use in close relation with public transport services.

- Residential areas: These urban areas are dominated by residential land-use, with least influence from the city centres, industrial areas or main railway stations (like Hauptbahnhof), which act as an origin for majority of travel routes. Unlike city centres or main transit stations, a city does not have a unique residential area, therefore within the scope of the research study residential areas which are identified within the city's urban development plans for the future and fall within the observational limits of the identified parameters are selected.

Amt für Statistik und Stadtforschung (2020), Amt für Statistik und Stadtforschung hat Analyse zu den Pendlern vorgelegt, Pressemitteilung, Wiesbaden, Retrieved from http://www.wiesbaden.de/presse
Gehl, J. and Svarre, B. (2013), How to Study Public Life, Island Press, United Kingdom.

3.2.1 Frankfurt am Main and its selected urban areas

Location and Demographics

The City of Frankfurt (248.3 square kilometres in area) is located within the state of Hessen with over 750,000 inhabitants in 2018, out of which more than 90% people work in the city forming the central node of the Rhein-Main urban agglomeration (Stadtplanungsamt Frankfurt 2021a). The city is growing with its urban population, and is expected to cross over 810,000 in 2030 followed by 840,000 in 2040 (Stadt Frankfurt am Main 2019). With diverse economic opportunities and constant influx of people, 30% of residents are foreign nationals. Within the foreign population, more than 50% come from countries outside Europe (Stadt Frankfurt am Main 2021a). The city continues to grow over the years as one of the poly-central cities in the state and country.

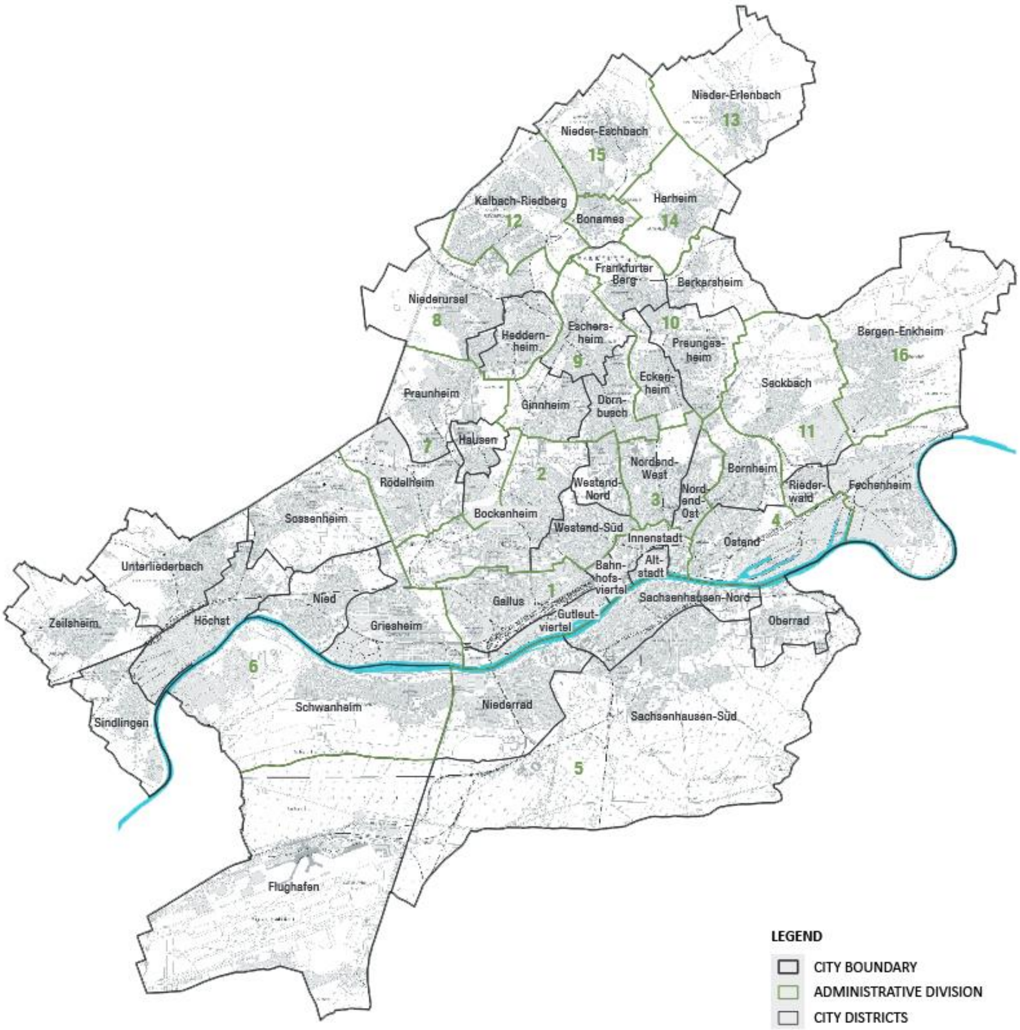

Figure 20: Different urban districts in Frankfurt am Main
Source (image modified): Stadt Frankfurt am Main (2020a)

Stadtplanungsamt Frankfurt (2021a), Urban Development, Frankfurt am Main. Retrieved from https://www.stadtplanungsamt-frankfurt.de
Stadt Frankfurt am Main (2019), Frankfurt 2030+ Integriertes Stadtentwicklungskonzept, Frankfurt am Main. Retrieved from https://www.stadtplanungsamt-frankfurt.de
Stadt Frankfurt am Main (2021a), Bevölkerung am 30. Juni 2021, Frankfurt am Main. Retrieved from http://www.frankfurt.de/statistik_aktuell
Stadt Frankfurt am Main (2020a), Statistisches Jahrbuch Frankfurt am Main 2020, Frankfurt am Main. Retrieved from www.frankfurt.de/statistisches_jahrbuch

The Main river bisects the city of Frankfurt in two parts (see Fig. 20), which leads to the name 'Frankfurt am Main' translating to Frankfurt on Main. On the whole, the city of Frankfurt consists of 46 districts distributed on the north and south of the river Main, with five districts located on the southern part and rest on the northern side. Over the years, different districts have shown varying growth patterns with regards to the population density. With respect to all districts within Frankfurt am Main during the pandemic in 2021, the overall population figure fell by approximately 9500 inhabitants. As a result, this led to the city having a population of 749, 421 i.e. going below the 750,000 mark since 2019. The decrease in 2021 was mostly due to the aftermath of local elections, which led to deregistering inhabitants who no longer lived in Frankfurt. Most of these were foreign nationals who left the city, with high probable reason of moving abroad, without informing the city registration authorities. Considering the downfall in the overall population within the districts, the major ones included that of Bahnhofsviertel (i.e. the neighbourhood adjacent to the east of the main railway station) which fell by 4.8% and Innenstadt (i.e. the city centre), whose inhabitants decreased by 4.4% in 2021 (Stadt Frankfurt am Main 2021). This shows the impact coronavirus pandemic had directly or indirectly on the inhabitants (mostly foreign nationals) living within the city, comprising of major destination areas including city centre and the area surrounding main railway station i.e. Hauptbahnhof.

Urban development and Frankfurt 2030+

The city's spatial location within the urban agglomeration of Rhein-Main region forces it to adapt the urban development planning in a scale which is not only limited to the local boundaries but also takes into consideration the perspective of regional growth for both the city and the Rhein-Main region. Currently, the city authorities are focused on establishing an integrated urban development plan 2030 for the city of Frankfurt. The integrated urban development plan is conceptualized to ensure a sustainable growth within the growing urban community which is getting diverse and interconnected. To fulfil its plan, the concept has prioritized six objectives which includes urban development in a climate-friendly manner through urban mobility. This involves focusing on more promotions regarding eco-friendly modes of mobility and investments in public transport in order to sustain the growing population of the city in future.

Within the framework of Frankfurt 2030+, the concept has identified certain areas which would be prioritized for the urban development showing particularly good opportunities for the same. These include (with certain objectives per area):

- A new city district i.e. Frankfurter Nordwesten, which would have mixed-use quarters along with added connections via public transport through S-Bahn (i.e. a city rapid rail service) and extension of U-Bahn (i.e. underground rail service) network.
- Mittlerer Norden, which would have urban development of existing settlements within certain areas; improved connections through green areas and better U-Bahn connection.
- Bornheim-Seckbach, which would involve a spatial urban weaving between the two districts. This includes establishing new residential areas which would be free from motorway noise; better landscape connections; and creation of new green public spaces to expand the existing parks and improve quality of stay.
- Innenstadt (i.e. the city centre), where implementation of Innenstadtkonzept would take place. This includes certain revitalization projects around the area along with residential development. Within the domains of mobility and user-groups, this area is also being specifically prioritized to reduce the conflict points between cyclists and pedestrians in

Wallanlangen. It also involves redesign of streets including Mainuferstrasse and Berliner Strasse.

- Gutleuthafen, which involves extension of Mainuferweg along with mixed-use urban development. The residential share of land-use is planned to increase in the district.
- Am Römerhof, which plans to extend to Europaviertel along with establishing new mixed-use urban quarters. This also includes development of new school infrastructure in the west; spatial planning for parking spaces and connection of green belt with access to river bank.
- Griesheim-Mitte and Nied, where improvement around railway station in Griesheim is one of the objectives in the area followed by good network of open spaces in the district.
- Sossenheim-Rödelheim, which mainly involves the commercial site focusing on improving motorway connection along with urban reorganization of commercial areas which would also lead to making it more compact.

With areas being prioritized for the urban development plan Frankfurt 2030+, the plan also utilizes different urban planning concepts from the earlier projects within the city and tries to evolve in continuum through their objectives. One of these projects is included within the city centre i.e. Innenstadt via 'Innenstadtkonzept'. The development area for the project 'Innenstadtkonzept' was limited to the area within the green belt of Wallanlagen (which also has been prioritized as an area to reduce the conflicts between pedestrians and cyclists). Within the 'Innenstadtkonzept', some of the main objectives included: improving the pedestrian and cycling network to link the city centre with the Mainkai riverfront and the surrounding green areas within Wallanlagen; along with revitalization of public spaces in the area. The concept identified how the network of streets and traffic can act as a barrier towards movement of people, especially towards the city centre. Within the design for public space section of the concept, the plan focuses on reducing car traffic along the certain streets which resonates towards the car-friendly city during the mid-20th century post war period.

Mobility within the city

In the second-half of the 20th century, Frankfurt am Main was planned in a way to make it a car-friendly city. Over the years, there has been a paradigm shift where car-free planning approach has taken more prominence. Within the city, around 28% of the trips now are made through private motorized vehicles, with walking on foot having a higher modal share of 32% in the city, followed by 24% via public transport (infas, DLR, IVT and infas 360 2020) (see Fig. 21). The share of private motorized vehicles was 35% in 2013, which shows the shift in mobility behaviour of the people in the city. This impacts the overall space available on the streets, which in turn influences other modes of mobility functioning within the city. Frankfurt is the centre of Rhein-Main-Verkehrsverbund (i.e. Rhine Main Regional Transport Association or RMV) which is one of the biggest transport associations in Germany. The city has a network of several on-ground and underground transit services including S-Bahn (i.e. Stadtschnellbahn), U-Bahn (i.e. Untergrundbahn) and tram lines. Nine S-Bahn lines connect the city with other areas including neighbouring cities of Darmstadt, Wiesbaden, Hanau and more along with the international airport i.e. Flughafen. With respect to U-Bahn service system, the city has seven service lines which run underground (and some on ground) through the city centre including Hauptwache and Konstablerwache and connect different parts and urban areas of the city with one another. Similar to S-Bahn, there are nine tram lines running through the city along with several bus services which connect the districts on both sides of the river Main.

infas, DLR, IVT and infas 360 (im Auftrag des BMVI) (2020), Mobilität in Deustchland – MiD Regionalbericht Hessen, Bonn.

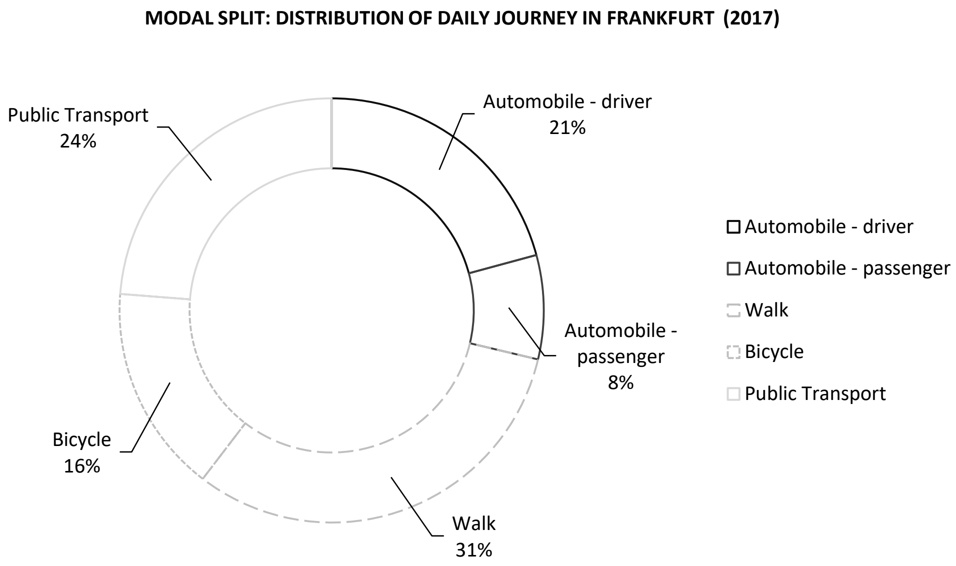

Figure 21: Modal split within Frankfurt am Main on daily journeys in 2017
Data source: infas, DLR, IVT and infas 360 (2020)

Figure 22: A cycle lane with dedicated signage adjacent to Konstablerwache plaza in Frankfurt am Main

The city has many cycle pathways around the city and the authorities continue to expand the cycling network of dedicated bicycle pathways, focusing more on short-distance active mobility mode. In order to have an efficient cycling network, the city of Frankfurt in 2014 defined a network of routes which would have signages posted in different districts within the city showing the direction and travel distance to a local and a major long-distance destination. In 2021, the city-wide signage for the network of bicycle pathways (see Fig. 22) was completed with more than 4000 locations through different urban districts (Stadt Frankfurt am Main 2021b). This measure assists in better orientation and navigation for cyclists within the city in an efficient manner. With respect to long-distance cycle connectivity, the city has been going through several bicycle-highway projects connecting it with neighbouring cities i.e. Darmstadt, Wiesbaden and more. With some projects being in their feasibility study stage, the first bicycle highway has been on its construction phase between Darmstadt and Frankfurt am Main with a planned route of approximately 35 kilometres long.

While the traditional modes of transport have been running within the city for several years, a new mode has been on the rise i.e. e-scooters (i.e. electronic scooters). The e-scooters favour short-distance travel and are allowed to operate with a maximum speed of 20 kmph in the city. Within the areas of its usage, pedestrian zones and sidewalks are prohibited, with cycle lanes being favoured maintaining similar speed of movement. With multiple operators providing the shared e-scooter services in the city, the utility of the mode has grown with more than 5000 scooters already functioning within the city in 2021 (ADAC Hessen-Thüringen 2021). With growing demands and ease of access to the mode, the numbers are expected to increase in future years within the city.

3.2.1.1 City centre in Frankfurt am Main

Location and spatial utility

The city centre of Frankfurt is located within the district of Innenstadt, which is surrounded by the old city district i.e. Altstadt, the green parks through the Wallanlagen, along with the river Main flowing in the southern end of the area. Other surrounding districts include Bahnhofsviertel in the west, Nordend, Westend and Ostend (see Fig. 23), with Sachsenhausen situated on the southern end of the Main river. The district of Innenstadt has an overall area of 1.49 square kilometres, with distribution of settlement area being dominated by industrial and commercial space (i.e. 33%). This is followed by 26% of the space being under sports, leisure and recreational area, 19% being utilized under mixed-use area, 5.5% within the residential land-use, with remaining space being for cemetery and special functional characteristic (Stadt Frankfurt am Main 2020b). This clearly shows the area being characterized as a shopping district with several retail shops located around several streets and open plazas, making it one of the popular destinations for people to travel to within the city. With respect to Altstadt, the distribution of settlement area is different. The old city district has an overall area of 0.51 square kilometres, with the mixed-use area having the majority of space within the settlement area (i.e. 37%). In contrast to the Innenstadt district, the industrial and commercial space in the old city district is limited to 8.8% of the overall settlement space. The sports, leisure and recreational area amounts to 7.3%, while 16.5% is for residential purpose. The remaining space which has a special functional character takes 30.4% of the area. The two districts of Westend and Nordend are located on the northern end of the city centre. While Nordend district has high share of residential space, Westend has more commercial and industrial area, followed by residential area. The presence of green

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Stadt Frankfurt am Main (2021b), Radnetzbeschilderung in Frankfurt abgeschlossen, Frankfurt am Main. Retrieved from https://www.radfahren-ffm.de/
ADAC Hessen-Thüringen (2021), E-Scooter-Check in Frankfurt, Hessen-Thüringen. Retrieved from https://www.adac.de/der-adac/regionalclubs/hessen-thueringen/sicherheit-mobilitaet/e-scooter-check-frankfurt/ (20-12-21)
Stadt Frankfurt am Main (2020b), Frankfurter Statistische Berichte 2020, Frankfurt am Main. Retrieved from www.frankfurt.de/statistische_berichte

landscape through Wallanlagen acts as a transition buffer space between the northern end of districts and the city centre in Frankfurt am Main.

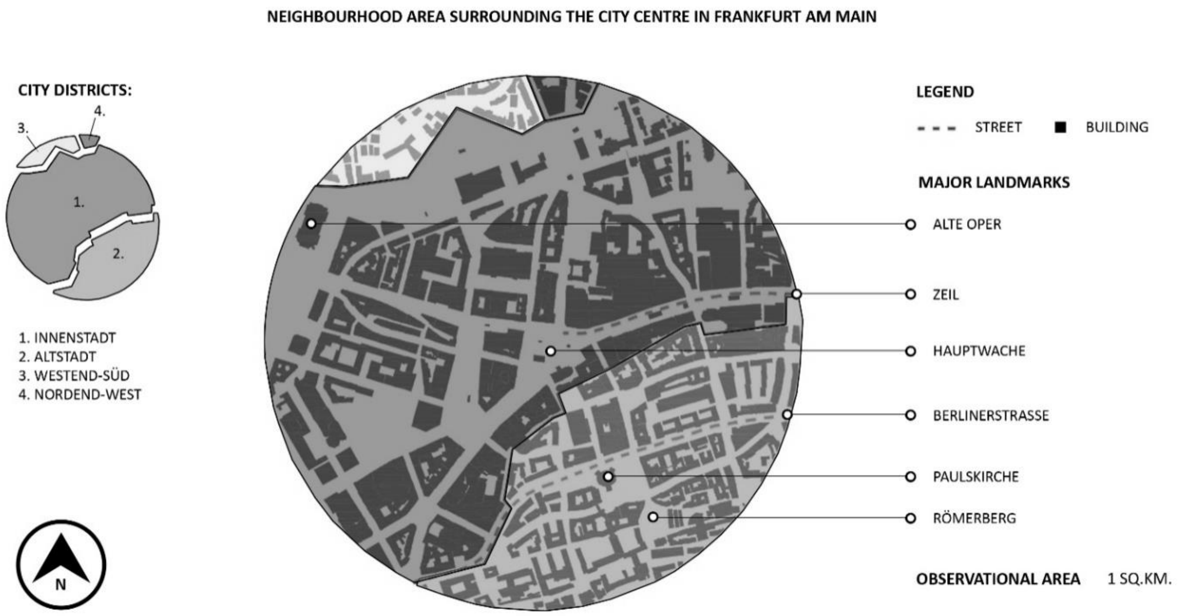

Figure 23: Immediate area surrounding city centre in Hauptwache with major landmarks (Figure ground map of 1 sq. km.)
Data source: Stadtplanungsamt Frankfurt (2021b)

Spatial configuration and characteristic

With two main urban districts surrounding the city centre i.e. Innenstadt and Altstadt, the configuration of space varies through the two areas (see Fig. 23). In Innenstadt, with the buildings being more commercial and wider in length, the distance between two adjacent streets is longer as compared to the ones in Altstadt. The streets in Altstadt district are more narrow and closer to each other, with shorter block sizes, which supports more pedestrian movement (Jacobs 1961) with added freedom of movement. The city centre also has a network of open spaces which include Römerberg plaza in south, Konstablerwache in the east, with Hauptwache being the central open public space. With many spaces within the old city district being of historical importance, i.e. Römerberg, Paulskirche, Kaiserdom etc., the area attracts tourists throughout the year especially with the medieval sections of the district undergone recent reconstruction. The district is also host to several museums ranging from modern art to history. The city centre area also functions as one of the important transit service stations (i.e. Hauptwache) for people traveling to and from the city centre to other individual districts within the city.

The pedestrianization of the area around Zeil in 1970s, i.e. the street connecting the Hauptwache and eastern end of the Innenstadt district (see Fig. 24), assisted in attracting more people around the shopping district. Today the pedestrian zone is prioritized towards walking, where even the people on

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Stadtplanungsamt Frankfurt (2021b), planAS. Retrieved from https://planas.frankfurt.de
Jacobs, J. (1961), The Death and Life of Great American Cities, New York, Random House.

bicycle are obliged to give way for the pedestrians. As discussed earlier, with constant plans to make the city and neighbouring areas more accessible to people using the space, the city introduced the ‘Innenstadtkonzept’ (i.e. the inner-city concept) in 2015. The plan gives accessibility a priority to make the city centre more attractive through services and ease of exchange through different transport modes within the city centre, which is a prerequisite.

Figure 24: Street across Zeil with retail and shopping areas overlooking the pedestrian space in the city centre of Frankfurt

The plan focuses on public spaces to improve the quality of stay with pedestrians and cyclists in focus. This involves looking over street network and connections which lead towards the city centre. Within the inner-city plan, certain streets (i.e. Mainkai and Berlinerstrasse) have been identified with high vehicular traffic density which in a way act as barriers for the north-south connection between the centre of the pedestrian zone and the Main river boulevard. Reducing the car lanes through these streets would assist in making the connection more barrier-free and allow a comfortable transition through different open spaces in between the shopping district and Main river. Similar to Zeil, Berlinerstrasse acts as the important east-west connection within the city centre. Although in contrast to Zeil, the street of Berlinerstrasse is open to vehicular traffic, providing less open space for active mobility user-groups.

3.2.1.2 Transit area in Frankfurt am Main

Location and spatial utility

The main railway station of the city of Frankfurt is located on the northern side of the river Main within the district of Gallus, with immediate surrounding districts including Bahnhofsviertel, Gutleutviertel and Westend-Süd (see Fig. 25). The main railway station though situated on the peripheral boundary of the Gallus urban district, its three major entrance points overlook three different districts. The district of Bahnhofsviertel is located directly opposite the main entrance of Hauptbahnhof i.e. (the main railway station) in the east, while the entrance on the southern side faces Gutleutviertel and northern side faces Gallus. The district of Gallus has an overall area of 4.51 square kilometres, with distribution of settlement area being dominated by residential space (i.e. 43.6%). This is followed by 30% of the space being under the industrial and commercial utility, 15.6% of space being under sports, leisure and recreational area, 5.5% within the mixed-use area and the remaining space falling under the spaces having special functional characteristic (Stadt Frankfurt am Main 2020b). This shows how transit-oriented development is taking shape around the district hosting main railway station, where major spaces are residential in nature along with spaces prioritizing commercial and leisure activities.

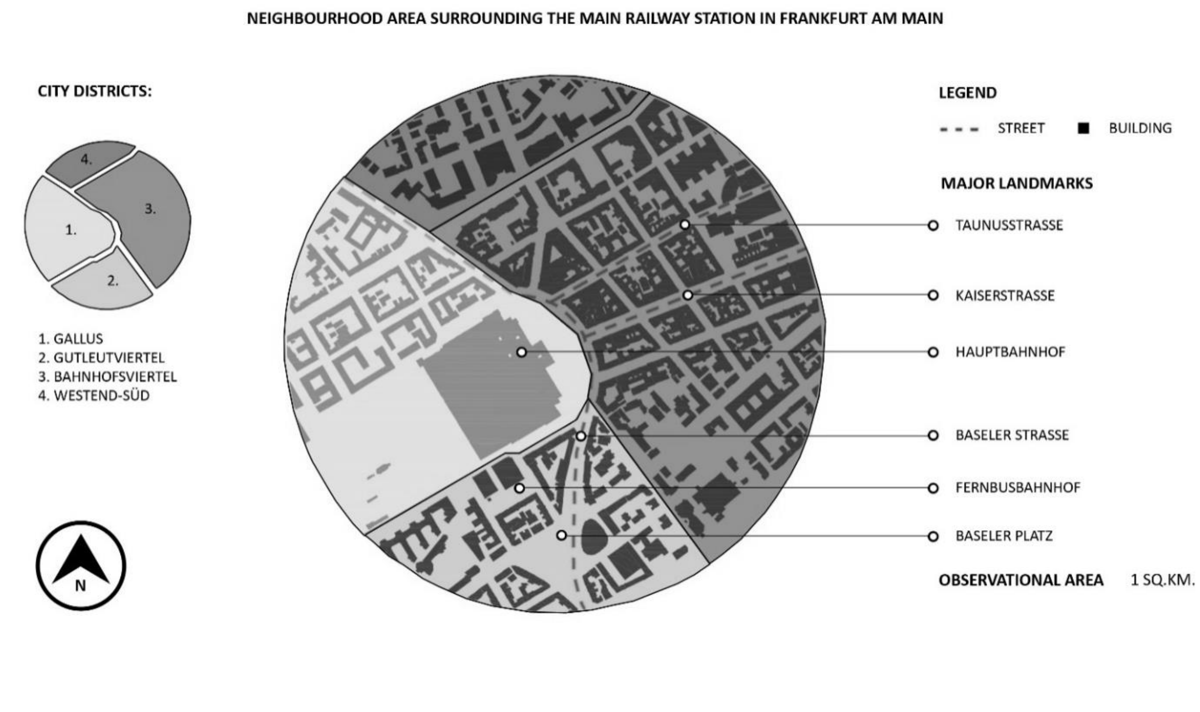

Figure 25: Figure: Immediate area surrounding main railway station in Hauptbahnhof with major landmarks (Figure ground map of 1 sq. km.) Data source: Stadtplanungsamt Frankfurt (2021b)

Bahnhofsviertel covers an overall area of 0.54 square kilometres, with the industrial and commercial area dominating the settlement area (i.e. 62%). This is in stark contrast to the residential nature of the Gallus district in the north. 17% of the settlement area in Bahnhofsviertel falls within the mixed-use

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Stadt Frankfurt am Main (2020b), Frankfurter Statistische Berichte 2020, Frankfurt am Main. Retrieved from www.frankfurt.de/statistische_berichte utility, followed by 8.2% of residential space. The proportion of spaces within sports, leisure and recreational amounts to 7.4%, with rest having special functional characteristic.

Considering the district in the southern end of the railway station i.e. Gutleutviertel, it occupies an overall area of 1.79 square kilometres, with similar characteristic as Bahnofsviertel where the commercial and industrial nature of space dominates the settlement area (i.e. 60%). This is followed by sports, leisure and recreational utility having 18% of the space, and 14% within the residential area. The mixed-use area has the least proportion of space (i.e. 2.5%), with the remaining 12.4% having special functional characteristic. Westend-Süd district, with an overall area of 2.49 square kilometres, also has a higher proportion of settlement area falling within industrial and commercial utility (i.e. 37%), followed by residential utility (i.e. 28%).

With respect to the three neighbouring districts around the main railway station, all showcase the industrial and commercial nature, while the district of Gallus has more proportion of settlement area within residential utility. Hauptwache and the main railway station are situated quite close to each other, i.e. within a Euclidean distance of 1.5 kilometres between the two. The Bahnofsviertel urban district in the east is the only district between Innenstadt and Gallus, and has the highest proportion of space which falls within the industrial and commercial utility. The residential nature of space varies from approximately 44% of settlement area in Gallus to 8.2% in Bahnhofsviertel, and falls down further to 5.5% in Innenstadt. This shows how the proportion of residential spaces drop while one moves from the Gallus district (having main railway station) to the Innenstadt district (comprising of the city centre).

Spatial configuration and characteristic

The immediate area opposite the main railway station in Bahnhofsviertel has a grid pattern where the majority of block sizes fall within 150 metre length. With block lengths within 100 metre length (ITDP 2018), neighbourhoods with such network offer pedestrian friendly environment with more frequent choices of different streets and routes to choose from. With shorter block sizes, a safer neighbourhood is established based on slow vehicular speed for pedestrians and cyclists. The streets responsible for making these blocks in Bahnhofsviertel have had an historical importance. The neighbourhood in Bahnhofsviertel has a set of boulevards which have been preserved post Second World War (see Fig. 25); these include Taunusstrasse, Kaiserstrasse, Niddastrasse (street parallel to Taunusstrasse in north), and Münchener Strasse (street parallel to Kaiserstrasse in south). These parallel streets run from the main railway station, originating from Am Hauptbahnhof street, towards the city centre merging through the green belt of Wallanlagen. As a central axis, Kaiserstrasse bisects the neighbourhood in Bahnhofsviertel into northern and southern parts, with wide street width making it and the adjacent streets as vital inner areas. The streets surrounding these inner areas, in contrast, have heavy traffic including Am Hauptbahnhof in the west and Mainzer Landstrasse in the north (second street parallel to Taunustrasse in north).

With respect to large open public spaces, majority of them are observed along the river Main in the southern peripheral boundary of the two districts i.e. Bahnhofsviertel and Gutleutviertel. In close proximity to the railway station, the green open spaces are less in number with Baseler Platz as an exception. Around 95% of the space in the Bahnhofsviertel district is covered through construction with only 5% having space for small green spaces. This has led to projects and plans in the past which involved making many parts of the area green via tree plantations on certain locations, including

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ITDP (2018), Streets for walking & cycling Designing for safety, accessibility, and comfort in African cities, Retrieved from africa.itdp.org streets such as Taunusstrasse and Gutleutstrasse (Stadtplanungsamt Frankfurt 2008). The open space in front of the main railway station overlooks the inner boulevards of Bahnhofsviertel and offers a transition space to change one's mode of travel where several bus and tram service stations are available on the ground level. With the nature of the railway station being terminal, i.e. acting as a final stop or the first stop in a journey, the western part of the railway station is covered with on-ground rail tracks (approximately 250 metres width), which takes a portion of open space away from the network of streets.

Figure 26: Street across Kaiserstrasse in Bahnhofsviertel with on-street vehicular parking facing the entrance of main railway station in Frankfurt

The Gallus district, which houses the main railway station, was earlier included in the urban revitalization plan 'Soziale Stadt' (i.e. social city in German). The district acted as a buffer between the earlier freight rail station in the north (which now is part of the Europaviertel, housing residential and commercial spaces along Europa-Allee) and the main railway station in south. Some green open spaces along the Europa-Allee have been realized such as the 'Europagarten' which is located approximately 2.3 kilometres in the west (in Euclidean distance) from the main entrance of the railway station i.e. Hauptbahnhof. The set of plans in the past project how the immediate area around the main railway

Stadtplanungamt Frankfurt (2008), Stadtumbau in Hessen Städtbaulisches Entwicklungskonzept "Bahnhofsviertel" BAUSTEIN 1/07, Frankfurt am Main. Retrieved from https://www.stadtplanungsamt-frankfurt.de station lacks open spaces (especially green open spaces) due to the dense building infrastructure and high utilization of open streets.

3.2.1.3 Residential area in Bornheim

Location and spatial utility

The residential area in the district of Bornehim is located in the eastern section of the city of Frankfurt on the northern side of Main river. The immediate surrounding districts include Nordend-Ost in the west (see Fig. 27), Ostend in the south, Riederwald in east and Seckbach in north. The district of Bornheim covers an overall area of 2.78 square kilometres, with the majority of the settlement area being under the residential utility (i.e. approximately 42%). This is followed by 28% of the settlement area being under sports, leisure and recreational activity related infrastructure. 13% of the area is within the mixed-use purpose while only 3.7% (~4%) of the area falls under industrial and commercial use. The remaining portion of the area either falls with those having a special function characteristic or area for cemetery. Similar to the district of Bornheim, the neighbouring district of Nordend-Ost, having an overall area of 1.53 square kilometres, also has a large share of settlement area for residential utility (i.e. 53.4%). This is followed by 16.7 (~17%) of the area falling under sports, leisure and recreational purpose. Approximately 15% of the settlement area is for mixed-use purpose, while 6.1% of the area falls under industrial and commercial use. The overall utility of settlement area within the two neighbouring districts of Bornheim and Nordend-Ost follow similar hierarchy, where residential space is given more priority followed by sports, leisure and recreational activities.

Figure 27: Figure: Immediate area surrounding Bornheim with major landmarks (Figure ground map of 1 sq. km.) Data source: Stadtplanungsamt Frankfurt (2021b)

Spatial configuration and characteristic

The spatial layout of the residential area in Bornheim has a branch-like structure where Seckbacher Landstrasse street (see Fig. 27) acts as a central axis and the streets along with buildings are set up in a way branching out from the axis street in east and west direction. The layout in the northern section of the residential area has more wide block lengths in comparison to the southern section of Bornheim. Before being an urban district within the city of Frankfurt, major parts of the Bornheim district were covered by forest. With respect to green spaces in the area, most can be found in the northern and eastern sections of Bornheim, along with a small rose garden i.e. Rösengartchen which also acts as a traffic roundabout with street connections leading to Seckbacher Landstrasse, Berger Strasse and more; followed by the neighbouring public park in west within the Nordend-Ost district. The street of Berger Strasse runs from the southern end of the Bornheim district, connecting Nordend-Ost to the northern district of Seckbach. With numerous restaurants and cafes along the Berger Strasse street (see Fig. 28), the area has been a popular destination for many locals and visitors from other parts of the city.

Figure 28: Neighbouring narrow street across Berger Strasse with restaurants and cafes overlooking the street (on the left); Seckbacher Landstrasse street with car parking on the street edges (on the right)

The residential area has numerous open spaces in comparison to the area surrounding main railway station, but less with respect to the city centre. With the church and surrounding open space of Johanniskirche as the central landmark of the area, the main streets of Sekbacher Landstrasse and Berger Strasse are located in close vicinity (within 200m distance approximately) in west and south direction respectively. The eastern and western ends of the residential area are surrounded by green open areas where Günthersburgpark, within the district of Nordend-Ost, serves as a large public park situated in the western section of the residential area. The northern peripheral area of the Bornheim district is surrounded by the A661 Autobahn (i.e. highway) which acts as a separating boundary with the neighbouring Seckbach district. This in turn has led to discontinuity of green spaces in the area along with immediate neighbourhood being noisy. The network of green areas is planned to be improved with Bornheim-Seckbach region being one of the prioritized areas within the master plan of Frankfurt 2030+.

3.2.2 Darmstadt and its selected urban areas

Location and Demographics

The city of Darmstadt (122.1 square kilometres in area) is located in the southern part of the state of Hessen, in proximity to the rivers Rhein, Main and Neckar. The city was the capital of the state of Hessen until the mid-20th century and lost its status to the city of Wiesbaden due to the severe war damage. The city has the official title of 'City of Science' since 1997, with many scientific and cultural institutions established in the city. Over the past decade, the city had been on a constant growth with respect to population, where it crossed 150,000 inhabitants mark in 2012. In 2020, with overall 164, 267 inhabitants, the growing trend came to an end during the pandemic period in 2020-2021.

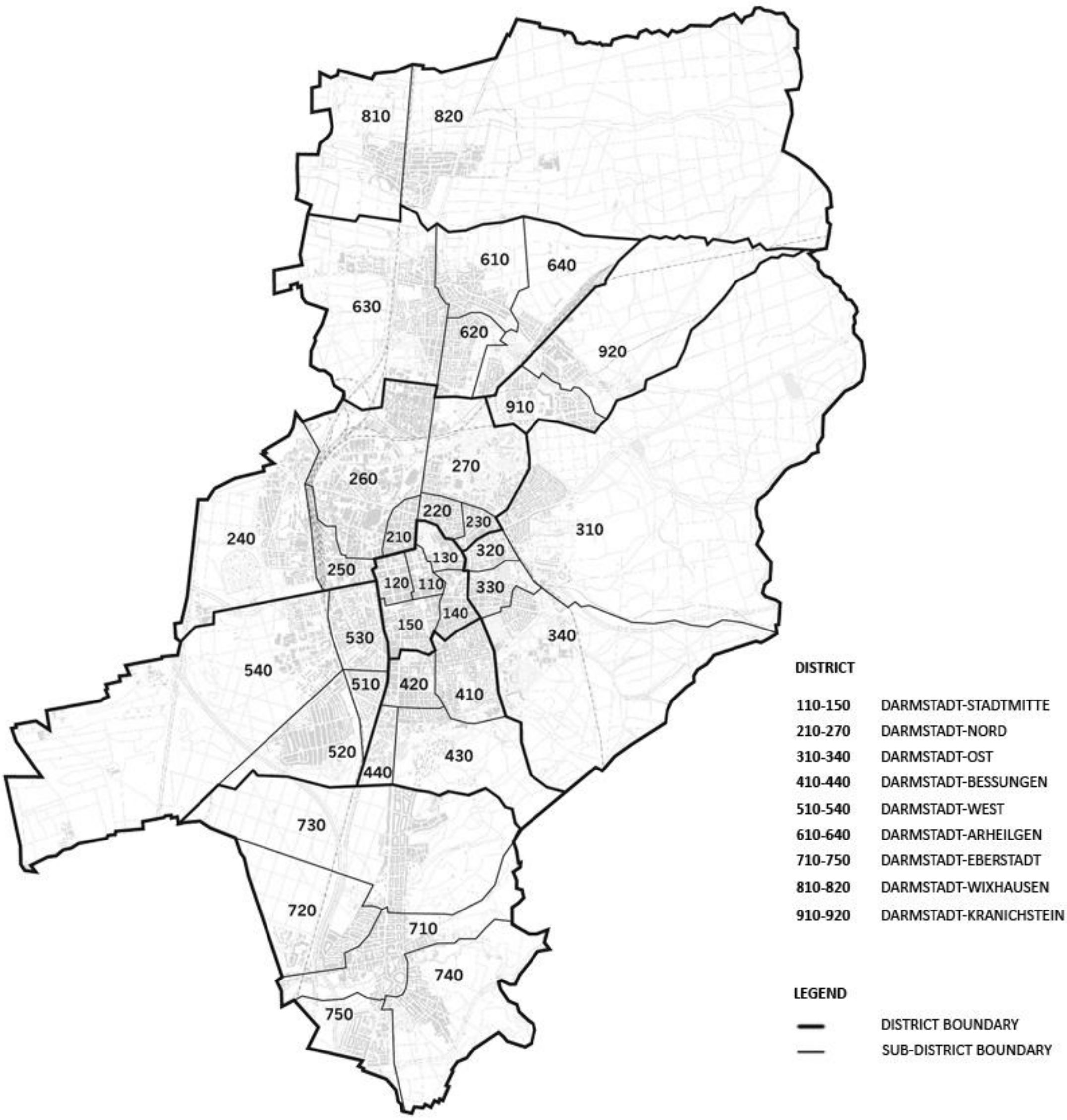

Figure 29: Different urban districts in Darmstadt
Source (image modified): Wissenschaftsstadt Darmstadt (2020a)

In 2020, the number of people with their main residence in the city of Darmstadt fell for the first time since 2008, by a margin of 808 inhabitants. The decline in the overall population was also recorded in 2021, by a rough margin of 200 inhabitants (although this was only based on the records until the middle of the year). In regards to inhabitants from foreign countries, 21% of the overall population reside with their main residence in the city (Wissenschaftsstadt Darmstadt 2021). Similar to the city of Frankfurt am Main, Darmstadt also saw the reduction in number of inhabitants within the city in 2020.

Darmstadt comprises of nine urban districts (see Fig. 29) which is combined further into two groups i.e. Darmstadt-Innenstadt (i.e. downtown in German) and Darmstadt-Außenbezirke (i.e. outskirts in German). Darmstadt-Innenstadt includes the five urban districts of Darmstadt-Mitte, Darmstadt-Nord, Darmstadt-Ost, Darmstadt-Bessungen and Darmstadt-West, which form the central areas of the city. Darmstadt-Außenbezirke includes the remaining four districts of Darmstadt-Arheilgen. Darmstadt-Eberstadt, Darmstadt-Wixhausen and Darmstadt-Kranichstein, which form the northern and the southern peripheral extensions of the city. With regards to the overall usage of spaces, the eastern part of the city has more residential areas while western areas show more commercial space usage. In 2020, around 63% of the inhabitants lived within the downtown area i.e. Darmstadt-Innenstadt comprising of five districts.

Urban development and Masterplan DA 2030+

The city planning office (i.e. Stadtplanungsamt) along with the office for economy and urban development (i.e. Amt für Wirtschaft und Stadtentwicklung) of Darmstadt developed a spatial development strategy between 2016 and 2020 i.e. Masterplan DA 2030+. The focus of the urban development plan is based on trends which include growth of the population, climate protection and sustainable use of resources, traffic and mobility culture, social cohesion and participation, digitalization and more. Within the Rhein-Main area, Darmstadt is fastest growing city with 18.7% increase in population from 2014 to 2050. This forecast of population growth in Darmstadt is the focal framework of the Masterplan DA 2030, which estimates the population to reach around 184,000 in the year 2035 (Wissenschaftsstadt Darmstadt 2020b). With respect to the climate and sustainability, the city plans to reduce its net carbon dioxide emissions to zero by 2035.

One of the focus areas of the Masterplan DA 2030+ is for the city of Darmstadt to use its resources and area in a responsible manner. With the city growing with its population over the years, it would be required to secure the demand for additional space, which is balanced through various principles. Some of these principles include:

- Development with a predetermined settlement boundary which preserves the landscape. This ensures a compact development area with clear settlement edge, which preserves the green landscape surrounding the city.

- Abolishing strict east-west division of spaces, with classic residential spaces in the east and central and well-connected commercial areas in the west, through mixed-use planning. With regards to the potential spaces for mixed-use, majority of the identified spaces are located in

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Wissenschaftsstadt Darmstadt (2020a), Datenreport 2020, Darmstadt. Retrieved from www.darmstadt.de/standort/statistik-und-stadtforschung/datenreport-2020
Wissenschaftsstadt Darmstadt (2021a), Statistische Berichte 2. Halbjahr 2020, Darmstadt. Retrieved from https://www.darmstadt.de/standort/statistik-und-stadtforschung
Wissenschaftsstadt Darmstadt (2020b), Masterplan DA 2030+ Räumliche Entwicklungsstrategie für Darmstadt, Darmstadt. Retrieved from www.darmstadt.de/masterplan-da2030

the western section of the city between Hauptbahnhof and Kasinostrasse street within the urban districts of Darmstadt-Nord and Darmstadt-West.

- Dense development of areas leading to more space saving. This would assist in avoiding greenfield projects and social segregation, which involves a minimum regional planning density with at least 60 residential units per hectare. This would also discourage new single-family house projects in future. Many settlement areas, especially residential areas are planned to be condensed through various measures which may include building on rear plots, additions through more floors, or by replacing the existing residential buildings with new ones having more residential units. Certain potential areas have been identified for the densification measure in different urban districts of the city. Some of these areas include spaces around Komponistenviertel in east, Heinrichstrasse-Heidelberger Strasse street junction in centre (i.e. neighbourhood in south of Staatstheatre), Arheilgen in north, Eberstadt in south and more.

- Transition in mobility with better access to public transport, and expansion of cycling routes along with safe open spaces for pedestrians, improving quality of stay on streets. This includes measures like less parking spaces and traffic calmed streets with slow movement of vehicles. Through the reduction of stationary traffic on streets, promotion of utilization of space for other uses would be possible.

Similar to these strategies, other focus areas have been put in place to strengthen the city as a place to promote science and business opportunities along with having a better quality of life in neighbourhoods. This has led to identifying certain areas for urban development involving new and mixed-use residential neighbourhoods. Most of these spaces are located in the northern and western parts of the city i.e. Arheiligen and Darmstadt-Nord district respectively.

Following this, the city identifies three key area for its masterplan DA-2030+ which overlay three perspectives of the city i.e. using its resources and area responsibly, strengthening its scientific, economic and technological opportunities, and ensuring spaces with high quality of life. The street and neighbouring areas around Rheinstrasse has been identified as a priority area to strengthen the city's scientific, economic and technological opportunities. Termed as 'Boulevard of Knowledge', the street surrounded by a row of trees runs between the main railway station and links it to the city centre i.e. Luisenplatz. The areas for individual motorized traffic would be reduced to building spaces which include public spaces (instead of parking spaces) and multi-functional buildings (instead of monofunctional spaces). Regarding the perspective of ensuring quality of life, the area that is prioritized is Pallaswiesenviertel which falls within the urban district of Darmstadt-Nord. Some of the measures include new spaces for sports, leisure and recreational activities, fast cycling lanes through the area along with better transport infrastructure, new network of green spaces which reduce the urban heat island effect and also give space other activities. With respect to the city's perspective of using its resources and area respectively, the southern belt of the city has been prioritized. The southern belt connects the Technical University Lichtwiese campus through the sports park around Böllenfalltor, the residential areas of Steinbergviertel and Bessungen-Süd with the Lincoln-Siedlung urban project of the city in the south. With new and affordable residential spaces being created, additional tram connections and cycle pathways would be planned for future development of the southern belt. In line with the three key areas within the masterplan DA 2030+, other areas in the city would also be taken into consideration apart from the three prioritized spaces.

Mobility within the city

The city of Darmstadt has been going through changes in the share of urban traffic by different modes over the years. In 2013, the modal share of traffic in Darmstadt was dominated by individual motorized vehicles (i.e. 38%), which was followed by walking (i.e. 28%). The modal share of public transport and cycling were 17% each, which showcased a car dominated city (DADINA 2019). The hierarchy of modal share in 2018 was slightly different (see Fig. 30). The motorized car traffic saw a 3% drop in its modal share after five years, resulting in 35% of the trips being made by car while cycling saw a 5% increase i.e. 22% (TU Dresden 2020). While walking also reduced by 3%, there was a slight increase within the modal share by public transport (i.e. an increase by 1% to 18%). This shows a positive shift towards cycling within the city, where new modes like e-scooters would influence the modal share in future years. The urban development goal of Masterplan DA 2030+ also focuses on shifting the share of modal split away from the motorized traffic in the city, which would in turn have a positive effect on the quality of stay. This involves achieving a minimum target by a reduced modal share of 25% by motorized vehicles (which was 35% in recent study) and having 75% share of traffic by environment-friendly modes (i.e. public transport, walking and cycling). This transition would require higher accessibility of active modes of mobility within the city and its neighbouring areas.

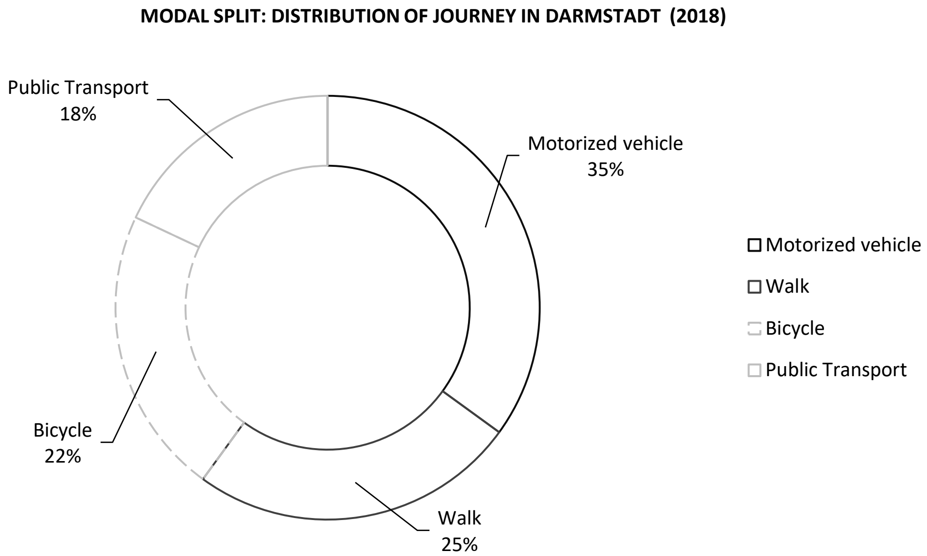

Figure 30: Modal split within Darmstadt on journeys in 2018
Data source: TU Dresden (2020)

The intra-city network of public transport services in Darmstadt includes on-ground trams and buses. There are nine tram lines which run in Darmstadt, with eight of them passing through Luisenplatz (i.e. the city centre), making it the central transit station. In contrast to the city of Frankfurt, where S-Bahn and U-Bahn rail services run through the city connecting different urban districts, Darmstadt is limited to tram and bus network. The S-Bahn and regional train services are available through the transit stations located away from the central district of Darmstadt-Mitte such as Hauptbahnhof and Nordbahnhof in the urban district of Darmstadt-Nord, TU-Lichtwiese in the eastern district of

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DADINA (2019), Gemeinsamer Nahverkehrsplan für die Stadt Darmstadt und den Landkreis Darmstadt-Dieburg 2019 - 2024, Darmstadt. Retrieved from https://www.dadina.de/nahverkehrsplan/nahverkehrsplan-2019-2024/
TU Dresden (2020), Sonderauswertung zum Forschungsprojekt „Mobilität in Städten – SrV 2018"Städtevergleich, Dresden. Retrieved from https://tu-dresden.de/srv

Darmstadt-Ost, Südbahnhof in Darmstadt-West and more. The city continues to expand its network of public transport services with projects such as Lichtwiesenbahn (involves extension of tram line 2 to the TU-Lichtwiese campus), Ludwigshöhviertel and Lincoln-Siedlung (involves new urban settlement with reduced infrastructure for motorized traffic and promotion for active modes) and more.

With the aim of achieving a traffic turnaround away from the individual motorized traffic, the city of Darmstadt is focused on developing a sustainable mobility concept i.e. Mobilitätskonzept 2030+. One of the key principles involves promotion of cycling to have a bicycle-friendly city via Radstrategie. One of the strategic goals is to achieve a total modal split of 30% by 2030, which was 22% in 2018. Initiatives include introduction of dedicated bicycle roads (i.e. Fahrradstrasse) where cyclists have a priority of way and the maximum speed of movement is 30 kmph. Some of these dedicated bicycle roads can be seen on streets of Wilhelminenstraße in the urban district of Darmstadt-Mitte, Pankratiusstraße in the Darmstadt-Nord district, Heinrich-Fuhr Strasse in Darmstadt-Ost district and more. With the aim of offering a seamless intersection-free bicycle route for long-distance commute, the 30-kilometre bicycle highway project between Frankfurt and Darmstadt has been in progress. In 2021, the construction phase is on-going post Wixhausen railway station to Arheiligen district (Mobilitätsamt Darmstadt 2021). This would assist in connecting the short-distance intra-city bicycle network to a long-distance inter-city broad bicycle network in the urban agglomeration.

The alternative modes via electronic scooters have also been visible in recent years in the city. While the parking areas for the e-scooters are excluded from the pedestrian zones, the immediate areas around the bus stops and large green spaces and parks, the city plans to create and provide 'hubs' in the central areas and places which are more frequently used by commuters such as railway stations and the city centre. The 'hubs' would be initially utilized as a storage spaces for e-scooters and are being planned in areas such as the railway stations (i.e. Hauptbahnhof, Nordbahnhof, Südbahnhof and Ostbahnhof), Staatstheater and Friedenplatz in the Darmstadt-Mitte urban district, and Bürgerpark in the Darmstadt-Nord urban district (Wissenschaftstadt Darmstadt 2020c). As e-scooter is one of the most recent diverse modes being used by public, its expansion as a mode is still restricted based on limited providers in the city and regulations for its utilization.

3.2.2.1 City centre in Darmstadt

Location and spatial utility

The city centre of Darmstadt is located within the central urban district of Darmstadt-Mitte with Luisenplatz as its central landmark (see Fig. 31). It is surrounded by other urban districts of Darmstadt-Nord, Darmstadt-Ost, Darmstadt-Bessungen, and Darmstadt-West. Surrounding Luisenplatz, the immediate space utilization is of mixed-use typology. In the north and south of the mixed-use typology, the common areas and special construction areas are located which include Klinikum, museum, the Technical University, the city castle i.e. Schloss and more. Majority of the mixed-use spaces in the city of Darmstadt are located in the Darmstadt-Mitte urban district within the peripheral streets of Bismarckstrasse in the north, Hindenburgstrasse in the west, Hügelstrasse in the south and Kirchstrasse in the east. The residential land-use is only allocated beyond these streets away from the city centre (mostly in north, south and east). The north-east section of the Darmstadt-Mitte district

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Mobilitätsamt Darmstadt (2021), Radschnellverbindung Frankfurt-Darmstadt, Darmstadt. Retrieved from https://www.darmstadt.de/leben-in-darmstadt/mobilitaet-und-verkehr/verkehrsentwicklung-und-projekte/aktuelle-projekte/radschnellverbindung-frankfurt-darmstadt
Wissenschaftsstadt Darmstadt (2020c), E-scooter, Darmstadt. Retrieved from https://www.darmstadt.de/nachrichten/darmstadt-aktuell/news/e-scooter

includes the green park i.e. Herrngarten, which is surrounded by residential spaces in the north within the Darmstadt-Nord urban district. With regards to the overall area, Darmstadt-Mitte occupies approximately 2.33 square kilometres of space (Wissenschaftsstadt Darmstadt 2020a), which is the least in comparison to all nine urban districts of the city.

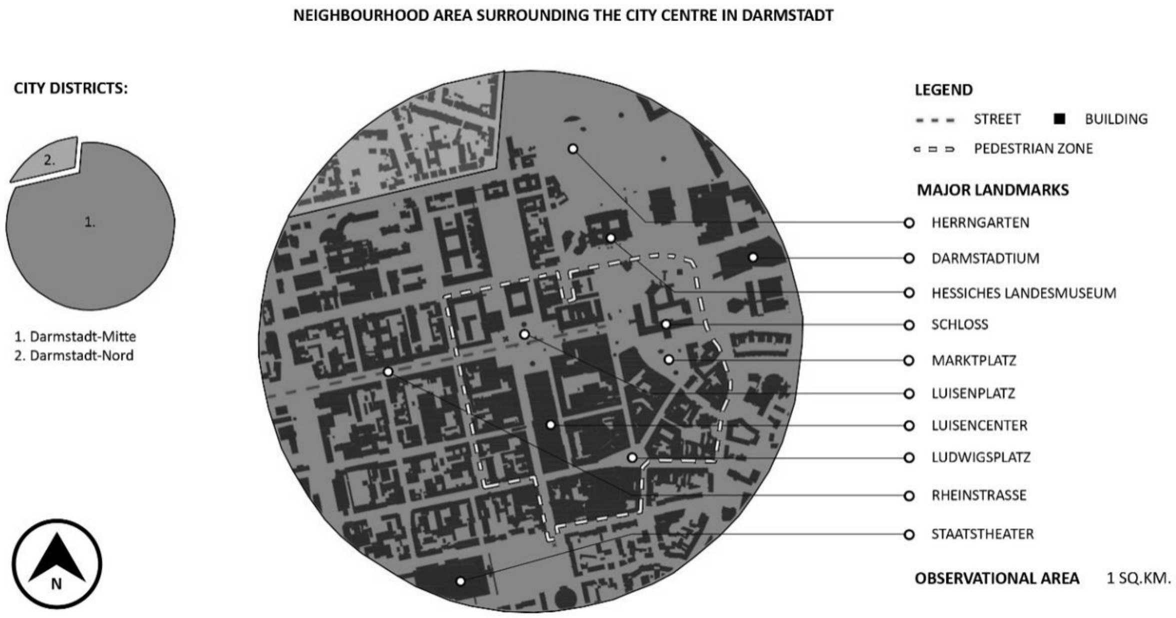

Figure 31: Immediate area surrounding city centre in Luisenplatz with major landmarks (Figure ground map of 1 sq. km.)
Data source: Wissenschaftsstadt Darmstadt (2021b)

Spatial configuration and characteristic

The spatial layout of the urban area surrounding city centre comprises of large block sizes and network of open spaces forming a grid pattern in the central and western parts of the area. Majority of the block sizes in the area are within the range of 100-150 metres in width, which contributes towards the walking environment in the city centre. The on-ground retail space in the south of Luisenplatz benefits from the nature of the block sizes in the city centre. Open spaces within the selected area are located around the street ends of Rheinstrasse, which acts as a central axis connecting Hauptbahnhof (i.e. the central railway station) in the west to the city centre. The network of open spaces includes Luisenplatz as the central node, Marktplatz in the east, Georg-Büchnerplatz in south (opposite Staatstheater), Herrngarten in the north-east, Ludwigsplatz in the south-east and many more (see Fig. 31). The immediate space around Luisenplatz acts as an important transit space with public transport to commute through the city centre to other urban districts.

Towards the second half of the 20^{th} century, the increase in the car traffic around the city centre started to interfere with the public transport. This led to the underground displacement of the car traffic (via Tunnel Wilhelminenstrasse) away from public transport lines on-ground, which was followed by further pedestrianization of the city square in late 1970s (Engels 2015). The redesign of the on-ground

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Engels P. (2015), Luisenplatz, Stadtarchiv Darmstadt, Darmstadt. Retrieved from https://www.darmstadt-stadtlexikon.de/l/luisenplatz.html
Wissenschaftsstadt Darmstadt (2021b), Stadtatlas Darmstadt, Darmstadt. Retrieved from https://stadtatlas.darmstadt.de

space with less cars, was one of the initial steps which led to making the city centre a pedestrian-friendly space. The current pedestrian zone extends from Zeughaustrasse (between Landesmuseum and Schloss) to Hügelstrasse (street adjacent to Staatstheater in the north) in the north-south direction and Grafenstrasse (street adjacent to Luisenplatz in west) to Schlossgraben street (opposite Darmstadtium) in east-west direction. The pedestrian zone puts pedestrians as a priority over other user-groups which include cyclists, and prohibits the use of e-scooters in the area.

With respect to the Masterplan 2030+, the urban development plan acknowledges the multimodal space (i.e. Luisenplatz) to be overloaded with trams and buses. This in turn affects the quality of stay, which implies developing alternative routes for public transport in the city centre. On the other hand, the open spaces in the east such as Herrngarten and Friedensplatz (opposite Landesmuseum, adjacent to Schloss) offer public sitting spaces without any public transport interference, which contributes towards the quality of stay in the area. As previously discussed, Friedenplatz along with Staatstheater would be one of the focal areas for developing mobility 'hubs' which would have storage spaces for short-distance e-scooter services. With the importance of making the city centre more attractive and improving its quality of stay, the initiatives assist in setting a rhythm of measures which would impact the overall multimodal accessibility in the city.

3.2.2.2 Transit area in Darmstadt

Location and spatial utility

The main railway station of Darmstadt is located within the 2-kilometre radius in the west from the city centre. It is situated within the urban district of Darmstadt-Nord, which is surrounded by immediate urban districts of Darmstadt-West in the south (see Fig. 32) and Darmstadt-Mitte in the east. With respect to the Datenreport 2020, the urban district of Darmstadt-Nord is third largest in area (i.e. 12.31 square kilometres) but has the highest number of inhabitants (i.e. 32,655 in 2019) in Darmstadt-Innenstadt and Darmstadt city as a whole. It houses approximately 20% of the overall population of the Darmstadt city. With respect to the immediate land-use surrounding the main railway station (i.e. Hauptbahnhof), the space in the east mainly comprises of mixed-use and commercial area, with the adjacent area in the north being dominated by commercial and industrial space. While the district has high number of inhabitants, majority of these come from sub-districts away from the main railway station. This can be seen with the number of inhabitants within the immediate sub-district of Mornewegviertel (approximately 0.5 square kilometres in area) in the east having less than 900 inhabitants. In the west of main railway station, the land-use is slightly different, with spaces being residential and mixed-use in nature.

The street of Rheinstrasse acts as a peripheral boundary between the two urban districts of Darmstadt-Nord and Darmstadt-West. It also acts as one of the axial streets connecting the main railway station to the city centre in east. Considering the urban district of Darmstadt-West, it occupies a larger area of 15.14 square kilometres with approximately 18,500 inhabitants in 2019. The immediate spaces around Rheinstrasse in the Darmstadt-West district mainly comprise of green forest spaces towards the west and mix of commercial and residential spaces in the east. In Darmstadt-Nord district, the areas in close proximity to the Rheinstrasse are of mixed-use nature in the east of main railway station, while in the west it is covered with green forest area. With respect to the Darmstadt Masterplan 2030+, the immediate areas around Rheinstrasse (north and south) and Hauptbahnhof (east and west) have been identified as a potential area for mixed-use planning. This would assist in further densifying the area with more inhabitants in future, with a transit-oriented development having access to public transport services.

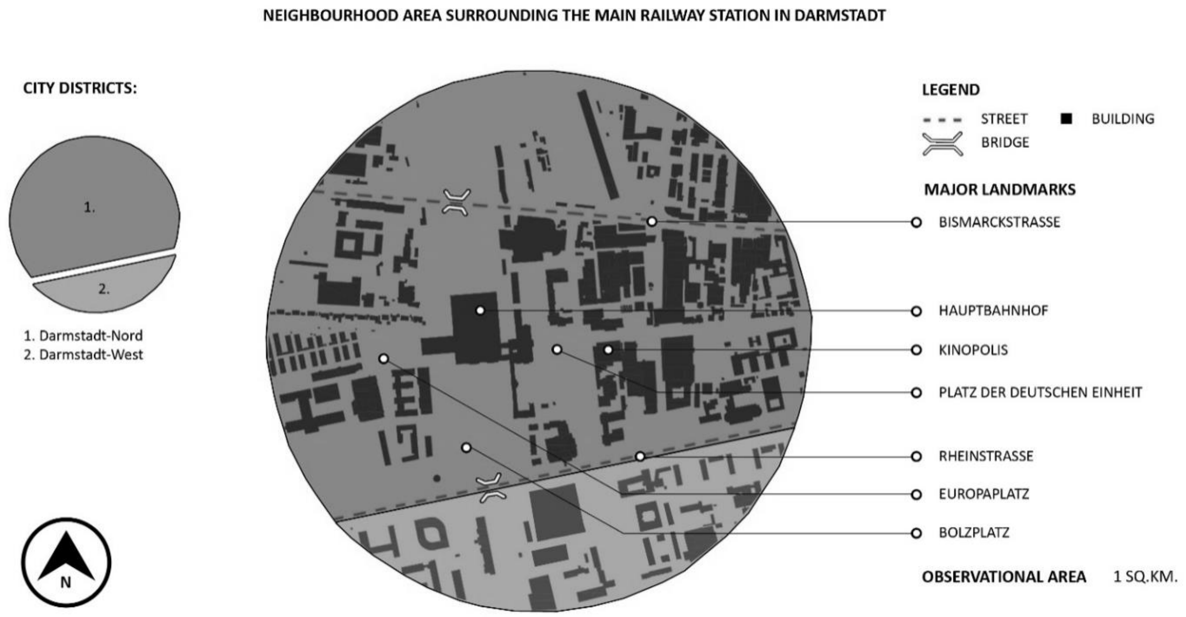

Figure 32: Immediate area surrounding the main railway station in Darmstadt with major landmarks (Figure ground map of 1 sq. km.) Data source: Wissenschaftsstadt Darmstadt (2021b)

Spatial configuration and characteristic

The density of building infrastructure around the area surrounding main railway station is less in comparison to the city centre in Darmstadt. With the rail tracks running in north-south direction through the two bridges of Bismarckstrasse and Rheinstrasse (see Fig. 32), along with separate freight rail space north of Bismarckstrasse, the freedom of space for movement is reduced to a certain extent. With commercial and industrial land-use typology, certain block sizes in the east of main railway station are beyond 300 metres in width, which has a negative impact on the walking scenarios for pedestrians due to less interval of spaces and freedom of choice. With regards to open spaces, the immediate area around main railway station has a range of spaces including Platz der Deutschen Einheit and Am Hauptbahnhof in front of the main facade of railway station in the east, Europaplatz in the rear end in west, Bolzplatz and neighbouring green spaces adjacent to Rheinstrasse and more. The open space in between the main railway station and the Platz der Deutschen Einheit acts as a transition space for changing one's mode of travel. In regards to public transport, tram and bus services are available in this space with other alternative options like taxis and cycle-on-rent in close proximity.

The two roads in the north and south of main railway station, i.e. Bismarckstrasse and Rheinstrasse respectively, carry vehicular traffic to and from the city in east and west direction. In contrast to these two streets, the ones adjacent to the main railway station in the east mostly comprises of public transport services. The restriction of car traffic from the public transport in front of the main railway station in the east helps in better inter-modal transition, which is in contrast to the main railway station in Frankfurt. With city centre in the east, the green forest spaces in the west act as peripheral boundary of the city of Darmstadt via highway route which connects the city of Frankfurt in the north.

3.2.2.3 Residential area in Komponistenviertel

Location and spatial utility

The selected residential area of Komponistenviertel is located on the peripheral boundary of the Darmstadt-Ost urban district in the east. It is within 2.5-kilometre radius (in Euclidean distance) from the city centre i.e. Luisenplatz. The peripheral boundary in the west of the residential area acts as a segregation space between the two urban districts of Darmstadt-Ost and Darmstadt-Nord (see Fig. 33). With respect to the Datenreport 2020, the urban district of Darmstadt-Ost has the largest overall area (i.e. 27.57 square kilometres) in the city, with approximately 9.1% of the overall inhabitants of the city living in the area. With respect to the land-use allocation of spaces in the urban area, the area within the two merging streets of Im Emser in north and Dieberger Strasse in south is residential in nature; while the adjacent space around the Im Emser street also includes area for rail tracks going underneath. The natural cover of the green forest area in the east also acts as a natural boundary to the residential area of Komponistenviertel. With respect to the Darmstadt Masterplan 2030+, the peripheral boundary in the east also acts a boundary for limiting further construction and to preserve the green landscape in the east.

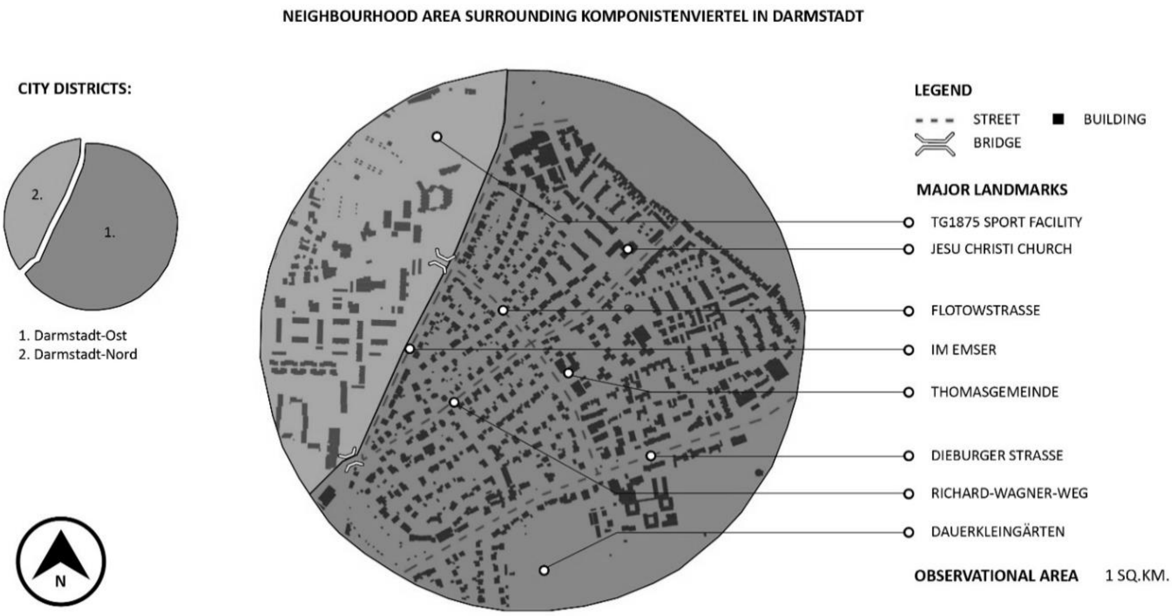

Figure 33: Immediate area surrounding Komponistenviertel in Darmstadt with major landmarks (Figure ground map of 1 sq. km.)
Data source: Wissenschaftsstadt Darmstadt (2021)

Spatial configuration and characteristic

The residential area of Komponistenviertel was planned as the Darmstadt's garden city in the north-east, which was later densified in the mid-20th century. The area being residential in nature has a collection of major detached housing spaces located along the branched streets (which are named after composers) from the central axial street of Flotowstrasse (see Fig. 33). The street of Flotowstrasse bisects the residential area of Komponistenviertel in eastern and western parts, and at the same time also connects the peripheral streets of Im Emser in the north and Dieberger Strasse in the south. The block sizes, composed of housing units between the two streets of Im Emser and Dieberger Strasse, range from approximately 35 metres in the east to around 200 metres in close proximity to the

Flotowstrasse in the centre. The presence of rail track going underneath the two bridges, adjacent to the Im Emser street, acts as a peripheral boundary of the Komponistenviertel in the west.

Figure 34: Narrow residential street parallel to Richard-Wagner-Weg in north (on the left); Flotowstrasse street with green landscape and pedestrian pathway (on the right)

In regards to the large green spaces surrounding the residential area, several garden allotments i.e. Dauerkleingärten, are located in the northern and southern peripheral areas, along with sports facility of TG1875, and large green forest area in the east i.e. Fasanerie. With majority of the residential buildings being individual and detached, the density of inhabitants within the area is less as compared to neighbouring residential areas closer to the city centre (for e.g. Martinsviertel in Darmstadt-Nord). The Darmstadt Masterplan 2030+ identifies the residential area of Komponistenviertel as one of the potential areas to increase its residential density. The further densification of the residential area would be limited within the existing eastern boundary which is also the settlement edge of the city of Darmstadt, to safeguard the green landscape surrounding the city.

3.2.3 Offenbach am Main and its selected urban areas

Location and Demographics

The city of Offenbach is located within the state of Hessen east to the city of Frankfurt along the river Main. Unlike Frankfurt, the city covers an overall area of 44.9 square kilometres south of river main. With an overall population of 140,496 inhabitants in 2020, the city has the second highest population density within the state of Hessen after Frankfurt am Main (Hessisches Statistisches Landesamt 2021). In the past century, the city was concentrated with many industries in its vicinity, and now is transforming into being one of the important nodes within the Rhein-Main urban agglomeration.

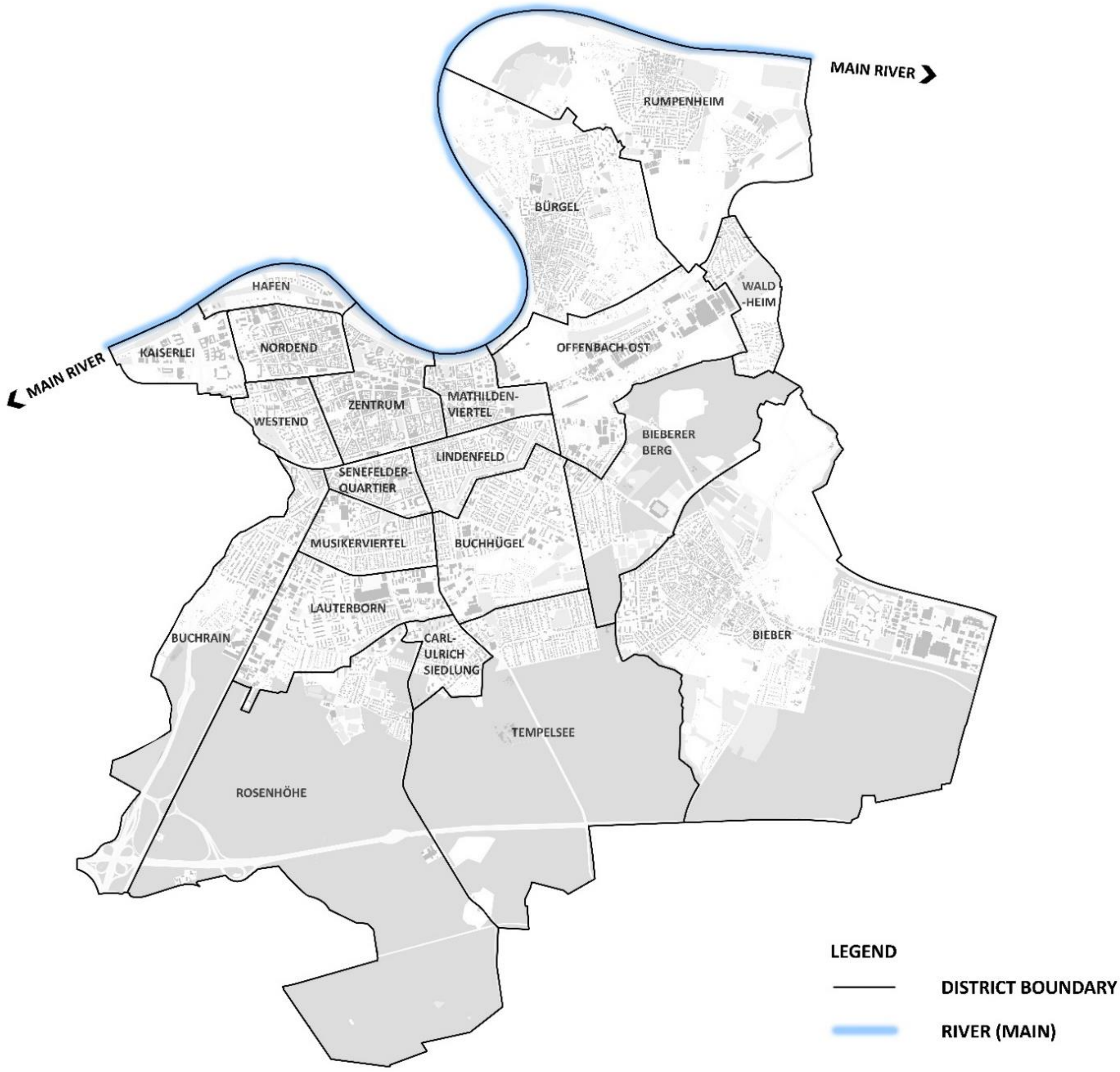

Figure 35: Different urban districts in Offenbach am Main
Data Source (image modified): Stadtverwaltung Offenbach (2021)

Hessisches Statistisches Landesamt (2021), Die Bevölkerung der hessischen Gemeinden, Wiesbaden. Retrieved from https://statistik.hessen.de
Stadtverwaltung Offenbach (2021), Stadtpläne mit Gliederungseinheiten, Offenbach. Retrieved from https://www.offenbach.de

In contrast to many large German cities, the city of Offenbach was not divided into urban districts until 2019. The city had defined boundaries for nine districts until 2019, which included Mathildenviertel, Bieber, Bürgel, Rumpenheim, Waldheim, Tempelsee, Rösenhöhe, Kaiserlei, and Lauterborn (Bielert 2019). The new districts were identified and later added, which included the underdeveloped green spaces such as forest and agricultural areas in the peripheral boundary of the city. This led to the city being composed of 21 urban districts overall with natural boundaries of Main river in the north and green landscape in south (see Fig. 35). Adjacent to the river Main, there are six urban districts which have the river as its peripheral boundary in the north. These include Kaiserlei, Hafen, Zentrum, Mathildenviertel, Bürgel, and Rumpenheim.

Unlike the neighbouring cities of Darmstadt and Frankfurt, where there was a downfall in population growth during the pandemic in 2020, the city of Offenbach continued its growing population trend (i.e. 0.5% growth as compared to 2019). Considering the foreign population, the city had approximately 40% of its population from other countries in 2020 (Stadt Offenbach am Main 2021), which is the highest from the other cities of Darmstadt and even Frankfurt am Main.

Urban development and Masterplan Offenbach am Main 2030

The city of Offenbach planned to implement set of measures focusing on aspects such as traffic and mobility in the city, education, climate and environmental protection, and more within its Masterplan 2030 in 2015 (Stadt Offenbach am Main 2015). With the city's location in close vicinity to Frankfurt along with green spaces surrounding its peripheral boundary, it is one of the regional centres in the Rhein-Main urban agglomeration. With high population density compared to other cities of similar number of inhabitants, the city is compact in its urban structure. Regarding the growing population within Offenbach, the Masterplan was structured to meet the residential demand within the city which was predicted to reach around 126,000 inhabitants in population by 2030. This number was surpassed in 2020 and puts the accessibility of infrastructure and services to the residing population in priority. The masterplan was developed with focus on four strengths (or opportunities) the city inherits for the future years. These include identifying Offenbach am Main as an open, technological, creative and a small global city (i.e. a compact city). The open city relates to the coexistence of different cultures through large international community, while the technological aspect stems from its industrial history. The education institutions along with the natural landscape in periphery and high population density contribute towards its creative and compact global aspect.

The masterplan identifies certain potential areas for its urban development catering to the city and its neighbouring areas. Some of these identified areas and the scope of development include:

- New developments on Green Main belt. This relates to the 10km long riverside which stretches from Kaiserlei district in the west to the Rumpenheim district in the east. With existing green parks in Rumpenheim and Zentrum districts alongside river Main, the plan includes creation of new park along Hafen district, with Main river crossing for pedestrians and cyclists through Schloßstrasse in Zentrum district.
- Extension of Anlagenring through the inner city and making the city greener. The measure focuses on existing green belt, i.e. Anlagenring, which is a network of green spaces through

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Bielert, S. (2019), Neue Stadtteile für Offenbach, Frankfurter Rundschau, Frankfurt am Main. Retrieved from https://www.fr.de/rhein-main
Stadt Offenbach am Main (2021), Statistischer Vierteljahresbericht IV/2020, Offenbach am Main. Retrieved from https://www.offenbach.de
Stadt Offenbach am Main (2015), Masterplan Offenbach am Main: 2030, Offenbach am Main. Retrieved from https://www.offenbach.de

peripheral boundaries of Westend, and shared boundaries of Musikerviertel-Senefelderquartier and Lindenfeld-Buchhügel districts. The green leisure space would be made attractive with further extensions towards Main river via Nordend-Kaiserlei boundary in the west, and extension via Ostbahnhof (i.e. east railway station) through Offenbach-Ost district in the east. This includes possibility of new residential spaces along Anlagenring, with better connection of green spaces and introduction of more green avenues.

- Better urban core and inner quarters. This involves dense city centre with mixed-use area within the Zentrum district, which forms the urban core of Offenbach. It includes strengthening of compact shopping areas in the district, along with better working and residential environment around Berlinerstrasse. The districts surrounding the urban core within the Anlagenring (i.e. Nordend, Westend, Mathildenviertel, Senefelderquartier, Lindenfeld and Hafen) form the inner quarters of the city. These districts would be upgraded with block concepts, new neighbourhood squares, and better utilization of spaces with careful integration to new buildings.
- Suburban settlements and re-densification. The three urban districts of Bieber, Rumpenheim and Bürgel are identified as the suburban settlements which would require densification that would limit the urban sprawl in future.

In order to attract more business opportunities within the city, the masterplan identifies around 100 hectares of commercial space to be developed through different districts. These include projects like Kaiserlei Business Park, which focuses on making office spaces diverse, smaller and livelier; DesignPort in close proximity to Hafen, which is planned as a future location of creative space with Hochschule für Gestaltung (HfG), a school of design; Innovation Campus Design Park in the east through Offenbach-Ost district, which uses the commercial space within the inner quarters of Offenbach am Main as an opportunity for exchange in the design and innovation industry; Innenstadt Offenbach in the Zentrum district, which focuses on making the city centre more lively with increased residential space and upgrades in public spaces and buildings; and more. With respect to the city centre, concepts like Zukunftskonzept Innenstadt (i.e. the inner-city concept for the future) (Stadt Offenbach am Main 2020), have been introduced which acknowledges the nature of the inner city not to be characterized by the retail feature alone. It focuses on increasing the frequency of visits, along with improving quality and length of stay for the people. With respect to the residential spaces, approximately 110 hectares of area is identified for further developments. The districts of Bürgel, Rumpenheim and Bieber in the east have been identified as one of the potential spaces for increasing new residential units to meet the increasing population growth. In the city, the residential profile of spaces varies from the residential and commercial urban core, through the short-distance neighbourhood approach in inner quarters, via Anlagenring, towards the medium-density settlements beyond the inner quarters which have more green spaces.

The planned developments showcase the high density of commercial projects focused along the urban districts in the west, which also act as potential gateways to the city of Offenbach, while the eastern parts of the city represent potential areas for residential densification on a long-term basis. The masterplan focuses on the two aspects of economy and housing, through commercial and residential planning but also includes intermediate projects which focus on open space planning and related aspects through urban development.

Stadt Offenbach am Main (2020), Offendenken Zukunftskonzept Offenbach, Offenbach am Main. Retrieved from https://www.offenbach.de

Mobility within the city

The city of Offenbach am Main has been a car-dominated city in the past years. With respect to the modal-split in 2013, 41% of the overall traffic was dominated by motorized vehicles. The medium of walking contributed towards 29% of the overall movement traffic, followed by use of public transport (i.e. 19%). The share of cycling as a mode of mobility had the least share in modal-split i.e. 10% (SrV 2013, In: NiO Nahverkehr in Offenbach 2017). This reflected towards approximately 60% of the traffic being within the environmental-friendly share of transport. With respect to the MiD (i.e. Mobilität in Deustchland) 2017 report, the share of private motorized vehicle within the modal-split increased to 46% (see Fig. 36), which represented the dominant car traffic in the city. This shows that almost every second trip in the city is made on a car. The dominance of motorized vehicles was followed by walking (i.e. 26%) and public transport (i.e. 16%) within the modal-split of the city. The representation of cycling as a mode on daily trips retained its lower position in hierarchy at 11% in 2017 (infas, DLR, IVT and infas 360 2019). With car-traffic being dominant, the planned urban development changes within the city with respect to the Masterplan 2030 impacts the modal-split directly or indirectly. It focuses on reducing the distances between the public transport and place of residence, offering attractive walking and cycling network and other measures within its mobility framework.

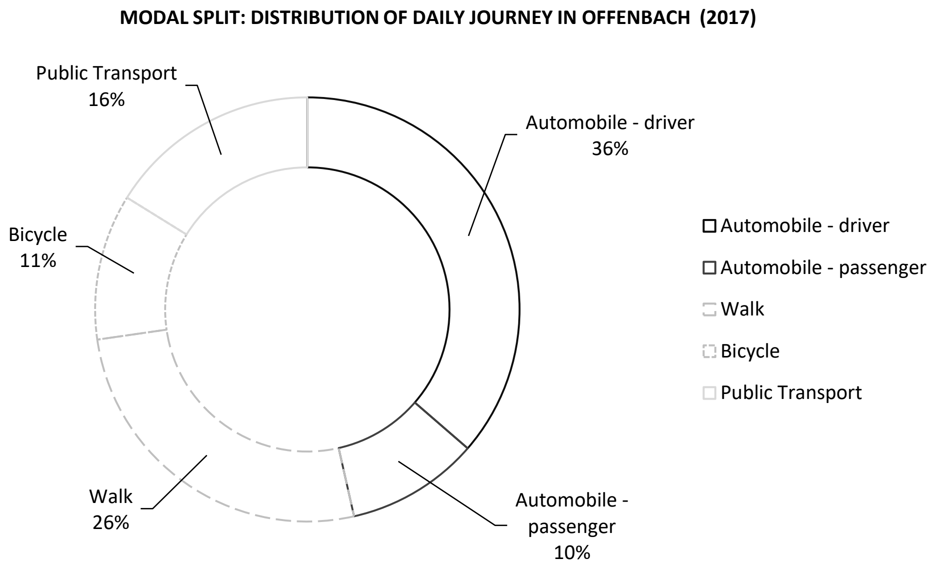

Figure 36: Modal split within Offenbach am Main on daily journeys in 2017
Data source: infas, DLR, IVT and infas 360 (2019)

The intra-city network of public transport services in Offenbach am Main includes buses and trains. With local and regional bus lines along with four S-Bahn lines operating through the city, Marktplatz (i.e. the city centre landmark within the Zentrum urban district) receives the majority of public transit services. All of the four S-Bahn lines go through the city centre, while several regional trains pass through the Hauptbahnhof (i.e. the main railway station). Overall the city of Offenbach am Main includes 6 railway stations mostly running in the east-west direction through the city. Unlike the

NiO Nahverkehr in Offenbach (2017), Mobilitätsplan für die Stadt Offenbach – Fortschreibung Nahverkehrsplan Stadt Offenbach 2018-2022, Offenbach am Main. Retrieved from https://www.offenbach.de/stadtwerke/mobilitaet
infas, DLR, IVT and infas 360 (im Auftrag des BMVI) (2019), Mobilität in Deustchland – MiD Regionalbericht Stadt Offenbach, Bonn.

neighbouring cities of Darmstadt and Frankfurt am Main, the city of Offenbach does not include a network of trams in the city. With respect to the transit infrastructure, the Mobility plan and the Master plan for the city of Offenbach acknowledges requirement of improvement within the main railway station (i.e. Hauptbahnhof), especially focusing on barrier-free environment.

The Mobility plan of the city of Offenbach focuses on shifting the share of traffic from less sustainable forms of mobility, i.e. motorized vehicles, to mobility by walking, cycling and public transport (NiO Nahverkehr in Offenbach 2017). In order to shift the on-street traffic away from motorized traffic, certain measures have been implemented by the city of Offenbach. New cycle paths were set up in the city which connect to important destinations including schools, leisure and supply activities. The introduction of Fahrradstrasse (i.e. cycle streets) focuses on prioritization of cyclists on the streets, with a speed limit of 30 kmph for everyone using the space (see Fig. 37). While the residents around these streets are allowed to use the space with their motorized vehicles, the general through traffic is excluded which forces them to use alternative routes. Bicycle streets have been implemented around city centre, along with urban districts of Bürgel, Nordend, Bieber, Senefelderquartier and more.

Figure 37: Fahrradstrasse (i.e. the bicycle street) on Von-Behring-Strasse in Bürgel district of Offenbach

Within the mobility frameworks of concepts like Zukunftskonzept Innenstadt, the plan focuses on making the city centre more accessible with features like multimodal hubs, which would offer e-scooter, cycling, and other modal services making the mobility system more flexible and fast within the urban core of the city. With new alternative modes like e-scooters becoming a part of the urban mobility system, the city of Offenbach is in the process of developing Traffic Development Plan 2035 (i.e. Verkehrsentwicklungsplan 2035) which would include subjects involving short-distance mobility catering to bicycle and pedestrian traffic, barrier-free accessibility, alternative mobility concept involving e-scooters, and more within its framework.

3.2.3.1 City centre in Offenbach am Main

Location and spatial utility

The city centre of Offenbach am Main is located within the central urban district of Zentrum with Marktplatz as its central landmark. It is surrounded by other urban districts of Hafen, Nordend, Westend, Senefelderquartier, Lindenfeld and Mathildenviertel. The northern Main riverside falls within the jurisdiction of Frankfurt am Main, which is connected to the city by Carl Ulrich Brücke (i.e. bridge) at the peripheral boundary of Zentrum urban district in the north-west. The immediate area surrounding Marktplatz is of a mixed land use typology with northern common areas comprising of Hochschule für Gestaltung (HfG) Offenbach, Stadtbibliothek (i.e. city library), with river Main acting as a natural boundary in the north (see Fig. 38). The immediate spaces in the north and south of Berlinerstrasse comprise of mixed-use spaces, with residential areas situated comparatively away from the street. The area of Büsigpark in the west offers a green public space which connects the Berlinerstrasse in the urban core to the Main riverside in the north.

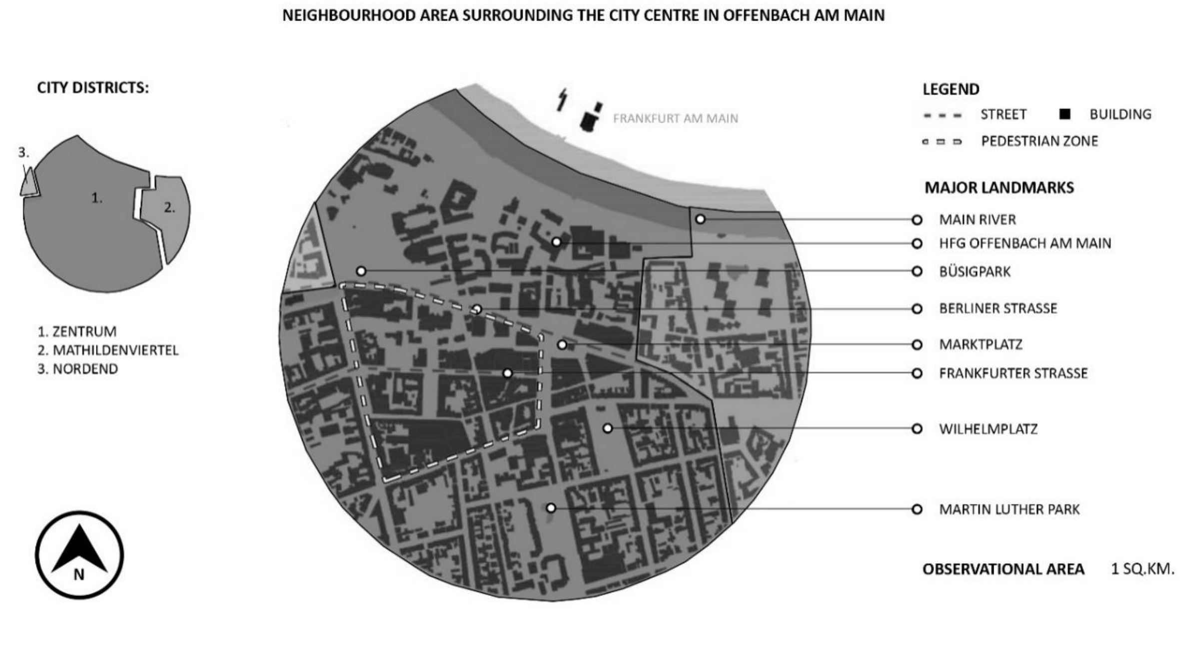

Figure 38: Immediate area surrounding city centre in Marktplatz with major landmarks (Figure ground map of 1 sq. km.)
Data source: Stadt Offenbach am Main (2019)

Spatial configuration and characteristic

The configuration of buildings towards the south of Berliner strasse showcase larger block sizes (with approximate range of 30-200 metres in block length) in comparison to majority of buildings towards

Stadt Offenbach am Main (2019), Satzung zur Festlegung und Benennung der Stadtteile im Gebiet der Stadt Offenbach am Main (Stadtteilsatzung), Offenbach am Main. Retrieved from https://www.offenbach.de the north of the street (with approximate range of 30-150 metres in block length). The area around the central landmark of Marktplatz includes a pedestrian zone which extends from Berliner strasse in the north, Marktplatz in the east, Geleitstrasse in the south and Kaiserstrasse in the west (see Fig, 38). The streets of Berlinerstrasse and adjacent Mainstrasse in the north have a dense car traffic moving in east-west direction; which is in contrast to the segregated Main riverside (in between Main river and Mainstrasse), having bicycle and pedestrian traffic (see Fig. 39). The central landmark i.e. Marktplatz acts an important open plaza with transit stations of underground train services (i.e. S-Bahn) and on-ground bus lines. The pedestrian zone within the urban core is bisected by the Frankfurter strasse in east-west direction, which acts as a central axis of retail shops and centres in the area. The area surrounding the city centre includes a network of open and green public spaces such as the central landmark i.e. Marktplatz, Wilhelmplatz and Martin Luther park (towards the south of pedestrian zone), Büsigpark in the west towards the common boundary of Nordend and Zentrum urban districts, and more.

Figure 39: Shopping area along Frankfurter strasse in the pedestrian zone (left), and the Main riverside with bicycle and pedestrian pathway (right) in the urban district of Zentrum

With the city centre being one of the focal points through the urban development plans (e.g. Zukunftsplan Offenbach), the range of planned projects would impact the existing characteristic of the space. Some of these projects focus on open spaces (such as Rathaus plaza towards the west of Frankfurter strasse within the pedestrian zone), pocket parks, housing and more within and around the pedestrian zone along with transfer and mobility hubs in close proximity to the pedestrian area.

The Zukunftsplan also acknowledges the relocation of Hochschule für Gestaltung (HfG) in the north and new residential projects towards the western part of the city to have an impact on the overall functionality of the city centre. One of the focal projects within the Masterplan Offenbach includes upgrading Marktplatz, involving improved transition between the pedestrian zone and the Marktplatz, with more green spaces along with opportunities improving quality of stay (such as installation of benches), reduction of lane and traffic speed and more. With the attempt of making the city centre more attractive, the city of Offenbach am Main with its range of urban development projects would have an impact on the immediate and surrounding environment, which would directly or indirectly address how people move through the city centre in future.

3.2.3.2 Transit area in Offenbach am Main

Location and spatial utility

The main railway station (i.e. Hauptbahnhof) of Offenbach am Main is located on the southern peripheral boundary of Zentrum urban district. It falls within the 1-kilometre radius from Marktplatz, showing its close proximity to the city centre. The immediate surrounding districts include Senefelderquartier and Lindenfeld towards the south, with Westend and Mathildenviertel in the north. The main railway station, which runs in east-west direction, is surrounded by two parallel streets of Bismarckstrasse in the north and Marienstrasse in the south (see Fig. 40). The immediate spaces towards the north of Bismarckstrasse are characterized by their mixed-use and residential buildings, while the ones towards the south of Marienstrasse (falling within the urban district of Senefelderquartier) are residential in nature. In comparison to the street of Kaiserstrasse, which connects Main riverside to the Hauptbahnhof, the adjacent spaces comprise of dense mixed-use typology of land-use. The main railway station along with its rail track acts as a peripheral boundary for immediate districts in its vicinity, while passing through the green Anlagenring in east and west.

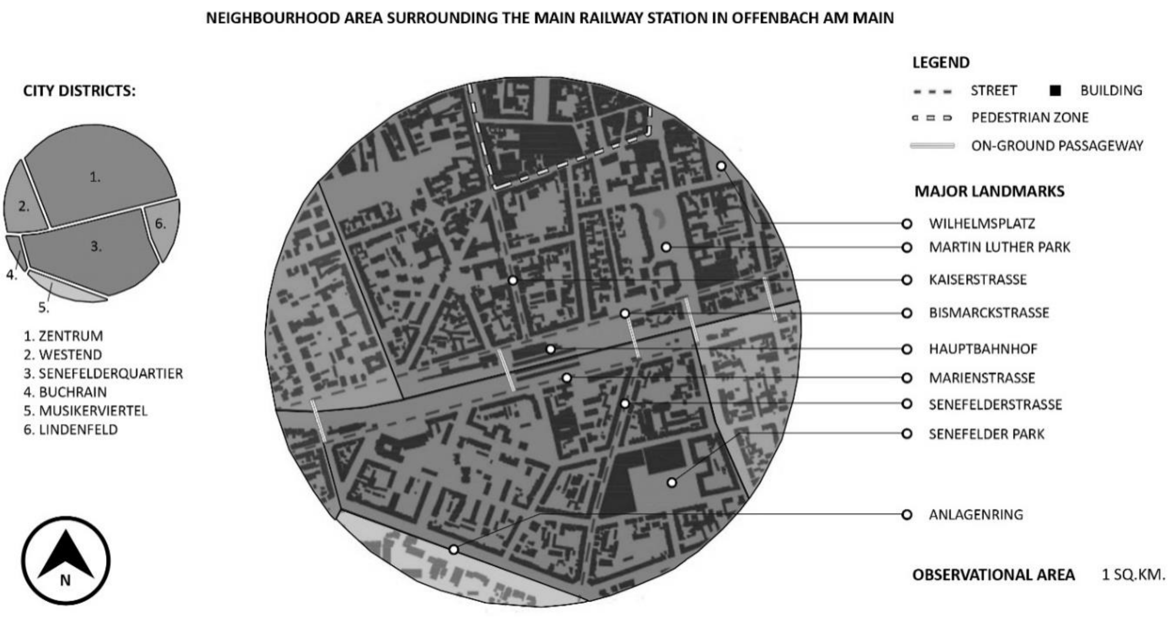

Figure 40: Immediate area surrounding the main railway station with major landmarks (Figure ground map of 1 sq. km.)
Data source: Stadt Offenbach am Main (2019)

Spatial configuration and characteristic

With the main railway station surrounded by two parallel streets running in east-west direction, the immediate area comprises of mixed-use and residential buildings. The block lengths towards the north of main railway station are longer (maximum block length being 300 metres approximately) in comparison to the ones in the south (maximum block length being 200 metres approximately). With elevated rail tracks running in east-west direction, there are four on-ground passageways connecting Bismarckstrasse and Marienstrasse within the observation area (see Fig. 40). While the main entrance of the railway station falls on the Kaiserstrasse-Bismarckstrasse junction, the immediate open space around the railway station is located towards the east, alongside Bismarckstrasse street, which acts as a bus transit station. Other open spaces in close proximity to the main railway station include Martin Luther Park in the Zentrum urban district, Senefelder Park in Senefelderquartier, Anlagenring and other small pocket spaces. With car-traffic prominent on the streets of Bismarckstrasse and Marienstrasse, the Fahrradstrasse initiative focusing on prioritizing cyclists on streets has been implemented on the neighbouring streets including Senefelderstrasse in the south.

Figure 41: The street of Bismarckstrasse adjacent to the main façade (green) of Hauptbahnhof (left), and the row of mixed-use buildings along the street of Kaiserstrasse overlooking main railway station building (right)

In accordance to the Masterplan 2030, the city of Offenbach am Main identifies the space around the main railway station to be utilized through business, residential and other purposes. It acknowledges the bus station in its near vicinity towards the east to be oversized along with the main station building being underutilized. The Masterplan also prioritizes to make the space barrier-free, with potential relocation of the service stations (i.e. bus stops) towards the street of Bismarckstrasse, which would provide more space for neighbourhood parking garage. The masterplan also identifies the potential of pocket parks and residential areas in the east, adjacent to Bismarckstrasse, which would imply more space for improving the quality of stay around the railway station.

3.2.3.3 Residential area in Bürgel

Location and spatial utility

The selected residential area in the urban district of Bürgel is located alongside Main river in the east. It falls within the 2.5-kilometre radius from the city centre landmark i.e. Marktplatz. The immediate districts surrounding Bürgel include Rumpenheim in the north, Mathildenviertel and Offenbach-Ost in the south, with Main river in the west acting as shared boundary with the city of Frankfurt am Main (Fig. 42). Majority of the land-use in the Bürgel district comprises of either residential or green space. The minor portion of area under commercial utility is located in close proximity to the cemetery (i.e. Friedhof) area in the north-west. Majority of mixed-use buildings are located along the street of Langstrasse and Offenbacher Strasse, characterized by shops, restaurants and services for daily needs on the ground floor. This proportion of residential and green space in the district of Bürgel is similar to its neighbouring district of Rumpenheim in the north, while Offenbach-Ost district has a large commercial space within its land-use, which includes accommodation of area for the Innovation Campus with respect to the Masterplan 2030. The urban development plan identifies the district of Bürgel as one of the suburban residential areas, and includes proposals to increase its residential space in eastern (towards the west of Mainzer ring street), western (adjacent to the commercial area west to cemetery) and southern (in close proximity to the Innovation Campus on the peripheral boundary of Bürgel) ends surrounded by green spaces.

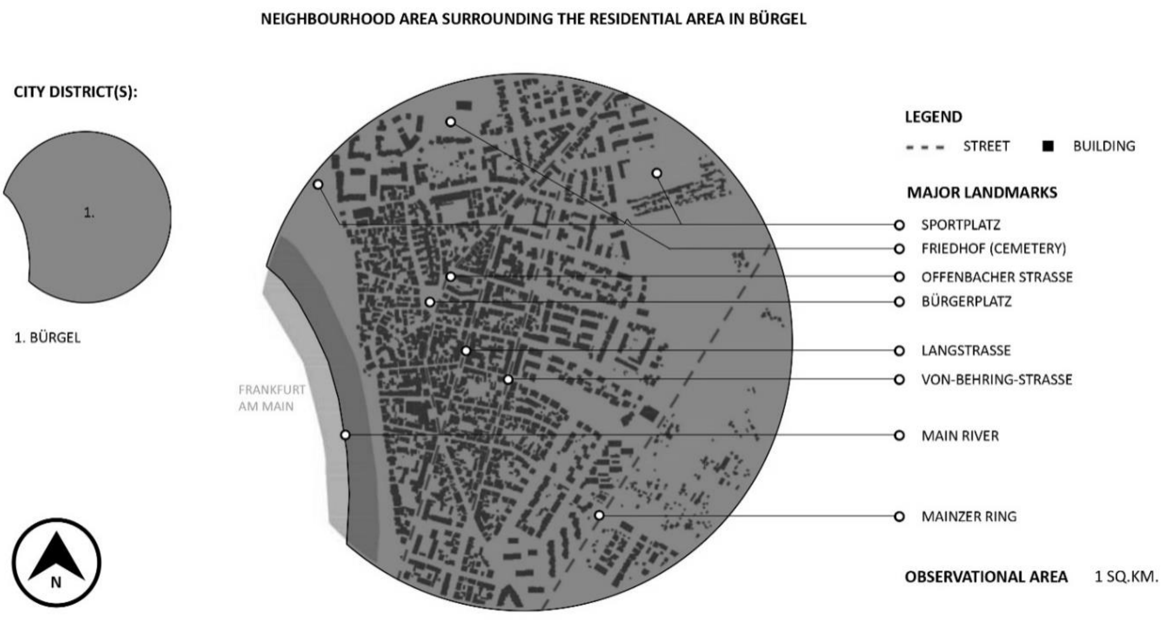

Figure 42: Immediate area surrounding the Bürgel residential area with major landmarks (Figure ground map of 1 sq. km.)
Data source: Stadt Offenbach am Main (2019)

Spatial configuration and characteristic

The residential area of Bürgel includes narrow one-way streets (e.g. Langstrasse, Offenbacher strasse alongside Bürgerplatz and more) forming majority of residential blocks within 150 metre block lengths (see Fig. 42). The network of streets is more linear towards the east of Langstrasse (or even Offenbacher Strasse), as compared to the west with many old detached (and semi-detached) houses in proximity to Main riverside. With respect to the open spaces around the residential area of Bürgel, Bürgerplatz alongside Offenbacher Strasse acts as the central district square with an elevated green space, and a gateway to the historical village centre. Other green open spaces include sport grounds (i.e. Sportplatz) in the north, with green riverside area along Main which includes pedestrian and bicycle pathway adjacent to elevated vehicular streets. The segregated riverside pedestrian and bicycle pathway runs in north-south direction connecting other urban districts of Offenbach am Main including Zentrum in the urban core.

Figure 43: The narrow streets in the residential area of Bürgel district (left), and the row of mixed-use buildings along the street of Offenbacher strasse overlooking Langstrasse (right).

The major vehicular streets within the residential area of Bürgel include Langstrasse, Offenbacher Strasse, and Rumpenheimer Strasse (i.e. the street beyond the northern junction of Langstrasse and Offenbacher Strasse). With narrow streets and on-street parking of vehicles and traffic flow, many streets in the district function within the traffic-calmed speed limit of 30 kmph. With the aim of making the residential district more accessible and attractive to growing population, the Masterplan 2030 along with the Integriertes Entwicklungskonzept (Amt für Stadtplanung, Verkehrs- und

Baumanagement 2018) suggests several measures including urban development of the area surrounding Bürgerplatz, cutting off the Offenbacher Strasse (also Mainstrasse) in the southern boundary of the district, to direct heavy traffic via Mainzer Ring and more. With the reduction of on-street car traffic through the inner-narrow streets of the residential area and with new measures like Fahrradstrasse (i.e. the bicycle street) on the Von-Behring-Strasse, the priority towards short-distance mobility would assist in improving the overall share of active modes of travel in the district and the city.

3.3 Summary

The chapter identifies the multimodal accessibility parameters (in subchapter 3.1) followed by the selection of different urban areas (in subchapter 3.2) for the on-site study. These parameters include connectivity, Space Syntax attributes of intelligibility and NACH, crowding and PTAL (see Fig. 13) which are influenced by design and layout of the street and built infrastructure for an urban area (as discussed in the previous chapter). The parameters also reflect different modes of mobility and involve street characteristics for its overall evaluation. While the literature study identified parameters excluding the five selected parameters, they were directly or indirectly related to them. The measure of distance, either topological, metric, or other through means of utility, was one of the common attributes to assess accessibility on a large-or small-scale perspective. While the measures of accessibility can be categorized into different groups, the topological measures were in favour of understanding and analysing the impact of street networks on the movement and overall accessibility. The topological measures do not evaluate existing opportunities (as per gravity or cumulative opportunities-based accessibility measure), but they do have the potential to be utilized as planning tools (Vale et al. 2016), either to identify intervention priorities or to identify impacts of the urban development proposals. The selection of the five parameters reflect on both micro-and macro scale perspectives, which helps in understanding different view-points of multimodal accessibility and address ways of prioritizing urban areas for improvement in their accessibility characteristic. This addresses the first research question, of identifying different domains of multimodal accessibility and narrowing down the parameters influenced by the urban design.

The Rhein-Main urban agglomeration being one of the major regions in Germany and Europe, provides an opportunity to study different urban areas focusing on a transition towards a sustainable mobility system through measures. Some of these common measures include establishing integrated cycling network, reduced walking times, improved network of public transport, and many more (as discussed in previous chapter). With the urban agglomeration showing an increase in its population with major cities being Frankfurt am Main, Darmstadt and Offenbach am Main, which also show high commuter flows within the region, the cities and the urban areas are selected accordingly. In order to select urban areas which represented large-and small-scale gathering of public, and where people commute to and from, the three urban areas of city centres, main transit area, and residential spaces were selected within the identified boundaries of the five parameters. Within these three urban areas in each city, two urban areas would be distinct i.e. the city centre and the main transit space, while there would be multiple residential areas. The residential areas were selected which were farthest from the city centre or the transit area, to have least influence on the residential area, but were also within the Euclidean distance boundaries of the identified accessibility parameters. The added perspective of master plans for the three cities in different areas and districts, also assisted in prioritizing certain areas for the

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Amt für Stadtplanung, Verkehrs- und Baumanagement (2018), Bürgel Integriertes Entwicklungskonzept, Offenbach am Main. Retrieved from https://www.offenbach.de study. The key measures from the urban planning concepts of *Innenentwicklung vor Aussenentwicklung* (i.e. internal development before external development) and *Doppelte Innenentwicklung* (i.e. double internal development) influencing short-distance mobility were also observed in master plans of the selected cities forming the Rhein-Main urban agglomeration.

The urban development plans in the three cities of Frankfurt am Main, Darmstadt and Offenbach am Main assist in narrowing down certain objectives which are related to accessibility, that can be addressed upon through the intra-and inter-city perspectives of the selected multimodal accessibility parameters. For example, the study of different spaces around the city centre in Frankfurt can be utilized to understand the potential and barriers of multimodal accessibility, where the urban development plans focus on linking the city centre to the Main riverside. The temporary experiments involving road-closure on certain streets can also be utilized to test parameters to see if there are ways to predict certain scenarios which may contribute towards a more accessible space in future. Similarly, other aspects can be utilized to pin-point the areas having higher potential for accessibility, or areas having low levels of accessibility to improve upon it within the defined limits of the identified parameters (unless they can be improved too). It also provides an opportunity to observe any relationship between the identified parameters to combine or interpret certain outcomes from the study.

SECTION 2

PILOT STUDIES AND ANALYSIS

CHAPTER 4

PILOT STUDY AND SPATIAL DIAGNOSIS

Preface

The pilot study is an experimental preliminary study, in order to evaluate the time (for data collection and analysis) and performance of the selected accessibility parameters, in turn also identifying problems pertaining to the process, prior to spatial assessment via identified parameters of other cities forming Frankfurt Rhein-Main region. With respect to the research timeline, the pilot study initiates within the city of Darmstadt. The urban areas identified for the pilot assessment include the city centre i.e. Luisenplatz, which represents the commercial high street environment within the city; the transit area i.e. Hauptbahnhof, which represents an important transit hub for the inter-city mobility within the urban agglomeration; and Komponistenviertel, which represents the residential area within the north-east section of the city that is also prioritized within the city's urban development framework. The chapter addresses second research question via spatial analysis and outcomes through intra-city parametric perspective initially, where the selected parameters are utilized and an urban area's multimodal accessibility characteristic is understood. Post pilot study, the inter-city perspective (discussed more in Chapter 5) is also discussed in brief, as other cities are analysed.

4.1 Reconnaissance study

Prior to pilot study of the selected urban areas, the surrounding streets and neighbourhoods were first examined on-site within the specified parametric observation boundaries. The study helps in preliminary understanding of the urban fabric, which assists and brings more clarity in later research stages, within the methodology involving selected parameters to be studied upon. The study assists in modifying the digitized spaces, which are usually skipped during the desk-based approach. Several advantages were noted down, which assisted in reducing the errors during the analysis, as follows:

- The reconnaissance study was carried out in the selected urban areas, which helped in drafting and verifying major streets and respective junctions, especially regarding the cul-de-sacs and adjacent street networks.

- Major conflicting areas, based on the pedestrian links were sorted, in order to link and de-link the axial lines to be digitized and converted into axial and segment maps, while utilizing Space Syntax theory through DepthmapX (DepthmapX development team 2017) software.

DepthmapX development team (2017), depthmapX (Version 0.6.0) [Computer software], Retrieved from https://github.com/SpaceGroupUCL/depthmapX (22-02-2019)

- The shortest routes leading to the selected landmark within the buffer area of transport modes, were cross-checked and verified, which later assisted in obtaining several Public Transport Accessibility Levels for the selected urban areas.

- With respect to obtaining crowding and movement restriction data, the reconnaissance visits in the area around the selected landmarks aided in selecting the major zones which would be crucial in gathering data, to capture the peak flows of different user-groups identified. It also helped in understanding the assistive tools that would be required to measure the urban street elements, which may act as a barrier while mapping the available width of space for movement.

Post reconnaissance visit, the parameters were examined with ease due to better knowledge of the immediate surroundings of the selected urban areas in the cities forming the Rhein-Main urban agglomeration.

4.2 Darmstadt and its selected urban areas for pilot study

As discussed in the previous chapter, there were three urban areas selected for the pilot study in the city of Darmstadt (see Fig. 44). These include areas surrounding the city centre i.e. Luisenplatz, which is the urban core of the city characterized by commercial, mixed-use spaces; the transit area i.e. Hauptbahnhof, which acts a transit hub within the urban agglomeration for inter-city and intra-city mobility patterns; and the residential area i.e. Komponistenviertel, which is one of the residential areas situated in the north-east from the city centre. The urban areas for the pilot studies are selected based on their diverse environment characteristic with respect to each other and to fit the cycle of a travel chain i.e. to initiate a travel, through the transit hub, in order to reach the destination.

Figure 44: Figure Ground Maps of area surrounding Darmstadt Hauptbahnhof (left), Komponistenviertel (centre), and Luisenplatz (right) within 1 sq. km. area

The selected urban areas are also identified as potential areas within the urban development framework of the Masterplan DA 2030+. Some of these measures include identifying mixed-use and prioritized development spaces around the main railway station i.e. Hauptbahnhof; saving spaces by living more densely in existing residential areas including Komponistenviertel and other areas; having a good quality of stay around the city centre i.e. Luisenplatz and more. With growing population and densification of urban areas through changes in land-use typology, while preserving the green spaces surrounding the urban settlement area of the city, these areas would be subject to more accessible mobility services for people to move through different areas within and around the cities forming the Rhein-Main urban agglomeration. With the city of Darmstadt planning to achieve 75% of its modal share under environment-friendly modes of travel (i.e. involving walking, cycling and public transport) within its Masterplan, the selected urban areas would play a crucial role in achieving the objective.

4.3 Parametric diagnosis of selected urban areas in Darmstadt

The identified performance measures were analysed through macro and micro-scale perspectives, via connectivity index (i.e. link-node ratio), intelligibility, Public Transport Accessibility Level (PTAL), route directness (which utilizes normalized angular choice) and crowding and movement restriction. These were carried post reconnaissance studies as follows:

4.3.1 Connectivity Index

The three selected areas surrounding the city centre, main railway station and the residential area were mapped based on their pedestrian networks within the observational area of one square kilometre as follows:

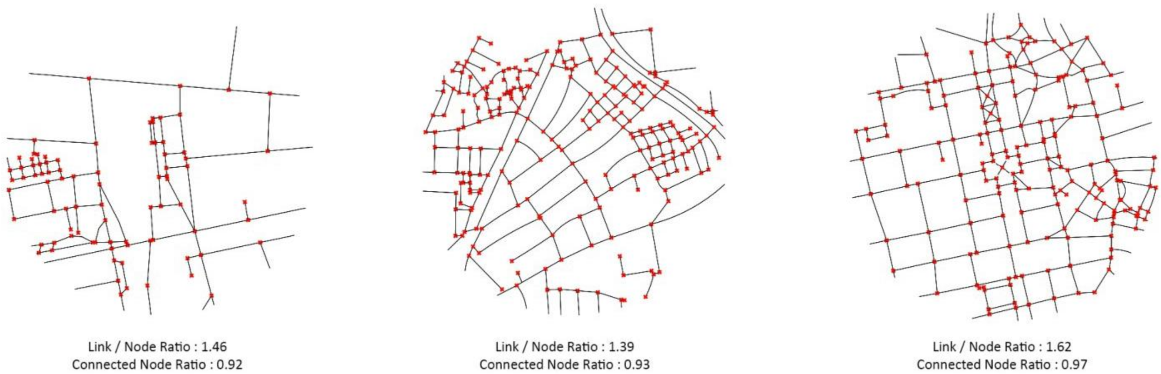


Figure 45: Node (or intersection) density mapping of area surrounding Darmstadt Hauptbahnhof (left), Komponistenviertel (centre), and Luisenplatz (right) within 1 sq. km. area

The Darmstadt Hauptbahnhof area recorded a density of 84 nodes (or intersections) per unit square kilometre and a link (i.e. the street between two nodes) density of 123 per unit square kilometre. The major cul-de-sacs were located in the east from the main station within the network area. The network of links and nodes around the main railway station, i.e. Hauptbahnhof, is influenced by less available space due to non-terminal nature of the transit station and its close proximity to the industrial and commercial land use area. This decreases the density of streets or intersections within the area, which reduces the freedom of choice for a person to move. With respect to the residential area of the Komponistenviertel, the density of 232 nodes (or intersections) per unit square kilometre was observed with a link density of 324 per unit square kilometre. The residential area of Komponistenviertel had the cul-de-sac density of 16, with major concentration in the north-west (see Fig. 45) and in the east direction from the street of Alfred Messel Weg, which is the peripheral boundary of the two urban districts of Darmstadt-Ost and Darmstadt-Nord.

The area around the city centre i.e. Luisenplatz had an overall network density of 188 nodes and 305 links per unit square kilometre. The cul-de-sac density was much lower, as compared to the residential area of Komponistenviertel, with major concentrations around the western and eastern ends of the urban area. The increase in cul-de-sacs leads to decrease in the Connected Node Ratio, which inversely effects the overall connectivity of the network system taken into consideration. The selected urban areas showcased the connectivity index value in close proximity to the link-node ratio of 1.4 (as per Ewing 1996), which denotes a bare minimum for a walkable network. The area surrounding the city centre had the maximum link-node ratio of 1.62, followed by 1.46 in the area surrounding Hauptbahnhof and 1.39 in the residential area of Komponistenviertel. The network of nodes and links around the high street zone of Luisenplatz, supports a more walkable network as compared to the selected residential and main transit area in Darmstadt. As observed previously, the spatial configuration of short block sizes along with low cul-de-sac density complimented the walkable network of spaces around the city centre i.e. Luisenplatz, which supports the commercial high street area within the pedestrian zone. With respect to the connected node ratio, a lower value was observed in the residential area due to increase in cul-de-sacs as compared to the other two urban areas. The connected node ratio observed was above 0.7 for the three areas with close proximity to 1.0. This denotes that users have more freedom of choice to navigate through the network of streets surrounding the city centre, as compared to the area around the main railway station and the selected residential area.

4.3.2 Intelligibility

In order to understand how the configuration of spaces forming the selected three urban areas in the city of Darmstadt influence navigating through the space, the network of streets was first transformed into the network of axial streets (i.e. lines of longest vision through the streets at human-eye level) in accordance to the Space Syntax theory. The axial maps were drafted with respect to the network of open spaces forming the selected urban areas and the axial lines were linked and de-linked (i.e. connected and disconnected based on their connections with other axial lines) in the DepthmapX software utilizing the Space Syntax theory. An example of de-linking an axial line could be in the case of city centre, where a bridge over the street in east would appear to be connected to the street below like an intersection on the axial map, while in reality the two axial lines are on two different planes and not connected directly.

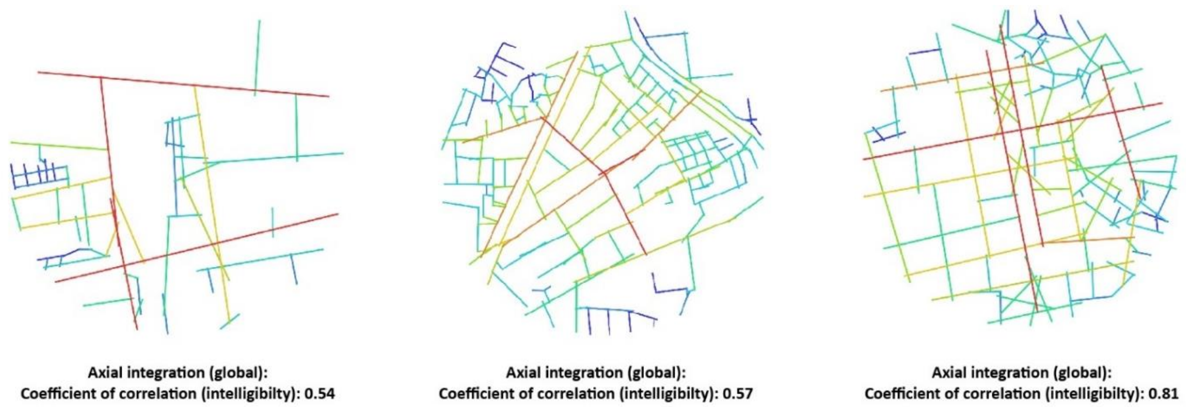


Figure 46: Axial maps of area surrounding Darmstadt Hauptbahnhof (left), Komponistenviertel (centre), and Luisenplatz (right) within 1 sq. km. area showing global integration characteristic

The axial lines around Darmstadt Hauptbahnhof showed major integrations on the streets of Bismarckstrasse and Rheinstrasse (see Figures 46 and 32), in the northern and southern ends of the main railway station, with a coefficient of correlation between the connectivity and global integration being 0.54 (see Fig. 47). This shows a good positive correlation between the identified parameters.

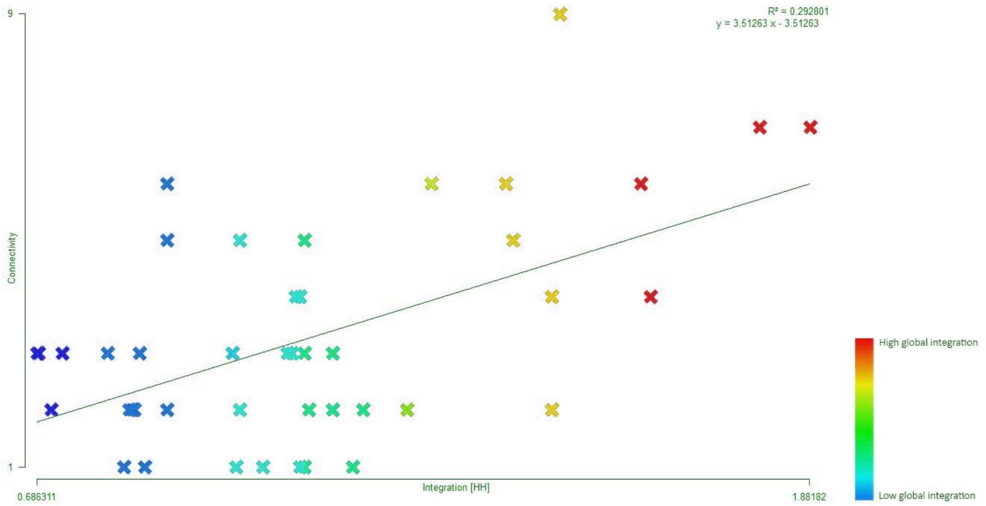


Figure 47: Scatterplot of Connectivity (r=1) and Global Integration (r=n) of axial lines surrounding Darmstadt Hauptbahnhof [1 sq. km.]

The global integration of the axial network in the residential area of the Komponistenviertel shows major integrations in the core area around the street of Flotowstrasse (see Figures 46 and 33), with a coefficient of correlation between the connectivity and global integration being 0.57 (see Fig. 48). The axial line with major connectivity lies in the north on the Alfred Messel Weg, in contrast to the major integrated axial line around Flotowstrasse.

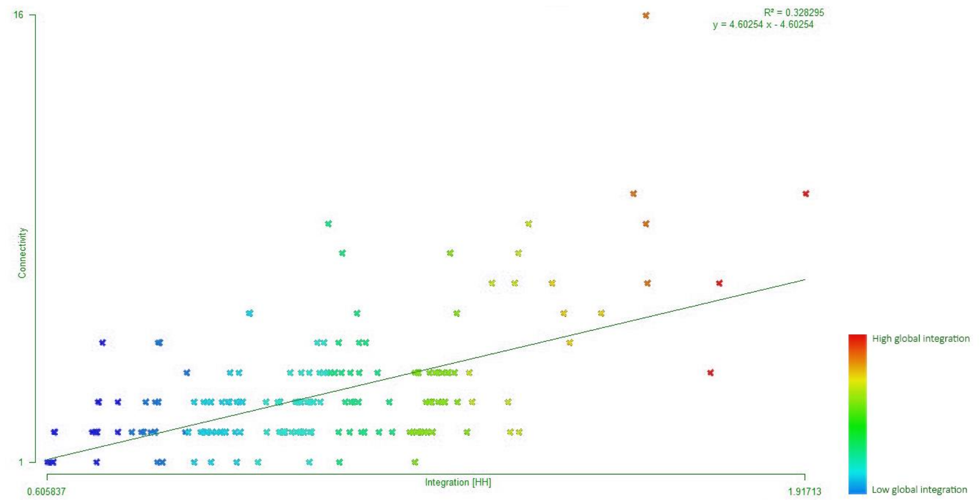


Figure 48: Scatterplot of Connectivity (r=1) and Global Integration (r=n) of axial lines surrounding Komponistenviertel [1 sq. km.]

With respect to Luisenplatz, the coefficient of correlation between the connectivity and global integration is the highest through the selected urban areas with a value of 0.81. This shows a strong intelligibility characteristic with major integrated axial lines on the north from the central Luisenplatz landmark (see Figures 46 and 31) on the street of Bismarckstrasse, which is also one of the strong integrated streets surrounding the main railway station i.e. Hauptbahnhof area.

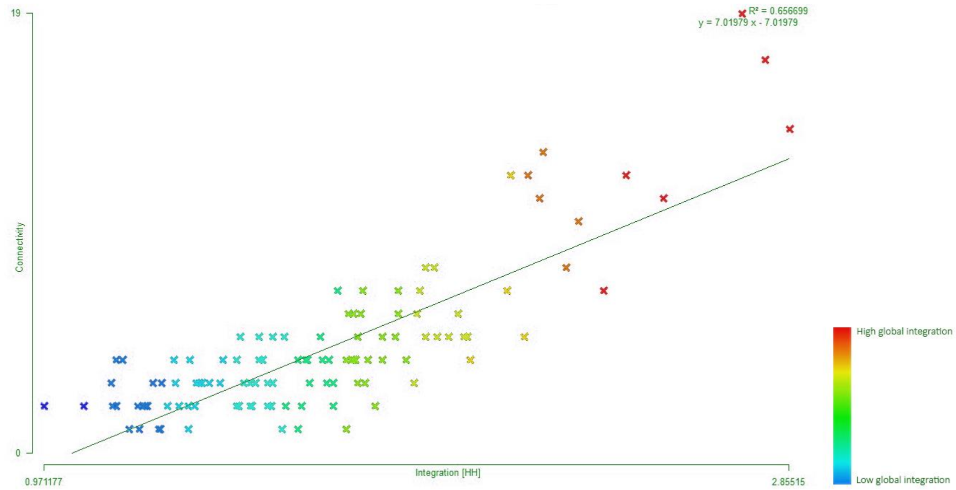


Figure 49: Scatterplot of Connectivity (r=1) and Global Integration (r=n) of axial lines surrounding Luisenplatz [1 sq. km.]

The axial maps of the selected urban areas show a positive correlation between the connectivity and the global integration, with the highest coefficient of correlation value 0.81 in the city centre of Darmstadt i.e. Luisenplatz. This shows a high intelligibility characteristic of the area as compared to the main transit station and the residential area i.e. Komponistenviertel. This indicates that the axial network of the city centre allows more ease of navigation as compared to the axial network of the other two areas. Within the three selected areas, the scatterplot shows the axial network with better connectivity value and within the high integration value range, showed better intelligibility, which was the case in the Luisenplatz (see Fig. 49). In Hauptbahnhof and the residential area, the links with highest connectivity were not within the range of high integration value, whereas in the city centre, the link with high connectivity correlated to high integration value. With further observations in other selected areas within the urban agglomeration, more clarity in the relation to the intelligibility factor would be understood.

4.3.3 Public Transport Accessibility Level

The Public Transport Accessibility Level i.e. PTAL for the selected areas in Darmstadt are recorded for the transportation modes of buses and trams within 640 metres of radius, and trains within the maximum radius of 960 metres. The major factors contributing towards the calculation for the PTAL include the frequency of the modes on the service station with respect to their route, and the shortest accessible pathway for the pedestrians from the point of interest to all the service stations taken into consideration. The data collection for every service station was recorded within the time interval of morning peak hour between 08:15 - 09:15, during the weekdays. Darmstadt Hauptbahnhof is served with three modes of public transport (i.e. buses, trains and trams) taken into consideration, which is the highest as compared to the other areas around the city centre i.e. Luisenplatz and residential area around Komponistenviertel.

Several modal frequencies were recorded around Hauptbahnhof, with the farthest service station being at approximately 480 metres from the point of interest (considering the boundary limits for the parameter). Diverse routes of buses, trams and trains were recorded with maximum frequency of 6 within the observed time interval. The modal routes were only considered once during the assessment for a single selected area, with consideration to the service station closest to the point of interest, as compared to the other service station with similar modal routes.

Figure 50: Shortest pedestrian access route between the point of interest A at Hauptbahnhof and B at Berliner Allee service station

Due to the pandemic and lockdown restrictions in the 2020-2021, the pre-pandemic data was revised for January 2021 data to have a fair comparison with data collected during pandemic in the other cities forming the urban agglomeration. The PTAL indexes for respective service stations around Darmstadt Hauptbahnhof were recorded as follows:

Site	Service	Stop	Route	Distance	Frequency	Weight	Walktime	SWT	Access	EDF	Index
Darmstadt Hbf.	Bus	Hauptbahnhof	H	105	6	1	1.31	7.00	8.31	3.61	3.61
			40	105	1	0.5	1.31	32.00	33.31	0.90	0.45
			WE4	105	1	0.5	1.31	32.00	33.31	0.90	0.45
			671	105	1	0.5	1.31	32.00	33.31	0.90	0.45
			672	105	1	0.5	1.31	32.00	33.31	0.90	0.45
			GB	105	1	0.5	1.31	32.00	33.31	0.90	0.45
			AIR	105	2	0.5	1.31	17.00	18.31	1.64	0.82
			RH	105	2	0.5	1.31	17.00	18.31	1.64	0.82
			K	105	4	0.5	1.31	9.50	10.81	2.77	1.39
			MO1	105	1	0.5	1.31	32.00	33.31	0.90	0.45
			WE3	105	1	0.5	1.31	32.00	33.31	0.90	0.45
			R	105	4	0.5	1.31	9.50	10.81	2.77	1.39
		Westseite	FU	270	2	0.5	3.38	17.00	20.38	1.47	0.74
			F	270	3	0.5	3.38	12.00	15.38	1.95	0.98
	Tram	Hauptbahnhof	1	35	2	0.5	0.44	15.75	16.19	1.85	0.93
			2	35	5	0.5	0.44	6.75	7.19	4.17	2.09
			3	35	6	1	0.44	5.75	6.19	4.85	4.85
			5	35	5	0.5	0.44	6.75	7.19	4.17	2.09

	Berliner Allee	9	480	5	0.5	6.00	6.75	12.75	2.35	1.18
		4	480	4	0.5	6.00	8.25	14.25	2.11	1.05
Train	Hauptbahnhof	S3	150	2	1	1.88	15.75	17.63	1.70	1.70
		RB66	150	1	0.5	1.88	30.75	32.63	0.92	0.46
		RB68	150	1	0.5	1.88	30.75	32.63	0.92	0.46
		RB75	150	2	0.5	1.88	15.75	17.63	1.70	0.85
		RB81	150	1	0.5	1.88	30.75	32.63	0.92	0.46
		RE60	150	1	0.5	1.88	30.75	32.63	0.92	0.46
		RB67	150	1	0.5	1.88	30.75	32.63	0.92	0.46
		RE80	150	1	0.5	1.88	30.75	32.63	0.92	0.46
									PTAL:	30.38

Table 5: PTAL for area surrounding Darmstadt Hauptbahnhof through different public transport services

The overall PTAL value of 30.38 fell within the index range of 25.01-40.00, depicting an excellent index value under group 6a (in Table 4). The major contribution to the overall PTAL value (i.e. ~43%) is given by bus through a combined value of 12.89, followed by 12.18 by the mode of tram (contributing 40%) and 5.31 index value through train (in Table 5). The proximity and high frequency of trams, buses and train services assist in the overall PTAL value for the transit area. This shows a balance of services and frequencies between trams and buses in the area surrounding main transit station in Darmstadt.

Figure 51: Figure: Shortest pedestrian access route between the point of interest A at Flotowstrasse and B at Regerweg service station in Komponistenviertel

With respect to the residential area of Komponistenviertel, the major service stations within the radius of observation were recorded to be only 2. Both being on the northern and southern ends of the selected residential area, identified as Regerweg (in Fig. 51) and Alfred Messel Weg respectively.

The PTAL indexes for the service stations within the observation area of Komponistenviertel are as follows:

Site	Service	Stop	Route	Distance	Frequency	Weight	Walktime	SWT	Access	EDF	Index
Komponistenviertel	Bus	Regerweg	FU	355	2	0.5	4.44	17.00	21.44	1.40	0.70
			F	355	2	0.5	4.44	17.00	21.44	1.40	0.70
		Alfred Msl. Weg	H	335	3	1	4.19	12.00	16.19	1.85	1.85
										PTAL:	3.25

Table 6: PTAL for the residential area of Komponistenviertel through different public transport services

The residential area of Komponistenviertel has a service of three bus routes through two service stations located on the northern and southern ends of the residential area. The modal service of H bus, is attained within the area with maximum frequency of 3, during the peak hour, at the northern end of Alfred Messel Weg. This contributes towards the combined PTAL index value of 3.25 (in Table 6), which falls within the index range of 2.51-5.00 (in Table 4), denoting a poor value. Overall, the three service routes were the least in numbers as compared to the other selected urban areas for the study in Darmstadt.

The city centre i.e. Luisenplatz, is served with the maximum service stations, with respect to bus and tram services, accounting to 27 service routes. The area has a close proximity to the available service stations around the major landmark of the central bust in the pedestrian plaza, making the services accessible on a level ground. During the peak hour consideration for the PTAL index within the selected radii for the modal services, the majority of service routes were covered within the service station of Luisenplatz as compared to the neighbouring stations, as they were excluded due to similar route pattern. With added choice of several service stations offering similar travel route, for e.g. tram 9 service passing through Schloss station and Luisenplatz service station, the service station in close proximity to the origin i.e. Luisenplatz is taken into consideration (which excludes the Schloss station).

The PTAL indexes for several service routes within the city centre area surrounding Luisenplatz were obtained as follows:

Site	Service	Stop	Route	Distance	Frequency	Weight	Walktime	SWT	Access	EDF	Index
Luisenplatz	Bus	Luisenplatz	H	15	6	0.5	0.19	7.00	7.19	4.17	2.09
			F	15	2	0.5	0.19	17.00	17.19	1.75	0.87
			FU	15	2	0.5	0.19	17.00	17.19	1.75	0.87
			671	15	6	0.5	0.19	7.00	7.19	4.17	2.09
			672	15	2	0.5	0.19	17.00	17.19	1.75	0.87
			673	15	1	0.5	0.19	32.00	32.19	0.93	0.47
			674	15	1	0.5	0.19	32.00	32.19	0.93	0.47
			693	15	1	0.5	0.19	32.00	32.19	0.93	0.47
			AIR	15	1	0.5	0.19	32.00	32.19	0.93	0.47
			GB	15	2	0.5	0.19	17.00	17.19	1.75	0.87
			K	15	8	1	0.19	5.75	5.94	5.05	5.05
			L	15	8	0.5	0.19	5.75	5.94	5.05	2.53
			MO1	15	1	0.5	0.19	32.00	32.19	0.93	0.47
			NHX	15	2	0.5	0.19	17.00	17.19	1.75	0.87

		RH	15	4	0.5	0.19	9.50	9.69	3.10	1.55
		X71	15	1	0.5	0.19	32.00	32.19	0.93	0.47
		X74	15	1	0.5	0.19	32.00	32.19	0.93	0.47
		X78	15	1	0.5	0.19	32.00	32.19	0.93	0.47
		WE2	15	4	0.5	0.19	9.50	9.69	3.10	1.55
		WE1	15	6	0.5	0.19	7.00	7.19	4.17	2.09
Tram	Luisenplatz	2	15	6	0.5	0.19	5.75	5.94	5.05	2.53
		3	15	11	1	0.19	3.48	3.66	8.19	8.19
		4	15	4	0.5	0.19	8.25	8.44	3.56	1.78
		5	15	6	0.5	0.19	5.75	5.94	5.05	2.53
		6	15	4	0.5	0.19	8.25	8.44	3.56	1.78
		7	15	4	0.5	0.19	8.25	8.44	3.56	1.78
		9	15	4	0.5	0.19	8.25	8.44	3.56	1.78
									PTAL:	45.38

Table 7: PTAL for area surrounding Luisenplatz through different public transport services

As compared to the other two selected areas, Luisenplatz served with the highest PTAL index value of 45.38 (in Table 7), which fell in the highest attainable range of 40.01+ within the 6b category (in Table 4). The major share of the PTAL index is contributed by bus modal services (i.e. 55%) through overall index value of 25.03, followed by tram services with an index value of 20.35.

The public transport services contributed to the highest modal PTAL index in Luisenplatz amongst the three selected areas, with bus service meeting the highest share in each observation area. While the city centre did not have a rail service in its proximity, the area of Luisenplatz with its close proximity to service stations and high frequency of services dominated the PTAL index value of area surrounding main railway station i.e. Hauptbahnhof, which had access to three different modes of public transport in its vicinity.

4.3.3.1 Added perspective through reduced mobility

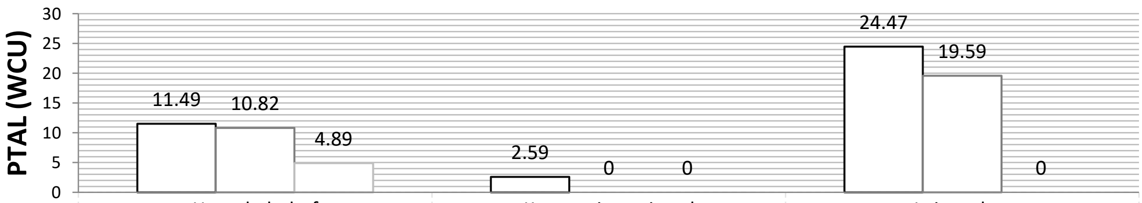
The present index of Public Transport Accessibility Level takes into consideration the normal human mobility speeds of 4.8 kmph into the accessibility analysis. The shortest mobility route taken into consideration for the pilot studies are mapped in accordance to the distance and time measure. The additional human perspective with respect to the wheelchair users was taken into consideration for the study to understand how these spaces function with a reduced human speed, taking the acquired speeds from literature studies. The measure shows another viewpoint of how the same area within similar radius of public transport services serve to a different user group and showcases the inequity of the same services in these urban spaces.

In order to reflect the average speed of the wheelchair users, several research studies have taken the bouts of wheelchair mobility into consideration. Bouts of mobility, described as the continuous movement phase of a wheelchair or the continuous segments of movement, is often signified as the means of wheelchair movement. Several studies have been utilized to understand the average moving speeds of diverse wheelchair users (in Table 8), ranging from athletes, people with spinal cord injury (SCI) to children, in diverse environments, which include nursing homes and rehabilitation hospitals.

Study	Sample subject	Distance travelled per day	Quotidian moving time	Quotidian average speed
Sonenblum et al. (2012)	Adults	1.9 kilometre	58 minutes	0.48 m/s
Oyster et al. (2011)	SCI	1.9 Kilometre	47 minutes	0.63 m/s
Cooper et al. (2008)	Children	1.6 kilometre	n/a	0.67 m/s
Tolerico et al. (2007)	Athletes	2.5 kilometre	48 minutes	0.80 m/s
Karmarkar et al. (2010)	Adults	1.5 kilometre	n/a	0.48 m/s
Range		1.5 - 2.5 kilometre	47 - 58 minutes	0.48 - 0.80 m/s

Table 8: Different average moving speed for sample subjects (i.e. persons on wheelchairs)

With respect to the daily average speed of the wheelchair users, the domain falls between 0.48 m/s to 0.80 m/s. Considering the selected studies, a mid-range value of 0.64 m/s (or 2.3 kmph) is taken into consideration for an added perspective of wheelchair users' mobility within the PTAL index value. Post alteration within the PTAL indexing, new index values were generated. The revised indexes for the three selected areas within the pilot study, can be observed as follows:



	Hauptbahnhof	Komponistenviertel	Luisenplatz
Bus	11.49	2.59	24.47
Tram	10.82	0	19.59
Train	4.89	0	0

Bus **Tram** **Train**

Table 9: Revised PTAL for selected urban areas in Darmstadt focusing on users with reduced mobility (i.e. wheelchair users)

With respect to the revised indexes, there is a 10% decrease of index value in Hauptbahnhof area, 20% decrease of index value in the residential area of Komponistenviertel and 3% decrease of index value in the city centre i.e. Luisenplatz. The revised PTAL range for the selected urban areas remained the same but with respect to residential area, it dropped closer to the poor access range of 1a i.e. < 2.50

Sonenblum, S. E., Sprigle, S., and Lopez, A. R. (2012), Manual Wheelchair Use: Bouts of Mobility in Everyday Life, Rehabilitation Research and Practice, DOI: 10.1155/2012/753165
Oyster, M. L., Karmakar, A. M. et al. (2011), Investigation of factors associated with manual wheelchair mobility in persons with spinal cord injury, Archives of Physical Medicine & Rehabilitation, 92 (3), pp- 484-490
Cooper, R. A., Tolerico, M. et al. (2008), Quantifying wheelchair activity of children: a pilot study, American Journal of Physical Medicine and Rehabilitation, 87 (12), pp. 977-983
Tolerico, L. M., Ding, D., Cooper, R. A. et al. (2007), Assessing mobility characteristics and activity levels of manual wheelchair users, Journal of Rehabilitation Research & Development, 44 (4), pp. 561-572
Karmakar, A. M., Collins, D. M. et al. (2010), Manual wheelchair-related mobility characteristics of older adults in nursing homes, Disability and Rehabilitation: Assistive Technology, 5 (6), pp. 428-437

value. A major drop with respect to the residential area, signifies how the public transport with respect to the wheelchair users within the selected residential area, is more inaccessible as compared to the other urban spaces.

4.3.4 NACH

The existing axial network from the intelligibility study, for understanding the bicycle route directness, is converted into a segment map in the DepthmapX software (in order to perform angular segment analysis). The Normalized Angular Choice (NACH) for the selected urban spaces is analysed, where the street segments with high potential of bicycling based on least angular deviations displayed high NACH values. The NACH segment maps for the pilot studies through two varying radii, i.e. 565m (~1 sq.km) for the selected urban areas (in Fig. 52) and 2500m covering the city (in Fig. 53), are as follows:

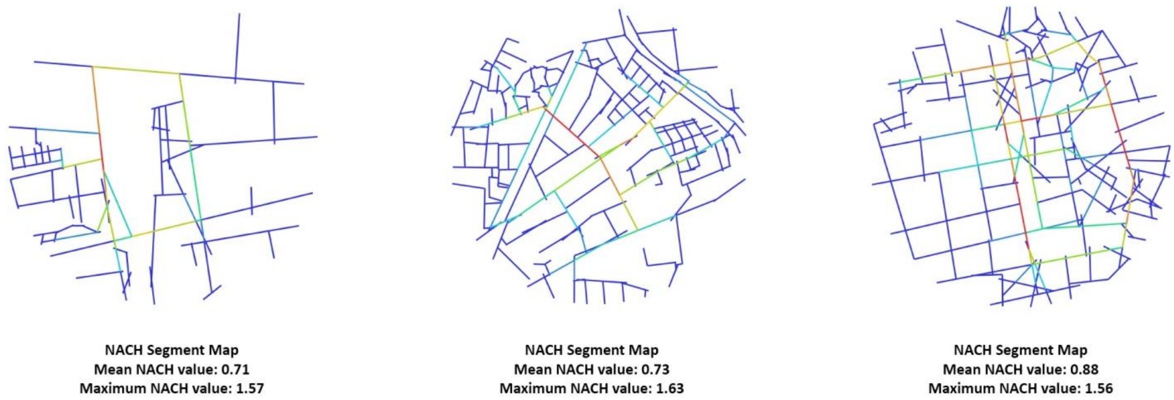


Figure 52: Segment maps showing normalisation of angular choice through areas surrounding Darmstadt Hauptbahnhof (left), Komponistenviertel (centre) and Luisenplatz (right) within the limited boundary of 1 sq. km.

Small scale perspective

With respect to the urban area surrounding the main railway station i.e. Hauptbahnhof, the street of Bismarckstrasse in the north, Zweifalltorweg in the west and the Rheinstrasse segment in the south (in Figures 32 and 52) showed high NACH values followed by the Goebelstrasse segment in the east. The maximum NACH value of 1.56 was recorded on the Zweifalltorweg segment in the west, with an overall mean NACH value of 0.71. The residential area of Komponistenviertel recorded marginally better NACH values as compared to the Hauptbahnhof in Darmstadt. The Flotowstrasse segments (in Figures 33 and 52) bisecting the residential area from North to South showed relatively high NACH values, followed by the eastern segments on the street of Richard Wagner Weg from the four-way junction with respect to the other segments in the area. The maximum NACH value of 1.63 was recorded in the northern segment of the Flotowstrasse, with an overall mean NACH value of 0.73. With respect to the urban area surrounding the city centre i.e. Luisenplatz, the overall mean NACH value of 0.88 dominated over the other selected urban spaces in Darmstadt, with a maximum NACH value of 1.55 on the Schloßgrabenstrasse on the adjacent eastern street from the Schloss (i.e. castle) (in Figures 31 and 52). Though the residential area showed maximum NACH value with respect to the potential of using bicycles as a mode of travel, the overall spatial structure around the city centre i.e. Luisenplatz showed high potential of cycling pathways, with more frequency of segments falling within a higher range of NACH values. The high values within the selected areas showcases the high potential of the streets to be utilized for bicycling, with least angular deviations and direct routes.

The majority of segments, i.e. 39, recorded NACH values greater than 1.20 in the Hauptbahnhof area, whereas 136 segments within the residential area recorded the same. 174 segments within Luisenplatz area recorded NACH values greater than 1.20, which shows the highest frequency of segments among the three selected urban areas. With respect to the overall number of segments within the same observation boundary for the three urban areas, the highest number recorded was 635 in the residential area of the Komponistenviertel, followed by 541 segments in Luisenplatz and 180 segments in Hauptbahnhof. Due to large proportion of space within the Hauptbahnhof area being utilized for the rail infrastructure, the density of the potential streets as compared to the other spaces is low, which leads to prioritizing the existing potential streets and the ones with low NACH values, as compared to other spaces. The streets with higher NACH values provide an accessible bicycle network with respect to the least angular deviations, and along with better cycling infrastructure would assist in maximizing the potential of the urban network for cyclists. With respect to the study, the overall mean NACH values for each urban space is utilized in order to compare the accessibility of network with respect to bicycle users.

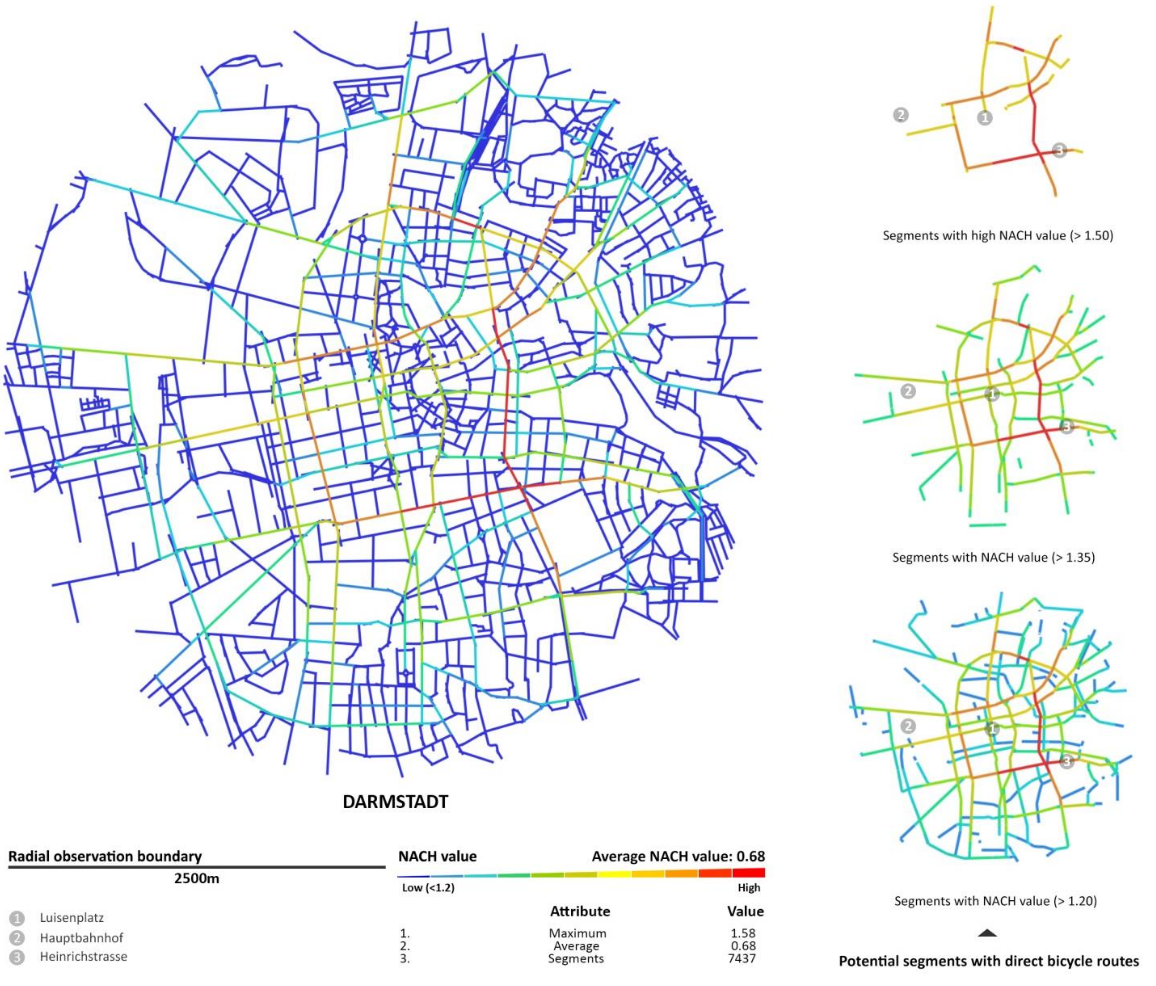


Figure 53: Segment maps showing normalisation of angular choice (NACH) through Darmstadt within an observational radius of 2500m from the city centre i.e. Luisenplatz.

Large scale perspective

In order to implement a long-term planning structure for the overall city, a larger perspective based on daily bicycle trips is required to prioritize dedicated bicycle lanes irrespective of the selected urban areas. The segment map within 2500m radial boundary from the city centre (see Fig. 53), assists in showcasing a larger network of direct bicycle pathways which have potential for through bicycle movement, that can be later connected to secondary networks based on the study via small scale perspective. The analysed segment map of Darmstadt resulted in streets with high NACH values on the eastern part of the city, recording 1.58 through the street of Teichhaustrasse. The network of high NACH values form an enclosed ring with an important junction along the streets of Heinrichstrasse and Neider-Ramstädter Strasse in south-east from the city centre. The series of high potential bicycle routes depict the importance of the respective streets, giving priority for direct and shortest routes throughout the street network of the city within 2500m. Due to the lack of segments in the western end of the city relative to the other parts, a shift in the central core of the high NACH segments is observed towards east. The overall mean NACH value for the segment network is 0.68. Comparing the NACH segment map (>1.20), the high valued segments corresponded to the high values recorded through the selected urban areas within 1 sq. km. The progression of NACH network from 1.20 to 1.50 and above indicates the set of segments (or streets) which should be given priority for dedicated bicycle lanes as they influence the cycling trips regarding short-distance mobility.

4.3.5 Crowding and movement restriction

Post the route directness study of the three selected urban spaces, the street network was taken into consideration for the assessment of the crowding and movement restriction including the streets identified to be assessed post reconnaissance and intelligibility studies, identifying more integrated street sections i.e. control gateways. With respect to the type of the selected area, the time for accumulating the on-site data was realized during the summer months of 2020. Luisenplatz fell within the 'High Street' category as the major area surrounding the place included retail shops and markets, hence the data was recorded during the recommended period of 14:00-18:00 hours on weekdays and weekends (Tuesday-Thursday, Saturday). The data for Komponistenviertel, falling under the 'Residential' category due to individual housing within the radius, was recorded between the recommended timeline of 14:00-18:00 during weekdays (Tuesday - Thursday) and 09:00-16:00 during Saturday. Hauptbahnhof, being the major 'Transit' area for travel modes within the city and the Frankfurt Rhein-Main region, was taken into consideration within the peak timeline of 08:00-10:00 and 16:00-18:00 on weekdays (Tuesday-Thursday).

The weather and immediate environment for the data collection was taken into consideration, i.e. it was made sure that the peak hour pedestrian flows were not recorded during the extreme weather conditions (e.g. snowfall or rainfall), on public holidays or on days with any specific social festivities, which may hinder with the normal pedestrian flow. Overall 11 control gateways were selected throughout the residential area of Komponistenviertel (in Fig. 54), with ongoing marginal construction work which did not cause any major hindrance with the overall pedestrian flows. The selected control gateways for the study recorded similar peak hour crowding within the least movement restriction category. The available footway widths were measured with respect to each control gateway (see Appendix), and buffer widths were taken into consideration with respect to the street elements and immediate environment. With respect to the available footway widths for the pedestrians, the tertiary roads connecting several residential units had shared four-wheeler parking space alongside the pedestrian pathway, due to which the vehicular roadway section was being used by the pedestrians. Users with reduced mobility (URM) were seen utilizing vehicular roads on the Flotowstrasse, which had pedestrian pathways on either side. Absence of pedestrian pathways on some tertiary street sections forced a shared space of vehicles and pedestrians. The peak hour flows for the pedestrians and vehicles within the selected control gateways were recorded, with sub-categories of cyclists, users with reduced mobility (i.e. wheelchair users, walkers etc), baby strollers, users with electronic (or manual) scooter and boards (i.e. longboards or skateboards) and four-wheeler and two-wheeler automotive vehicles under non-active mode of transport, as follows:

Gateways:	FN	N1	N2	N3	N4	N5	S4	S3	S2	S1	FS
Pedestrians	42	12	18	12	12	24	18	12	42	30	96
Cyclists	54	12	24	12	12	24	12	6	36	18	60
URM	12	0	0	0	0	0	6	0	6	0	18
Baby strollers	12	0	0	0	0	0	0	0	6	0	24
Boards / Scooters	18	6	0	0	0	0	6	0	0	0	6
Four-wheelers	222	24	12	6	12	30	24	6	60	18	192
Two-wheelers	6	0	0	0	0	0	0	0	0	0	0
Total	114	30	42	24	24	48	36	18	78	48	162
Footway width (m)	2.8	1.7	5.94	2.79	3.45	2.15	5.2	3.25	3.4	3.25	2.3
ppm	40.71	17.65	7.07	8.60	6.96	22.33	6.92	5.54	22.94	14.77	70.43
ppmm	0.68	0.29	0.12	0.14	0.12	0.37	0.12	0.09	0.38	0.25	1.17

Table 10: Peak hour modal flows in selected control gateways around Komponistenviertel, Darmstadt (where ppm = persons per metre and ppmm = persons per metre minute)

Maximum peak hour pedestrian flows were recorded on the northern and southern ends of the Flotowstrasse street, with the northern end recording 42 pedestrians and the southern end recording 96 pedestrians. The cyclists also peaked on the ends of the Flotowstrasse through the control gateways FN and FS. Excluding the street ends, the central junction through control gateways N5 and S4 in the east-west direction, recorded relatively higher flow of pedestrians as compared to others.

Figure 54: Peak hour crowding and movement restriction around Komponistenviertel (1 sq. km.), Darmstadt

With respect to the peak hour crowding, the maximum was recorded as 1.17 ppmm in the southern end of Flotowstrasse street through control gateway FS, followed by 0.68 ppmm in the northern end of Flotowstrasse through control gateway FN. All gateways fell within the comfortable peak hour crowding range below 3 ppmm with a <3% movement restriction (see Table 10 and Fig. 54). The streets within the residential area of Komponistenviertel gave the least movement restriction with respect to the pedestrian flows, though the amalgamation of shared vehicular and pedestrian spaces, in tertiary roads, would cause a considerable movement restriction if the pedestrian flows increase in future, due to absence of pedestrian pathways. In order to calculate the representative peak hour crowding value of the residential area, overall mean value of all control gateways i.e. 0.34 ppmm is taken into consideration, which falls with the most comfortable range of peak hour crowding.

Gateways:	1	2	3	4	5	6	7	8	9	10	11
Pedestrians	36	168	18	294	264	78	1374	552	90	474	258
Cyclists	66	30	24	66	18	0	150	78	234	114	432
URM	6	0	0	12	6	0	30	6	0	0	0
Baby strollers	0	6	0	6	6	0	24	12	0	6	0
Boards / Scooters	0	0	0	0	0	0	18	0	0	6	6
Four-wheelers	0	0	0	0	0	0	0	0	432	258	2124
Two-wheelers	0	0	0	0	0	0	0	0	12	6	24
Total	102	198	42	360	282	78	1542	630	324	594	696
Footway width (m)	3.6	8.6	3.3	17.46	14.6	2.8	12.8	19.8	4.6	5.5	7.89
ppm	28.33	23.02	12.73	20.62	19.32	27.86	120.47	31.82	70.43	108.00	88.21
ppmm	0.47	0.38	0.21	0.34	0.32	0.46	2.01	0.53	1.17	1.80	1.47

Table 11: Peak hour modal flows in selected control gateways around Hauptbahnhof, Darmstadt (where ppm = persons per metre and ppmm = persons per metre minute)

In the urban area surrounding the main railway station i.e. Hauptbahnhof, 11 control gateways were selected covering the street of Bismarckstrasse in the north, Zweifalltorweg in the west, Rheinstrasse in the south and the main street sections in front of the main entrance of the Hauptbahnhof building. Among the selected control gateways, majority of the sections were within the pedestrian zones excluding the control gateways 9, 10, and 11 which included vehicular traffic (see Fig. 55). The existing potential of the lanes, with respect to bicycle route directness, was seen through availability of bicycle lanes on major street sections in the northern and southern ends of the area. Regarding the available footway widths, the transit area surrounding Hauptbahnhof had a mean width of 9.18 metres, which was approximately thrice as compared to the residential area of Komponistenviertel (i.e. 3.29 metres). The overall clear footway widths were greater as compared to the residential area of Komponistenviertel. The maximum peak hour pedestrian flow recorded 1374 pedestrians in the street section adjacent to the Hauptbahnhof building through the control gateway 7 (which extends through the outdoor transit shelter to the edge of the elevated shared space) (in Appendix), followed by 552 pedestrians in close proximity along gateway 8 (in Table 11). High proportion of cyclists among the active user-groups dominated on the street of Rheinstrasse, with 72% of the pedestrian traffic using bicycle, followed by 65% on the control gateway 1 in the eastern side of the park and 62% on the control gateway 9 on Bismarckstrasse. The high proportion of cyclists complimented the higher NACH values as observed through the potential of streets being more accessible through bicycle route directness. The control gateway on the street of Zweifalltorweg showed decent share of bicycle users, but lacked a separate bicycle lane for the users. This in turn reduces the overall safety measure as compared to the other street sections, i.e. Rheinstrasse or Bismarckstrasse, which included bicycle lanes complimenting the good proportion of cyclists on the streets.

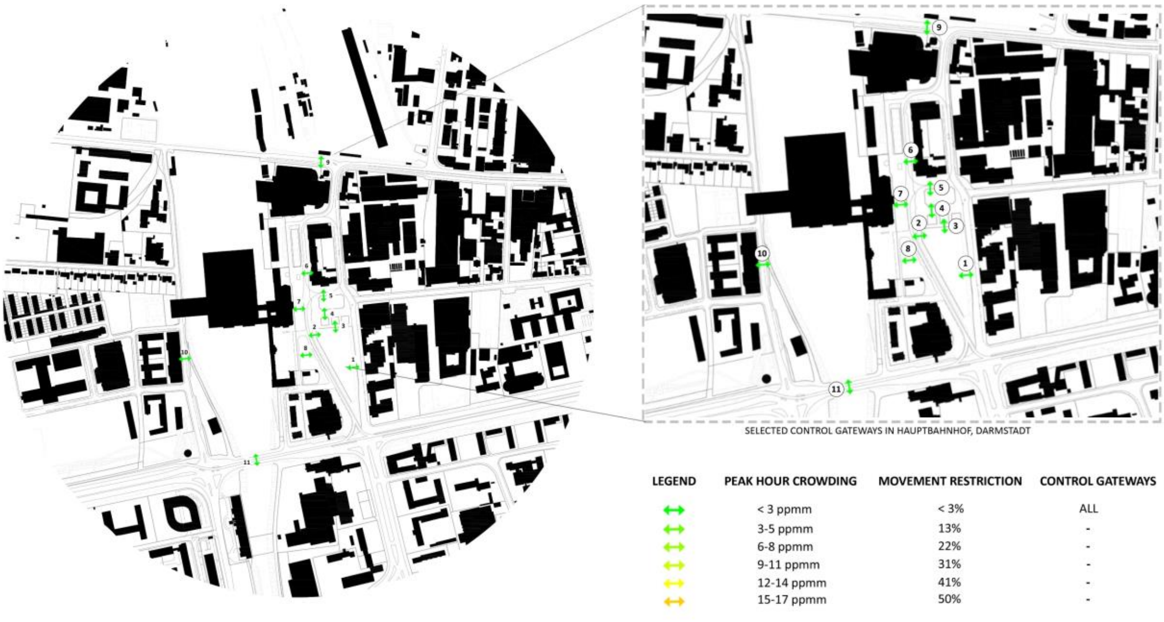


Figure 55: Peak hour crowding and movement restriction around Hauptbahnhof (1 sq. km.), Darmstadt

With respect to the peak hour crowding around the transit area of Hauptbahnhof, the maximum was recorded along the control gateway 7 with a measure of 2.01 ppmm, followed by 1.80 ppmm on the control gateway 10 through the street of Zweifalltorweg in the west. The selected control gateways within the Hauptbahnhof region recorded comfortable peak hour recording within 3 ppmm through a movement restriction of <3%. As compared to the residential area of Komponistenviertel, the crowding value fell within the similar range with least movement restriction with an average peak hour crowding of 0.83 ppmm, considering all of the control gateways.

Gateways:	1	2	3	4	5	6	7	8	9	10	11
Pedestrians	342	1086	1698	2136	564	360	348	102	576	180	540
Cyclists	120	372	186	342	246	84	0	54	66	390	498
URM	12	6	36	12	24	6	0	0	6	6	0
Baby strollers	18	42	12	78	12	0	6	0	12	6	6
Boards / Scooters	0	0	0	6	0	6	0	0	6	0	6
Four-wheelers	0	0	0	0	0	0	0	0	0	432	912
Two-wheelers	0	0	0	0	0	0	0	0	0	18	24
Total	462	1458	1884	2484	810	450	348	156	648	570	1044
Footway width (m)	3.1	20.74	5.95	13.66	6.085	14.78	2.1	5	5.45	4.4	10.9
ppm	149.03	70.30	316.64	181.84	133.11	30.45	165.71	31.20	118.90	129.55	95.78
ppmm	2.48	1.17	5.28	3.03	2.22	0.51	2.76	0.52	1.98	2.16	1.60

Table 12: Peak hour modal flows in selected control gateways around Luisenplatz, Darmstadt (where ppm = persons per metre and ppmm = persons per metre minute)

Eleven control gateways were selected around the pedestrian zone in city centre i.e. Luisenplatz excluding the gateways on Bismarckstrasse in the north and Schloßgrabenstrasse in the east, which included vehicular traffic (see Fig. 56). The two gateways included separate bicycle lane adjacent to the vehicular lanes and pedestrian pathways. The maximum peak hour flow of 2136 pedestrians were recorded on the control gateway 4, adjacent to Luisencenter in the west, followed by 1698 pedestrians in the east on control gateway 3 (see Table 12). With respect to the bicycle users, the maximum recorded was 498 at the peak hour on the control gateway 11 at the Schlossgrabenstrasse, followed by 390 cyclists in the north on Bismarckstrasse.

The higher NACH values on the Schlossgrabenstrasse and Bismarckstrasse correlated with the high on-site frequency values of the bicycle users. The availability of separate bicycle lanes ensured a higher level of safety as compared to Hauptbahnhof area or Komponistenviertel, where some of the streets with high NACH values and high frequency of bicycle users lacked separate bicycle lanes and shared the street section along with the motored traffic. With respect to the available footway widths in Luisenplatz, the overall mean value (i.e. 8.38 metres) was greater than the residential area of Komponistenviertel, which was similar to the transit area surrounding the main railway station i.e. Hauptbahnhof.

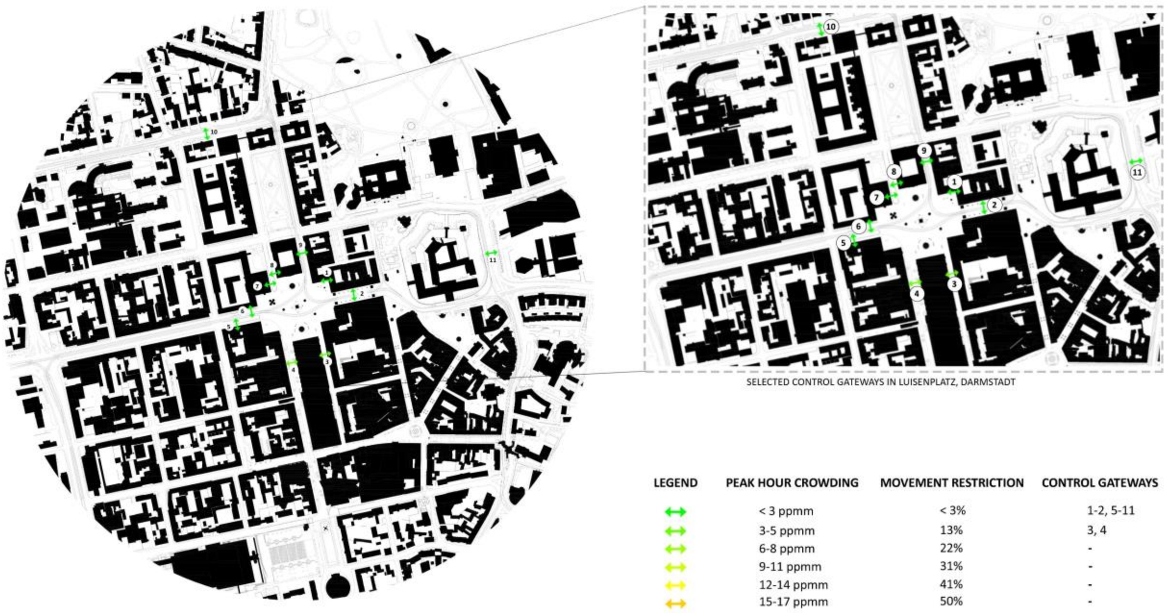


Figure 56: Peak hour crowding and movement restriction around Luisenplatz (1 sq. km.), Darmstadt

With respect to the crowding, the maximum value of 5.28 ppmm (showing a movement restriction between 13%-22%) was recorded on control gateway 3 falling on the street of Luisenstrasse in the east adjacent to the Luisencenter. This was followed by 3.03 ppmm, recorded with a movement restriction of 13% on control gateway 4 along the Wilhelminenstrasse in the west of the Luisencenter.

The overall peak hour crowding within the city centre recorded a mean value of 2.16 ppmm which is greater than the mean values of the other two urban areas within the pilot study. Majority of the control gateways fell within the peak hour crowding of 3 ppmm and a movement restriction of <3%. The two control gateways i.e. 3 and 4, around the Luisencenter recorded a higher movement restriction as compared to the other control gateways.

4.4 Initial diagnosis based on the performance measures

In order to have an overview of relative parameteric accessibility characteristic of areas in the pilot study, the selected urban areas are ranked through a comparative study. Post the completion of the pilot studies through an epistemological timeline with five performance measures, the multi-criteria decision analytic tool i.e. TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution), which bases the best measure to have the shortest distance (i.e. the Euclidean distance) from the ideal solution, is utilized. It also finds its application in project selection under land-use planning (Hwang & Yoon 1981).

Performance measures	Connectivity index (c)	Intelligibility (i)	PTAL (p)	NACH (n)	Crowding (cr)
Hauptbahnhof	1.46	0.54	30.38	0.71	0.83
Komponistenviertel	1.39	0.57	3.25	0.73	0.34
Luisenplatz	1.62	0.81	45.38	0.88	2.16
$\sqrt{[(x1)^2 + \dots (xn)^2]}$	2.59	1.13	54.71	1.35	2.34

Normalized Decision Matrix (NDM)

Performance measures	Connectivity index (c)	Intelligibility (i)	PTAL (p)	NACH (n)	Crowding (cr)
Hauptbahnhof	0.56	0.48	0.56	0.53	0.35
Komponistenviertel	0.54	0.51	0.06	0.54	0.15
Luisenplatz	0.63	0.72	0.83	0.65	0.92

Table 13: Normalized Decision Matrix of performance measures through selected urban environments

After the performance measures are normalized by $\sqrt{[(x1)^2 + \dots (xn)^2]}$ of every column 'x' (where n is the nth row), the weighted normalized decision matrix (in Table 13) is realized with equal distribution of weightage given to five parameters for the pilot study i.e. 0.20 (in Table 14). This weightage is subject to be altered with respect to the varied priorities of the people living in different urban areas. One of the possible ways for obtaining revised weightage for prioritization is through public perspective via survey outcomes (discussed in Chapter 6).

Weighted NDM

Performance measures	(c)	(i)	(p)	(n)	(cr)	E. distance from ideal best (eb)	E. distance from ideal least (el)	eb + el	Performance score (el/el+eb)	Rank
Hauptbahnhof	0.113	0.096	0.111	0.106	0.071	0.089	0.151	0.240	0.630	1
Komponistenviertel	0.107	0.101	0.012	0.108	0.029	0.163	0.156	0.319	0.490	3
Luisenplatz	0.125	0.144	0.166	0.131	0.185	0.156	0.164	0.320	0.513	2
Ideal (best) value	0.125	0.144	0.166	0.131	0.029					
Ideal (least) value	0.107	0.096	0.012	0.106	0.185					

Table 14: Performance Ranking of the selected urban areas based on performance measures

Hwang, C.L., and Yoon, K. (1981), Applications. In: Multiple Attribute Decision Making. Lecture Notes in Economics and Mathematical Systems, vol 186. Springer, Berlin, Heidelberg. https://doi.org/10.1007/978-3-642-48318-9_4

The performance ranking of the selected urban areas under pilot study, is based on the Euclidean distance under TOPSIS measure. It showcases the main transit area and the city centre i.e. Luisenplatz providing relatively higher level of multimodal accessibility under selected performance measures, followed by the residential area of Komponistenviertel. Prior to the consideration of crowding and movement restriction aspect, based on the remaining four performance measures, the city centre ranked higher in comparison to the other two urban areas. A relatively high pedestrian density with respect to the overall width of space available for movement in the city centre lead to decrease in its overall index value within the measure of TOPSIS. This intra-city pilot study starts to address the second research question through its case studies of different spatial configurations and typology.

Overall the outcome resists a part of the research hypothesis, which bases city centres to be more accessible but supports the aspect of it to be concentrated with better access to public transport (via PTAL). While the city centre had a higher frequency of pedestrians and cyclists, the crowding aspect (though within a comfortable range) influences its accessibility negatively. The data-driven outcome from the pilot study prioritizes the transit area to having a more accessible environment than the city centre, given its accessibility characteristics are utilized to its potential. Further urban studies in the cities of Frankfurt am Main and Offenbach am Main add to intra-city perspectives and initiate an inter-city parametric comparison.

4.5 Frankfurt am Main and its selected urban areas

Similar to the pilot study and the associated research timeline, the three urban areas in the city of Frankfurt am Main forming the Rhein-Main agglomeration were selected to study and understand their characteristics within the perspectives of the five identified performance measures (or parameters). These three urban areas (in Fig. 57) include spaces surrounding the city centre i.e. Hauptwache, which is the urban core of the city characterized by dense high street areas (including shopping plazas) situated north of the river Main adjacent to the old city; the main transit area i.e. Hauptbahnhof, which acts as an important terminal station for inter-city travel along with other public transport services for intra-city travel; and the residential area of Bornheim located within the observational boundaries similar to the pilot study in Darmstadt.

Figure 57: Figure Ground Map of area surrounding Frankfurt Hauptbahnhof (left), Bornheim (centre), and Hauptwache (right) within 1 sq. km. area

As discussed in the previous chapter, with the urban development plans like Frankfurt 2030+, the city of Frankfurt am Main prioritizes certain urban districts and spaces catering to the growing population. These include spaces like the city centre via Innenstadtkonzept, which focuses on streets and surrounding spaces identifying the dense traffic nature of neighbouring streets and making them less dense in the city centre; or the area surrounding the residential area of Bornheim, where quality of stay and more green spaces are prioritized, with less noise pollution through restricted motorways. With focus on active modes involving pedestrian and cycling pathways, along with improving public transport service connectivity in urban districts, there is a shift from the car-centric planning, and understanding the spatial configuration of urban areas to identify its potential to improve its accessibility (especially through active modes) would be beneficial for the people utilizing the space and the planning authorities.

4.6 Parametric diagnosis of selected urban areas in Frankfurt am Main

Within similar observational boundaries with respect to the pilot study, the selected urban areas in Frankfurt am Main were analysed through connectivity, intelligibility, NACH, PTAL, and crowding. The selected urban areas were mapped in accordance to the reconnaissance studies and analysed as follows:

4.6.1 Connectivity Index

The three selected urban areas in Frankfurt am Main were mapped based on their street networks within the observational area of one square kilometre covering links (including cul-de-sacs) and nodes (see Fig. 58). Similar to the pilot study mapping, the peripheral ends of the links which continued beyond the observational boundary of one square kilometre were not considered as dead ends or cul-de-sacs within the overall network system.

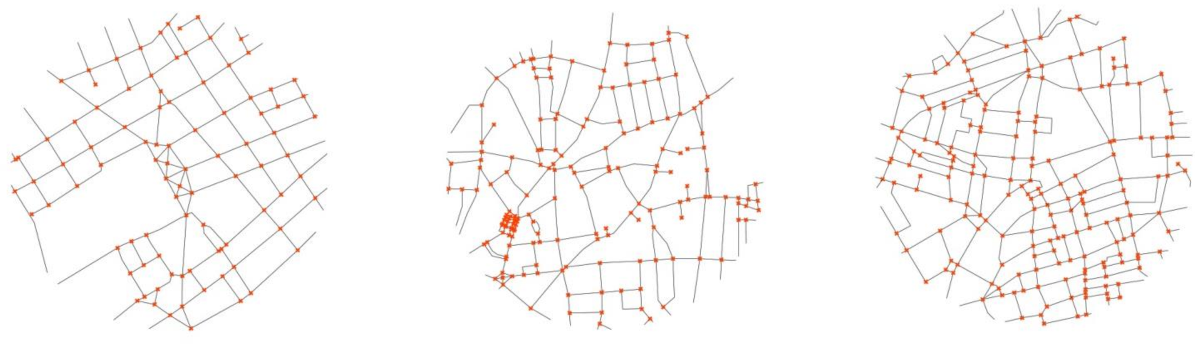


Figure 58: Node density mapping of the area surrounding Frankfurt Hauptbahnhof (left), Bornheim (centre), and Hauptwache (right) within 1 sq. km. area

With the terminal nature of the main railway station in Frankfurt i.e. Hauptbahnhof, the network surrounding Frankfurt Hauptbahnhof recorded high nodal density of 92 through a link density of 173 per sq. km. Major concentration of cul-de-sacs were observed in the north of Hauptbahnhof. Considering the residential area of Bornheim, higher nodal density of 167 per sq.km. was observed with a link density of 271 per sq.km. Similar to the pilot study, the residential area resulted in higher cul-de-sac density of 8 per sq. km. Majority of the cul-de-sacs were concentrated through the street of Berger Strasse which bisects the transit area in the east.

The area surrounding the city centre, i.e. Hauptwache, had the highest nodal density of 191 within the three selected urban areas in the city of Frankfurt, followed by link density of 331 per sq. km. Low cul-de-sac density, similar to that of Hauptbahnhof, was observed around the city centre showcasing less restriction through the freedom of movement. The three selected urban areas in Frankfurt am Main surpassed the minimum link-node ratio of 1.4 with greater margins as compared to the pilot study in Darmstadt, with the transit area recording highest link-node ratio of 1.88, followed by 1.73 in the city centre i.e. Hauptwache and 1.62 in the residential area of Bornheim. Although the residential area recoded low link-node ratio amongst the selected urban areas in Frankfurt, it was in close proximity to that of the city centre in Darmstadt which recorded the highest in the pilot study. Similar to the pilot study, the selected areas showed connected node ratio greater than 0.7. This inversely affects the walkable network through higher link-node ratios. Within Frankfurt, the density of links and nodes supported a more walkable network around the main railway station and the city centre i.e. Hauptbahnhof and Hauptwache respectively, as compared to the selected residential area of Bornheim in the north. This denotes that users have more choices to navigate around the Hauptbahnhof, as compared to the city centre in the east and the selected residential area. The spatial configuration with grid-iron pattern of blocks around the main railway station resulted in less density of cul-de-sacs in comparison to the network of spaces forming the city centre and the residential area. The terminal nature of the Frankfurt Hauptbahnhof influenced the network of links and nodes, leading to more frequency of streets and junctions as compared to the area surrounding Darmstadt Hauptbahnhof (where the nature of the rail tracks is continuous in north-south direction) and neighbouring commercial and industrial area which reduced the overall frequency of links and nodes supporting short-distance mobility in the urban area.

4.6.2 Intelligibility

Similar to the pilot study, the three selected urban areas in Frankfurt am Main were axially mapped (see Fig. 59) and analysed through the DepthmapX software following the Space Syntax theory. The axial lines on different planes, which were not intersecting directly (for example, the passageway underneath bridges or tunnels) with one another were mapped and de-linked manually in order to have correct representation of network showing integration on different steps (one for connectivity, three for local integration and 'n' for global integration). Following maps were generated post spatial analysis of the three areas through axial integration on global level:

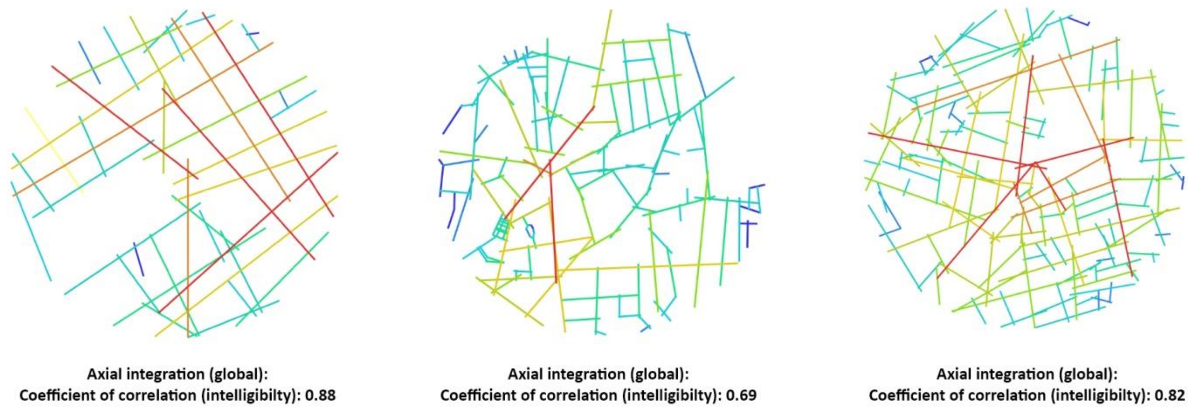


Figure 59: Global axial integration and relative intelligibility coefficient of area surrounding Frankfurt Hauptbahnhof (left), Bornheim (centre) and Hauptwache (right) within 1 sq. km.

The axial network of area surrounding Frankfurt Hauptbahnhof shows high integration (global) along the streets of Gutleutstrasse (adjacent to Baseler Platz) in south (see Fig. 25 and 59), Moselstrasse in east and Friedrich-Ebert-Anlage in north. Moselstrasse also showcased high connectivity, followed by

Niddastrasse and Am Hauptbahnhof. The high positive correlation coefficient of 0.88 (in Fig. 60) reflects high intelligibility of space around the main railway station. The row of multiple axial lines with strong integration value within the surrounding area of Hauptbahnhof assists in contributing towards the intelligible characteristic through its spatial configuration.

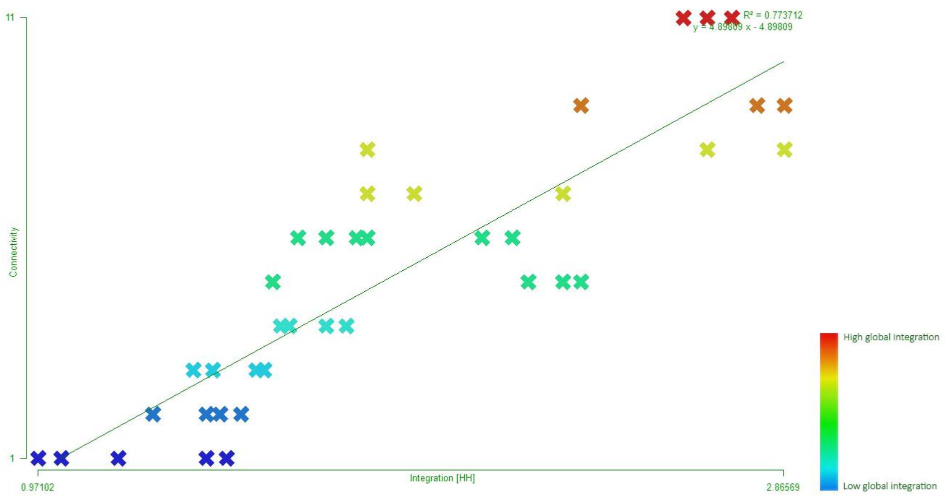


Figure 60: Scatterplot: Connectivity (r=1) vs Global Integration (r=n) of axial lines surrounding Frankfurt Hauptbahnhof [1 sq. km.]

With respect to the residential area of Bornheim in north-west of the city centre, the high integrated streets of Sechbacher Landstrasse (see Fig. 27 and 59) and Rendelstrasse were in proximity and were observed near the core of the network. The overall axial network of Bornheim showed comparatively lower intelligibility characteristic with a correlation coefficient of 0.69 (in Fig. 61) as compared to Hauptbahnhof. The high number of cul-de-sacs reduced the overall connectivity of the network as compared to the other urban areas. The street with highest connectivity i.e. Nebelstrasse, didn't correspond to high global integration.

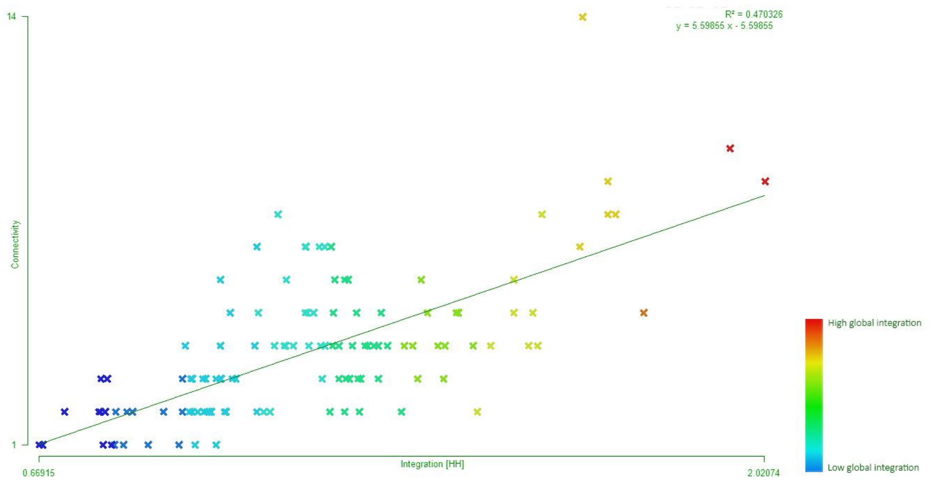


Figure 61: Scatterplot: Connectivity (r=1) vs Global Integration (r=n) of axial lines surrounding Bornheim [1 sq. km.]

The city centre i.e. Hauptwache showcased high intelligibility through its high positive correlation coefficient of 0.82 (in Fig. 62), with high global integrated streets through Kaiserstrasse, Bockenheimer

Strasse, Zeil (in Fig. 23 and 59) and Hassengasse. The streets with high number of immediate connected streets, showed high correlation to global integration and indicated a navigable environment.

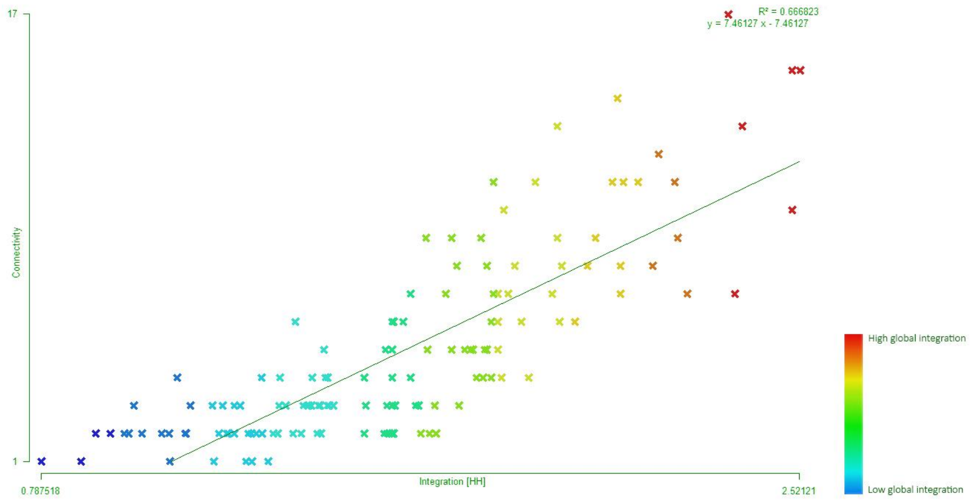


Figure 62: Scatterplot: Connectivity (r=1) vs Global Integration (r=n) of axial lines surrounding Hauptwache [1 sq. km.]

Within the selected urban areas in Frankfurt am Main, the area surrounding main railway station i.e. Hauptbahnhof showed high intelligibility characteristic followed by the city centre i.e. Hauptwache and the residential area of Bornheim respectively. The uniform closeness of streets to their connectivity and global axial integration characteristic, along with the arrangement of highly integrated axial lines influenced how navigable the overall street network was for a person to locate themselves.

4.6.3 Public Transport Accessibility Level

Similar to the pilot study, the PTAL index for the selected urban areas in Frankfurt are recorded for the transportation modes of buses and tram services within 640 metres of radius, and train services within the maximum radius of 960 metres. The data collection for every service station was recorded within the same time interval of morning peak hours between 08:15 - 09:15, during the weekdays in the month of January 2021. In major contrast to the pilot study in Darmstadt, where the mode of public transport services differed, all the three selected urban areas in Frankfurt am Main had three modal services of trams, buses and trains. The large network of trams and trains in Frankfurt am Main, contributed to a better choice of public transport modes in comparison to the city of Darmstadt within the Rhein-Main urban agglomeration.

With respect to Frankfurt am Main Hauptbahnhof, the farthest public transport service station with different route of travel was located approximately 945 metres from the point of interest in Willy-Brandt Platz in the east from the main railway station. Diverse routes of buses, trams and trains were recorded with maximum peak-hour frequency of 13 by U-Bahn (i.e. U4) within the observed time interval (see Table 15). The tram service stations were located in proximity to the entrance of the main railway station building and required less travel time to reach the service stop as compared to other public transport modes.

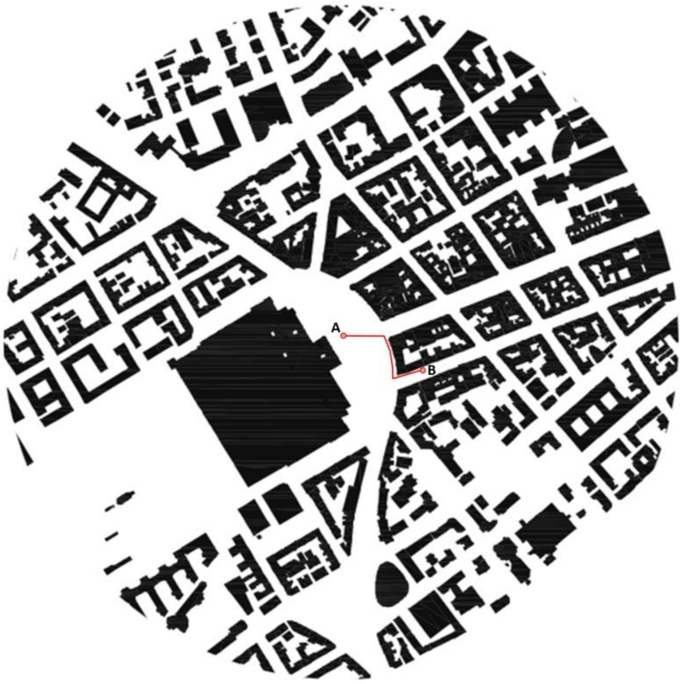


Figure 63: Shortest pedestrian access between the point of interest A at Hauptbahnhof and B at Münchener Strasse service station

The PTAL indexes for respective service stations and modes in the selected transit area surrounding Frankfurt Hauptbahnhof were recorded as follows:

Site	Service	Stop	Route	Distance	Frequency	Weight	Walktime	SWT	Access	EDF	Index
Frankfurt Hbf	Bus	Hauptbahnhof	33	75	6	0.5	0.94	7.00	7.94	3.78	1.89
			37	75	7	0.5	0.94	6.29	7.22	4.15	2.08
			46	75	8	1	0.94	5.75	6.69	4.49	4.49
			64	75	3	0.5	0.94	12.00	12.94	2.32	1.16
	Tram	Hauptbahnhof	11	50	8	0.5	0.63	4.50	5.13	5.85	2.93
			14	50	6	0.5	0.63	5.75	6.38	4.71	2.35
			16	50	6	0.5	0.63	5.75	6.38	4.71	2.35
			17	50	8	0.5	0.63	4.50	5.13	5.85	2.93
			21	50	9	1	0.63	4.08	4.71	6.37	6.37
		Münchener Str.	12	180	6	0.5	2.25	5.75	8.00	3.75	1.88
			18	180	2	0.5	2.25	15.75	18.00	1.67	0.83
	Train	Hauptbahnhof	RB10	120	1	0.5	1.50	30.75	32.25	0.93	0.47
			RB12	120	2	0.5	1.50	15.75	17.25	1.74	0.87
			RB15	120	1	0.5	1.50	30.75	32.25	0.93	0.47
			RB22	120	1	0.5	1.50	30.75	32.25	0.93	0.47
			RB51	120	1	0.5	1.50	30.75	32.25	0.93	0.47
			RB61	120	1	0.5	1.50	30.75	32.25	0.93	0.47
			RB67	120	1	0.5	1.50	30.75	32.25	0.93	0.47

	RB68	120	1	0.5	1.50	30.75	32.25	0.93	0.47
	RE14	120	1	0.5	1.50	30.75	32.25	0.93	0.47
	RE2	120	1	0.5	1.50	30.75	32.25	0.93	0.47
	RE5	120	1	0.5	1.50	30.75	32.25	0.93	0.47
	RE50	120	1	0.5	1.50	30.75	32.25	0.93	0.47
	RE55	120	1	0.5	1.50	30.75	32.25	0.93	0.47
	RE60	120	1	0.5	1.50	30.75	32.25	0.93	0.47
	RE70	120	1	0.5	1.50	30.75	32.25	0.93	0.47
	RE85	120	1	0.5	1.50	30.75	32.25	0.93	0.47
	S1	290	2	0.5	3.63	15.75	19.38	1.55	0.77
	S2	290	4	0.5	3.63	8.25	11.88	2.53	1.26
	S5	290	2	0.5	3.63	15.75	19.38	1.55	0.77
	S6	290	2	0.5	3.63	15.75	19.38	1.55	0.77
	S7	290	2	0.5	3.63	15.75	19.38	1.55	0.77
	S8	290	2	0.5	3.63	15.75	19.38	1.55	0.77
	S9	290	2	0.5	3.63	15.75	19.38	1.55	0.77
	S3	290	2	0.5	3.63	15.75	19.38	1.55	0.77
	S4	290	2	0.5	3.63	15.75	19.38	1.55	0.77
	U4	160	13	1	2.00	3.06	5.06	5.93	5.93
	U5	160	12	0.5	2.00	3.25	5.25	5.71	2.86
	ICE23	120	1	0.5	1.50	30.75	32.25	0.93	0.47
	ICE1656	120	1	0.5	1.50	30.75	32.25	0.93	0.47
	ICE275	120	1	0.5	1.50	30.75	32.25	0.93	0.47
	ICE1672	120	1	0.5	1.50	30.75	32.25	0.93	0.47
	ICE527	120	1	0.5	1.50	30.75	32.25	0.93	0.47
	ICE9556	120	1	0.5	1.50	30.75	32.25	0.93	0.47
	ICE772	120	1	0.5	1.50	30.75	32.25	0.93	0.47
	ICE935	120	1	0.5	1.50	30.75	32.25	0.93	0.47
	ICE571	120	1	0.5	1.50	30.75	32.25	0.93	0.47
	ICE820	120	1	0.5	1.50	30.75	32.25	0.93	0.47
	ICE374	120	1	0.5	1.50	30.75	32.25	0.93	0.47
Willy-Brandt Platz	U1	945	7	0.5	11.81	5.04	16.85	1.78	0.89
	U2	945	8	0.5	11.81	4.50	16.31	1.84	0.92
	U3	945	4	0.5	11.81	8.25	20.06	1.50	0.75
	U8	945	4	0.5	11.81	8.25	20.06	1.50	0.75
								PTAL:	61.76

Table 15: PTAL for area surrounding Frankfurt Hauptbahnhof through different public transport services

The overall PTAL value of 61.76 fell within the highest index range beyond 40.00+, depicting an excellent access value under group 6b. The major contribution to the overall PTAL value (i.e. ~53%) is given by train services through a combined value of 32.51, followed by 19.64 by the mode of trams (contributing 32%) and the remaining 9.61 (i.e. 15%) index value through bus services. The high frequency of U-Bahn and S-Bahn services along with proximal stations of trams and buses contribute majorly towards the high PTAL value for the area surrounding of Frankfurt Hauptbahnhof. The PTAL index contribution by the train services in Frankfurt Hauptbahnhof was itself comparable to the overall PTAL index in the pilot study.

The selected residential area in Frankfurt i.e. Bornheim is served by trams, buses and train services, with farthest service route located approximately 745 metres from the point of origin. The residential area also had more service stops with different travel routes as compared to the city's Hauptbahnhof. Similar to Frankfurt Hauptbahnhof, the train service of U-Bahn (i.e. U4) dominated with a peak hour frequency of 13 (see Table 16). To use the bus services, it required less travel time to reach the service station as compared to other public transport modes.

Figure 64: Shortest pedestrian access between the point of interest A in Bornheim and B at Prüfling service station

The PTAL indexes for respective service stations and modes within the residential area of Bornheim were recorded as follows:

Site	Service	Stop	Route	Distance	Frequency	Weight	Walktime	SWT	Access	EDF	Index
Bornheim	Bus	Weidenbornstrasse	38	270	12	1	3.38	4.50	7.88	3.81	3.81
			M43	270	12	0.5	3.38	4.50	7.88	3.81	1.90
		Usinger Str.	M34	485	8	0.5	6.06	5.75	11.81	2.54	1.27
		Prüfling	103	505	2	0.5	6.31	17.00	23.31	1.29	0.64
	Tram	Bornheim Mitte	12	685	6	0.5	8.56	5.75	14.31	2.10	1.05
		Ernst May Platz	14	745	7	1	9.31	5.04	14.35	2.09	2.09
	Train	Seckbacher Landstr.	U4	415	13	1	5.19	3.06	8.25	3.64	3.64
										PTAL:	14.40

Table 16: PTAL for the residential area of Bornheim through different public transport services

The overall PTAL value for the residential area of Bornheim was recorded as 14.40, which fell within the index range of 10.01-15.00 under group 3 (i.e. in between worst and excellent access levels). The bus services contributed the maximum share of 53% for the overall PTAL value, with an index of 7.63. This was followed by similar index by trams and train services with values of 3.14 and 3.64 respectively. The availability of different public transport options along with high frequency of bus services, with less travel time to the service stop resulted in higher PTAL value which was better than the residential area in the pilot study.

Similar to the other urban areas for the study, the city centre i.e. Hauptwache is also served by the three modes of trams, buses and trains within the respective observation boundaries. The farthest route was located at the service stop of Alte Oper in the west (at approximately 640 metres). With respect to the peak hour frequency of services, the U-Bahn service recorded the highest frequency of 12 (see Table 17). In comparison to the selected urban areas, while the tram service stops were in close proximity in Hauptbahnhof, the bus service stops were closer in Bornheim from their respective points of origin. In the city centre, the train services were closer and required less travel time to reach the stop. The proximity of service stations plays a crucial role in providing access towards the public transport services, and can become an important aspect to attract active mode of transport in the overall mobility culture of the city.

Figure 65: Shortest pedestrian access between the point of interest A in Hauptwache and B at Römer/Paulskirche service station

The PTAL indexes for respective service stations and modes within the area surrounding city centre i.e. Hauptwache were recorded as follows:

Site	Service	Stop	Route	Distance	Frequency	Weight	Walktime	SWT	Access	EDF	Index
Hauptwache	Bus	Eschenheimer Tor	M36	385	6	0.5	4.81	7.00	11.81	2.54	1.27
		Alte Oper	64	640	4	0.5	8.00	9.50	17.50	1.71	0.86
		Konstablerwache	30	625	7	1	7.81	6.29	14.10	2.13	2.13

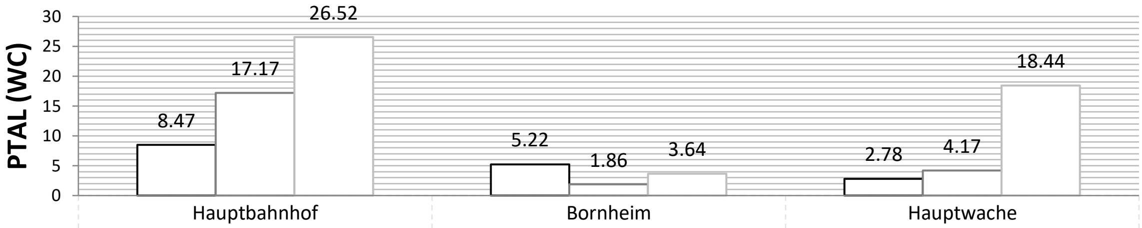
Tram	Römer/Paulskirche	11	440	8	1	5.50	4.50	10.00	3.00	3.00
		12	440	6	0.5	5.50	5.75	11.25	2.67	1.33
		14	440	6	0.5	5.50	5.75	11.25	2.67	1.33
		18	440	2	0.5	5.50	15.75	21.25	1.41	0.71
Train	Hauptwache	S1	210	3	0.5	2.63	10.75	13.38	2.24	1.12
		S2	210	4	0.5	2.63	8.25	10.88	2.76	1.38
		S3	210	2	0.5	2.63	15.75	18.38	1.63	0.82
		S4	210	2	0.5	2.63	15.75	18.38	1.63	0.82
		S5	210	4	0.5	2.63	8.25	10.88	2.76	1.38
		S6	210	2	0.5	2.63	15.75	18.38	1.63	0.82
		S8	210	2	0.5	2.63	15.75	18.38	1.63	0.82
		S9	210	2	0.5	2.63	15.75	18.38	1.63	0.82
		U1	185	6	0.5	2.31	5.75	8.06	3.72	1.86
		U2	185	8	0.5	2.31	4.50	6.81	4.40	2.20
		U3	185	4	0.5	2.31	8.25	10.56	2.84	1.42
		U6	185	9	0.5	2.31	4.08	6.40	4.69	2.35
		U7	185	8	0.5	2.31	4.50	6.81	4.40	2.20
		U8	185	6	0.5	2.31	5.75	8.06	3.72	1.86
	Konstablerwache	U4	470	12	1	5.88	3.25	9.13	3.29	3.29
		U5	470	12	0.5	5.88	3.25	9.13	3.29	1.64
									PTAL:	35.41

Table 17: PTAL for the area surrounding Hauptwache through different public transport services

The overall PTAL value for the city centre in Frankfurt was recorded as 35.41, which fell within the good access range of 25.01-40.00 under group 6a (i.e. near best PTAL range). The train services contributed towards the maximum share of 70% of the overall PTAL, with an index value of 24.78. This was followed by tram services with an index value of 6.37 (i.e. 18% of the overall PTAL) and bus services with an index value of 4.25 (i.e. 12% of the overall PTAL value). The bus and tram service stations were located at a much farther distance in comparison to the underground train services from the central landmark of the city centre, which had an impact on the overall index values and led to comparatively less contribution towards the accessibility index as compared to train services. While the city centre in the large-sized city of Frankfurt showed a good access to the means of public transport, the city centre in the city of Darmstadt showed a better range of PTAL index being contributed by tram and bus services, while it did not have availability of train services within the immediate observation boundaries. This reflects how the availability of multiple public transport modes and the size of the city does not always correspond towards the higher range of access levels, which resists part of the research hypothesis.

4.6.3.1 Added perspective through reduced mobility

Similar to the pilot study in Darmstadt, the PTAL index for the selected three urban areas in Frankfurt am Main was revised to reflect the perspective of users with reduced mobility. This assists in understanding how urban areas and spaces with low (or reduced) accessibility levels require priority with improved access to public transport based on the focus group's slow speed of movement to reach their desired destinations. The revised indexes for the three selected areas within the study in Frankfurt can be observed as follows:



	Hauptbahnhof	Bornheim	Hauptwache
Bus	8.47	5.22	2.78
Tram	17.17	1.86	4.17
Train	26.52	3.64	18.44

☐Bus ☐Tram ☐Train

Table 18: Revised PTAL for selected urban areas in Frankfurt am Main focusing on users with reduced mobility (i.e. wheelchair users)

With respect to the revised indexes, there is a 16% decrease in the index value of area surrounding main transit area, 36% decrease in the index value of the residential area in Bornheim and 28% decrease in the index value of the area surrounding the city centre i.e. Hauptwache (see Table 18). The revised PTAL group range for the area surrounding main transit station i.e. Hauptbahnhof and the city centre remained the same, but with respect to residential area, it dropped to a lower access group of 2 i.e. within the range of 5.01 - 10.00. Similar to the pilot study, a major drop with respect to the residential area portrays the perspective of how revised index fares with intervention catering to a user-group with reduced mobility.

4.6.4 NACH

The axial network of Frankfurt and its three selected urban areas were axially mapped and later converted into segment maps on DepthmapX platform, showcasing the direct bicycle routes through Space Syntax attribute of NACH. The analysis, similar to pilot study, varies through two varying radii i.e. 565m (~1 sq. km) for the selected three urban areas and 2500m for the overall city as follows:

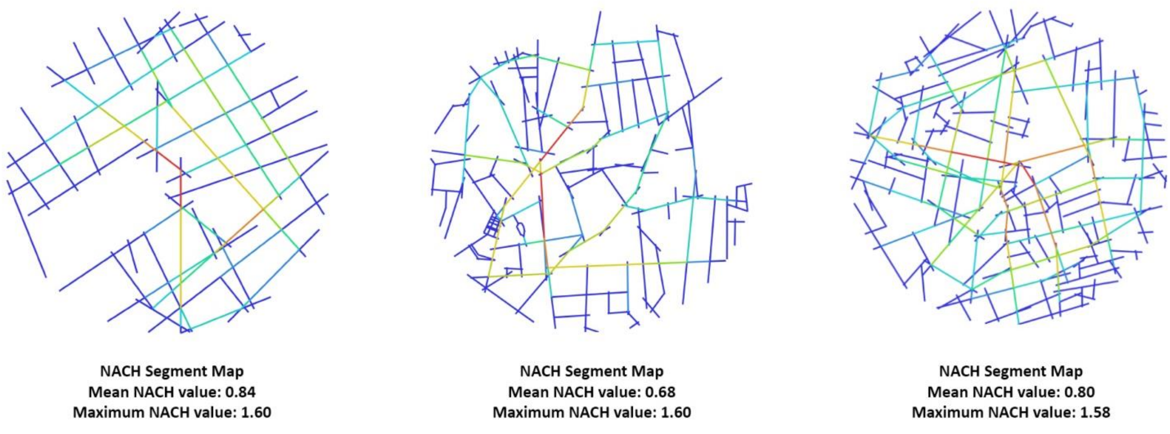


Figure 66: Segment maps showing normalisation of angular choice through area surrounding Frankfurt Hauptbahnhof (left), Bornheim (centre) and Hauptwache (right) within the limited boundary of 1 sq. km.

Small scale perspective

With respect to the area surrounding the main railway station i.e. Hauptbahnhof, the overall segments contributed towards a mean NACH value of 0.84 within the 1 sq. km. area with a maximum value of 1.60 on the streets of Am Hauptbahnhof at the core of the network. Most of the potential direct routes for bicycles were concentrated in the east facing the main entrance of Hauptbahnhof, including the streets of Gutleutstrasse, Düsseldorfer strasse and Moselstrasse. The residential area of Bornheim recorded a low mean NACH value of 0.68 with a similar maximum value of 1.60 on the Rendeler strasse. The streets with high potential for direct bicycle routes included Seckbacher Landstrasse towards north followed by Löwengasse street moving in east-west direction. Within the area surrounding the city centre i.e. Hauptwache, the overall segment network recorded a mean NACH value of 0.80 (in Fig. 66), with a maximum value of 1.58 falling along the streets of Zeil in the central core of the network. Major streets branching from the Zeil (in Fig. 66 and 23) area responded to high potential of direct routes, including Grosse Bockenheimer strasse, Neue Kräme, Hasengasse and more. Though the city centre showed network of high NACH valued streets, the area includes a pedestrian zone which gives pedestrians a higher priority and cyclists are obliged to cycle on lower speeds. This allows the focus to shift towards the set of segments which show high NACH characteristic and do not fall within the pedestrian zone, for planning bicycle pathways.

Considering the frequency of segments having their NACH value beyond 1.20, lowest number accounted around Hauptbahnhof with 116 segments observed, followed by 164 segments in the residential area of Bornheim. The city centre recorded the highest number of segments showing NACH values greater than 1.20 value i.e. 313. The areas indicate potential for direct bicycle routes, with Hauptbahnhof and Hauptwache showing concentration of high NACH segments in the central core of the network whereas the residential area shows a shift towards the west with respect to the central core (in Fig. 66). Similar to the pilot study, the area surrounding the city centre showed network of streets having higher frequency of direct routes for cyclists as compared to the residential or main transit station area within Frankfurt am Main. Priority towards having dedicated bicycle routes among the potential segments would assist the short-distance mobility aspect through improved bicycle accessibility.

Large scale perspective

In order to prioritize potential bicycle routes through a long-term perspective, irrespective of the selected urban areas and utilizing daily cycling trip boundaries, a larger radius of 2500m was taken into consideration (see Fig. 67) to digitize the map through a network of axial lines (which was later converted into segment network).

Within the segment network, highest NACH value recorded was 1.5968 (~1.6) along the street segment of Bockenheimer Landstrasse, leading towards Alte Oper (i.e. Opera House) (in Fig. 67 and 23). The high NACH values around the city centre i.e. Hauptwache in the north exhibit higher potential, though the area is currently a pedestrian zone in which cars are banned and cyclists are obliged to dismount from the bikes. The network also favours the two bridges i.e. Untermainbrücke and Alte Brücke, connecting the northern urban districts to the southern part of the city (for e.g. Brückenviertel and Sachsenhausen) through the river Main. The analysed segments show a range of potential direct cycling routes interconnected through a series of rings surrounding the city centre and run in the east-west direction. The radial routes showcase the priority to be given towards dedicated bicycle routes focusing on short-distance mobility and would enhance ease of movement for the bicyclists, given the slope of their pathways lies within 6-10%. The Hauptbahnhof street junction through Düsseldorfer strasse also acts as an important crossing for cyclists, which connects the city centre in the east and extends to the bridge of Friedenbrücke, towards the west of neighbouring Untermainbrücke bridge. The network of streets with high NACH value also favour the federal highway i.e. Bundesstrasse 8 (B8) towards the north of the city which runs in east-west direction.

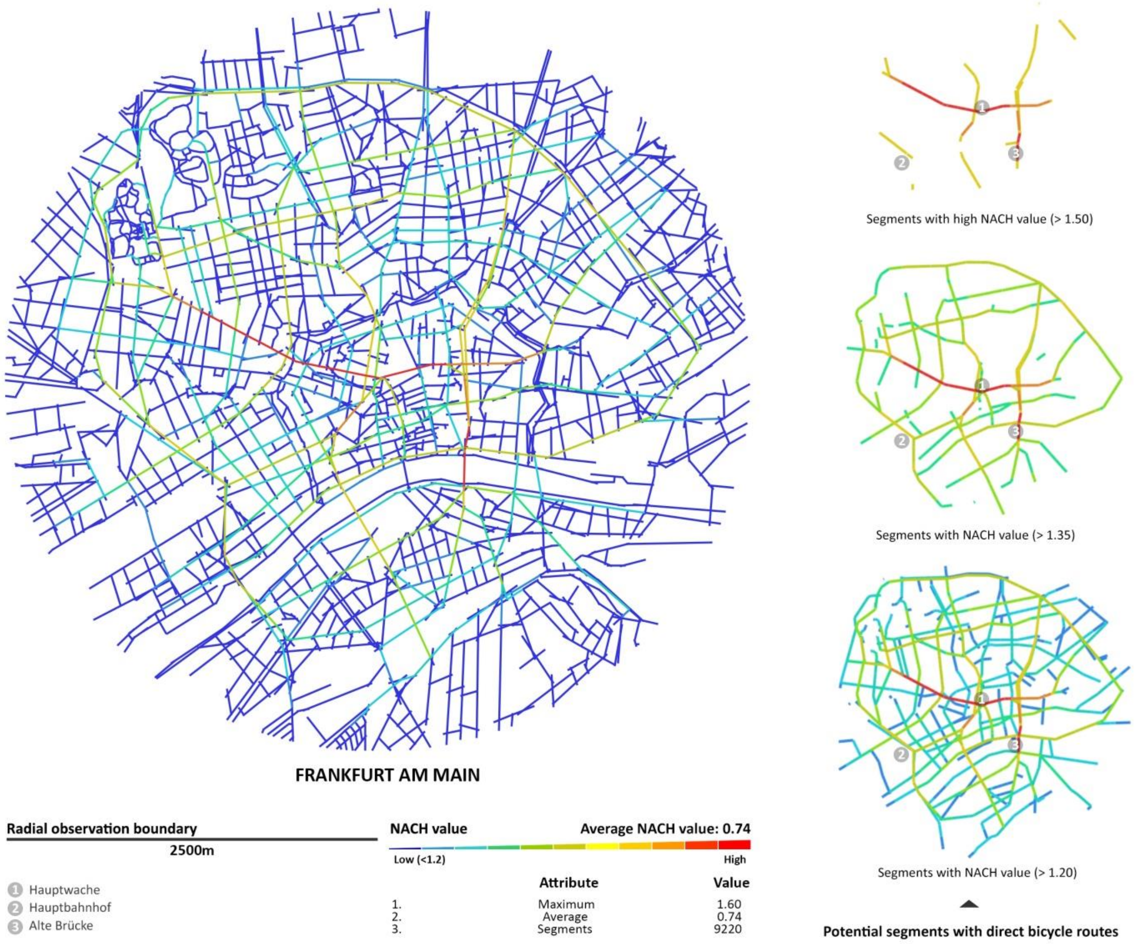


Figure 67: Segment maps showing normalisation of angular choice (NACH) through Frankfurt am Main within an observational radius of 2500m from the city centre i.e. Hauptwache.

With respect to the small-scale perspective of analysed segments through selected urban areas, giving priority to segments having NACH value greater than 1.20 (within 2500m observation area) would assist in taking the initial step of providing primary set of dedicated bicycle lanes (if not present on-site) followed by secondary segments having high values within the small-scale boundary (i.e. 1 sq.km). Considering both perspectives, a set of similar segments showcased high NACH values through varied observation radii, which assists in long-term planning including dedicating routes for bicycle pathways which would be helpful for inter-and intra-city cycling connectivity.

4.6.5 Crowding and movement restriction

The pedestrian and the other user-group data were collected on the designated timelines, similar to the pilot study, based on the different typology of urban areas. The city centre area around Hauptwache fell within the 'High Street' category as majority of streets surrounding the place included retail shops and markets; hence the data was recorded during the recommended period of 14:00-18:00 hours on weekdays and weekends (Tuesday - Thursday, Saturday). The data for the 'residential' area of Bornheim was recorded between the recommended time period of 14:00-18:00 during weekdays (Tuesday - Thursday) and 09:00-16:00 on Saturdays. The data collection for area surrounding Hauptbahnhof, being the main transit area for inter-and-intra city travel, was undertaken within the timeline of 08:00-10:00 and 16:00-18:00 on weekdays (Tuesday - Thursday).

Overall 15 control gateways were selected throughout the residential area of Bornheim (see Fig. 68). Similar to the pilot study in Darmstadt, the residential area recorded least mean peak hour crowding within the selected three case study areas in the city. The available footway widths were measured (see Appendix) with respect to each control gateway, and buffer widths were taken into consideration with respect to the street elements and immediate environment. Contrary to the residential area in the pilot study, Bornheim had wide mean width of pathway for pedestrians and cyclists among selected gateways which assists in low movement restriction. Majority of streets had space for car parking and separate pedestrian pathways.

The peak hour flows for the pedestrians, cyclists and vehicles within the selected control gateways were recorded, with sub-categories of users with reduced mobility (i.e. wheelchair users, walkers etc) and baby strollers, under pedestrian category along with users with electronic (or manual) scooter and boards (i.e. longboards or skateboards), four-wheeler and two-wheeler automotive vehicles (under non-active mode of transport), as follows:

Gateways:	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Pedestrians	186	192	456	198	492	126	246	162	66	84	90	306	30	60	216
Cyclists	42	108	168	84	210	96	132	48	36	150	18	270	18	156	186
URM	0	6	6	6	6	6	6	0	0	6	0	0	0	0	0
Baby strollers	12	6	6	6	12	0	6	6	0	0	0	12	0	0	12
Boards / Scooters	0	0	0	0	0	0	6	6	0	0	0	12	0	0	12
Four-wheelers	108	24	384	48	66	60	186	48	42	102	18	822	450	162	342
Two-wheelers	6	0	30	6	24	6	24	6	0	6	0	54	6	0	12
Total	228	300	624	282	702	222	384	216	102	234	108	588	48	216	414
Footway width (m)	7.55	7.53	12.2	2.7	4.9	3.6	3.88	3.4	2.53	6.96	5.3	7.23	2.16	2.97	5.75
ppm	30.20	39.84	51.15	104.44	143.27	61.67	98.97	63.53	40.32	33.62	20.38	81.33	22.22	72.73	72.00
ppmm	0.50	0.66	0.85	1.74	2.39	1.03	1.65	1.06	0.67	0.56	0.34	1.36	0.37	1.21	1.20

Table 19: Peak hour frequency and associated variables with respect to selected gateways in the residential area of Bornheim in Frankfurt am Main (where ppm = persons per metre and ppmm = persons per metre minute)

The maximum peak hour pedestrian frequency of 492 was recorded on the street of Berger Strasse in the south (i.e. Gateway 5), followed by Neebstrasse adjacent in the west (i.e. Gateway 3). With respect to the cyclists, the street of Seckbacher-Landstrasse in the north recorded the highest frequency of 270 (i.e. Gateway 12). The same street was also dominated by cars and two-wheelers, reaching maximum peak hour frequency of 822 (approximately three times that of the observed frequency of cyclists) and 54 respectively (see Table 19). Considering the selected gateways, the average pathway for active-modes was around 5.25 metres in the residential area. With respect to the residential area of Komponistenviertel in Darmstadt, Bornheim had more people using the e-scooter in majority of the selected street gateways which acknowledges the rising number of e-scooters in the city of Frankfurt am Main, even in the residential area away from the city centre.

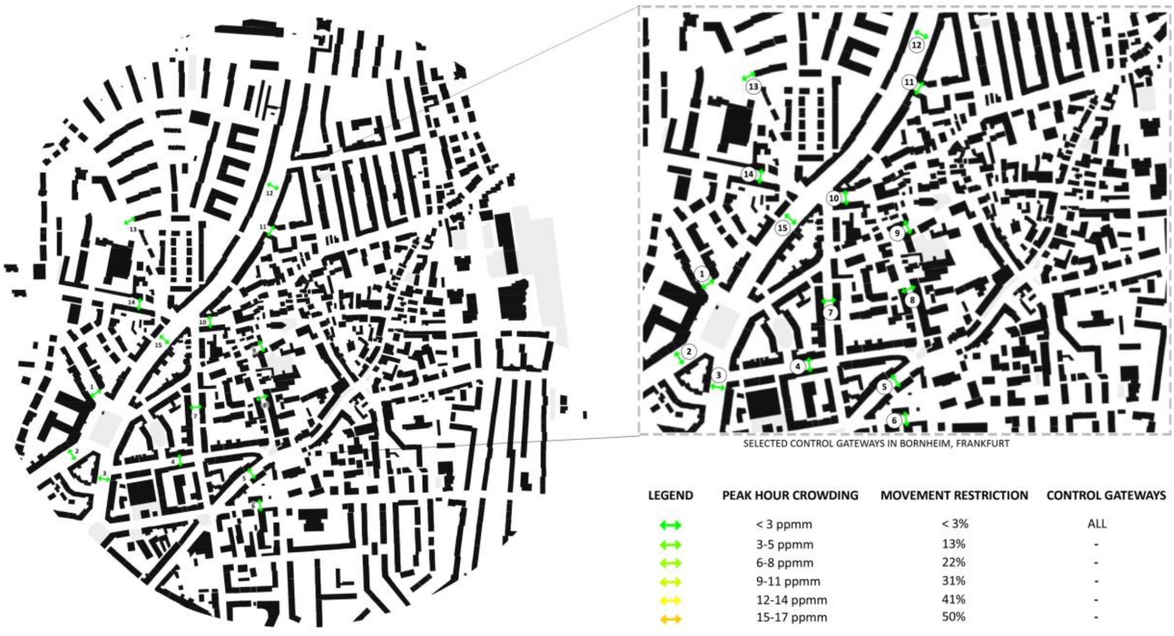


Figure 68: Peak hour crowding and movement restriction around residential area of Bornheim in Frankfurt am Main

The peak hour crowding was observed maximum at 2.39 ppmm (in Table 19), which fell within the least peak hour crowding category. This also led to all streets recording movement restriction <3% (in Fig. 68), showcasing a comfortable range of movement on the streets. The overall mean peak hour crowding for the selected gateways was 1.04 ppmm, which is approximately thrice as that of the residential area in Darmstadt (compared to a larger city i.e. Frankfurt).

Gateways:	1	2	3	4	5	6	7	8	9	10	11	12	13
Pedestrians	714	306	528	312	648	306	942	354	390	486	204	156	294
Cyclists	90	42	168	12	48	276	168	84	54	144	48	48	156
URM	6	0	0	0	6	0	18	0	0	6	0	0	0
Baby strollers	6	6	6	0	12	6	12	0	0	6	0	0	6
Boards / Scooters	12	12	18	0	6	6	6	6	0	18	0	0	24
Four-wheelers	306	156	2106	12	42	114	66	324	546	660	204	48	882
Two-wheelers	6	0	18	0	0	12	6	6	18	12	6	0	12
Total	816	360	714	324	702	588	1116	444	444	648	252	204	474
Footway width	8.59	6.05	5.91	5.71	2.85	5.25	7.89	4.25	4.9	8.03	4.97	2.76	9.84
ppm	94.99	59.50	120.81	56.74	246.32	112.00	141.44	104.47	90.61	80.70	50.70	73.91	48.17
ppmm	1.58	0.99	2.01	0.95	4.11	1.87	2.36	1.74	1.51	1.34	0.85	1.23	0.80

Table 20: Peak hour frequency and associated variables with respect to selected gateways surrounding Hauptbahnhof in Frankfurt am Main (where ppm = persons per metre and ppmm = persons per metre minute)

With respect to the transit area, 13 control gateways were selected for the peak hour data collection (in Fig. 69). Kaiserstrasse (i.e. Gateway 7), located opposite to the main entrance of Hauptbahnhof in the east, recorded maximum frequency of 942 pedestrians and Moselstrasse (i.e. Gateway 6) recorded high frequency of 276 cyclists. With a network of non-continuous cycle lanes, the streets had high frequency of cyclists around Hauptbahnhof. While Kaiserstrasse acts as a cul-de-sac for four-wheeler and two-wheeler traffic, it recorded frequent presence of users with reduced mobility, and baby strollers during the peak hours. The southern (i.e. Gateway 3) and northern (i.e. Gateway 13) ends of the immediate network around Hauptbahnhof recorded high frequency of cars i.e. 2106 and 882 respectively. These streets also recorded high number of cyclists using the space, though the southern end lacked a dedicated cycle lane. Considering the selected gateways, the average pathway of 5.92m for active user-groups in the transit area was slightly higher than the residential area.

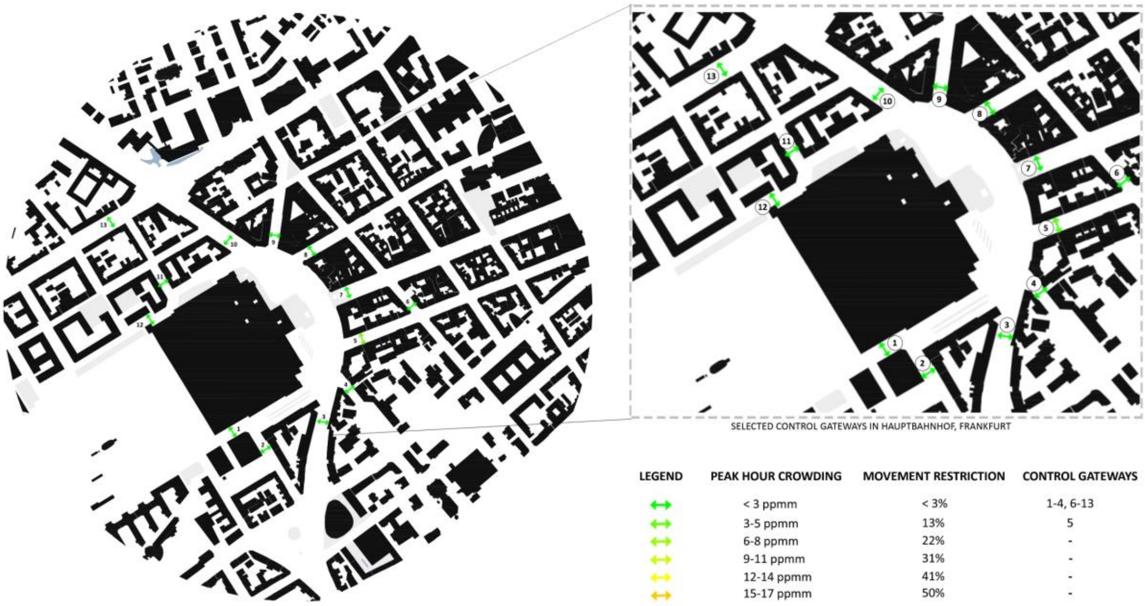


Figure 69: Peak hour crowding and movement restriction around Hauptbahnhof, Frankfurt

The peak hour crowding around Hauptbahnhof area recorded a maximum limit of 4.11 ppmm in Münchener Strasse (i.e. Gateway 5), falling below in the index within 3-5 ppmm category. This also indicated an increased movement restriction of 13% in the street. The other gateways recorded lower movement restriction (i.e. <3%) and peak hour crowding (i.e. <3 ppmm). The overall mean peak hour crowding for the transit area was 1.64 ppm, which was approximately double the mean crowding value of the transit area in Darmstadt, but still within the comfortable range.

Gateways:	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Pedestrians	684	2268	1050	1470	684	3456	14190	3624	2706	1404	3642	12	2046	312
Cyclists	54	330	96	318	24	78	276	432	108	84	276	0	306	30
URM	0	6	6	6	6	6	48	18	6	0	12	0	6	0
Baby strollers	6	66	18	18	6	96	192	36	48	30	102	0	54	0
Boards / Scooters	36	24	0	36	12	0	54	36	6	24	24	0	30	12
Four-wheelers	486	186	78	138	0	0	0	96	0	510	0	0	30	396
Two-wheelers	12	30	18	24	0	0	0	12	0	12	0	0	0	6
Total	774	2622	1146	1824	720	3534	14520	4092	2820	1512	3942	12	2382	354
Footway width	5.46	14.23	6.58	10.1	3.02	8.24	20.18	7.47	11.3	7.82	14.62	1.97	8.49	8.15
ppm	141.76	184.26	174.16	180.59	238.41	428.88	719.52	547.79	249.56	193.35	269.63	6.09	280.57	43.44
ppmm	2.36	3.07	2.90	3.01	3.97	7.15	11.99	9.13	4.16	3.22	4.49	0.10	4.68	0.72

Table 21: Peak hour frequency and associated variables with respect to selected gateways in Hauptwache, Frankfurt (where ppm = persons per metre and ppmm = persons per metre minute)

In the area surrounding the city centre in Frankfurt am Main, i.e. Hauptwache, 14 control gateways were selected for the peak hour data collection (see Fig. 70). Hauptwache recorded the maximum frequency of 14190 pedestrians along the street of Zeil (i.e. Gateway 7), while Grosse-Eschenheimer Strasse (i.e. Gateway 8) recorded maximum frequency of cyclists i.e. 432. With majority of the area falling within the pedestrian zone, maximum cars were recorded on streets surrounding the pedestrian zone along the streets of Börsenstrasse (i.e. Gateway 10) and Grosse Gallusstrasse (i.e. Gateway 1) with peak frequency of 510 and 486 respectively. With respect to the selected gateways amongst the three urban areas, the area around the city centre recorded the highest mean width of space available to active modes of transport i.e. 9.12 metres.

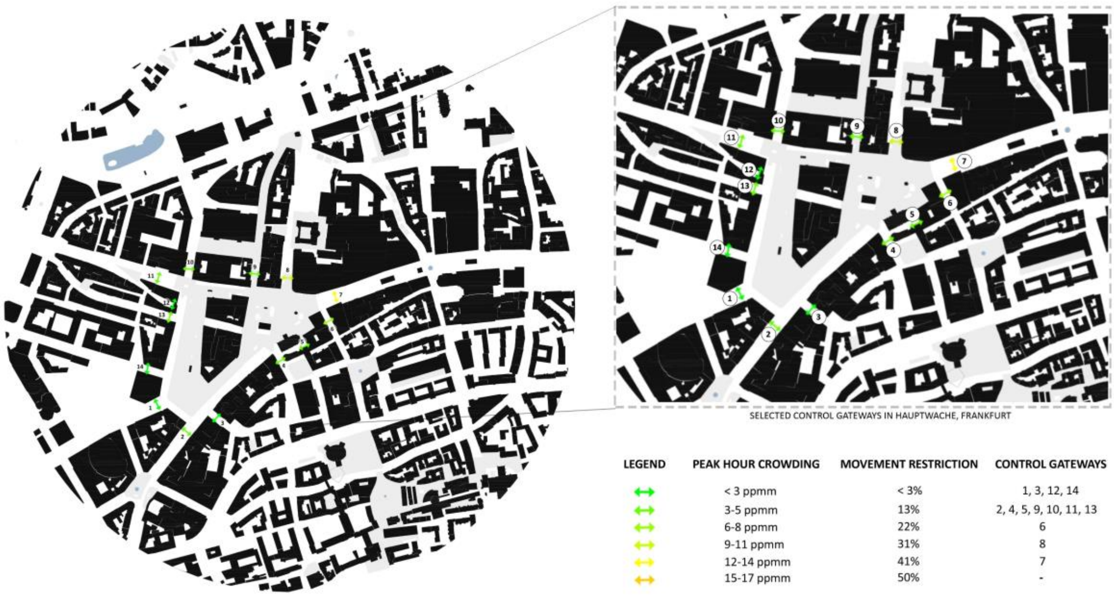


Figure 70: Peak hour crowding and movement restriction around Hauptwache, Frankfurt

With 11.99 ppmm, the city centre around Hauptwache recorded the highest individual peak hour crowding for a gateway, which fell along the street of Zeil (i.e. Gateway 7). This led to the street falling under one of the highest peak-hour crowding category of 12-14 ppmm with 41% movement restriction for user-groups (see Table 21). This was followed by the streets of Grosse-Eschenheimer Strasse and Liebfrauenstrase (i.e. Gateway 6) having peak-hour crowding of 9.13 ppmm and 7.15 ppmm respectively. The dominance of user-groups (excluding motorized vehicles) around the city centre area led to an overall high mean peak hour crowding of 4.35 ppmm, which was the highest amongst all selected urban areas in the three cities (including Offenbach in subchapter 4.7). The area around Hauptwache was the only urban area in the study, where majority of the streets (or gateways) had their respective peak-hour crowding values greater than 3 ppmm, resulting in higher movement restrictions. The hierarchy of crowding among different urban areas in the pilot study (i.e. Darmstadt), was replicated in Frankfurt, though the margins between the city centre and the other case study areas were greater in Frankfurt am Main.

4.7 Offenbach am Main and its selected urban areas

Similar to the pilot study and the associated research timeline, the three selected urban areas in the city of Offenbach am Main (adjacent to the city of Frankfurt am Main in the east forming the Rhein-Main agglomeration) were selected to study and understand their characteristics within the perspectives of the five identified performance measure (or parameters). These three urban areas include the city centre i.e. Marktplatz, which is the urban core of the city characterized by dense high street areas (including shopping plazas) and mixed-use spaces situated south of the river Main; the main transit station i.e. Hauptbahnhof, which acts as a transit station for inter-city travel along with other public transport services for intra-city travel; and the residential area of Bürgel located within the observational boundaries similar to the pilot study in Darmstadt.

Figure 71: Figure Ground Maps of area surrounding Offenbach Hauptbahnhof (left), the residential area of Bürgel (centre), and the city centre i.e. Marktplatz (right) within 1 sq. km. area

The Masterplan 2030 for the city of Offenbach am Main focuses on several areas around the city for its urban development, which includes the three selected case study areas. Some of the measures around the city centre involve making it a compact shopping district with better mobility hubs in close proximity, improving the area's quality of stay and more. With the city's growing population, the Masterplan also identifies Bürgel as one of the important residential settlement areas with potential spaces for densification, which would limit the urban sprawl towards the neighbouring green spaces. The immediate area surrounding Hauptbahnhof in Offenbach, which is situated in close proximity to the city centre, sees its role as a main transit station being diminished with more S-Bahn train lines bypassing it in the north. The transit area remains one of the important spaces for regional trains along with bus services, and is identified as a potential area for business, residential and other purposes within the Masterplan. Identifying the potential of these areas with respect to the overall mobility of the city and improving its access, would assist in strengthening the urban core and integrating it with districts, supporting the urban development plan of making a compact city.

4.8 Parametric diagnosis of selected urban areas in Offenbach am Main

Within similar observational boundaries as per the pilot study, the selected urban areas in Offenbach am Main were analysed through connectivity, intelligibility, NACH, PTAL, and crowding. The selected case study areas were mapped in accordance to the reconnaissance studies and analysed as follows:

4.8.1 Connectivity Index

Similar to the previous connectivity network studies in Frankfurt am Main and Darmstadt, the three selected areas in Offenbach am Main were mapped based on their pedestrian networks within the observational area of one square kilometre, covering links (including cul-de-sacs) and nodes as follows:

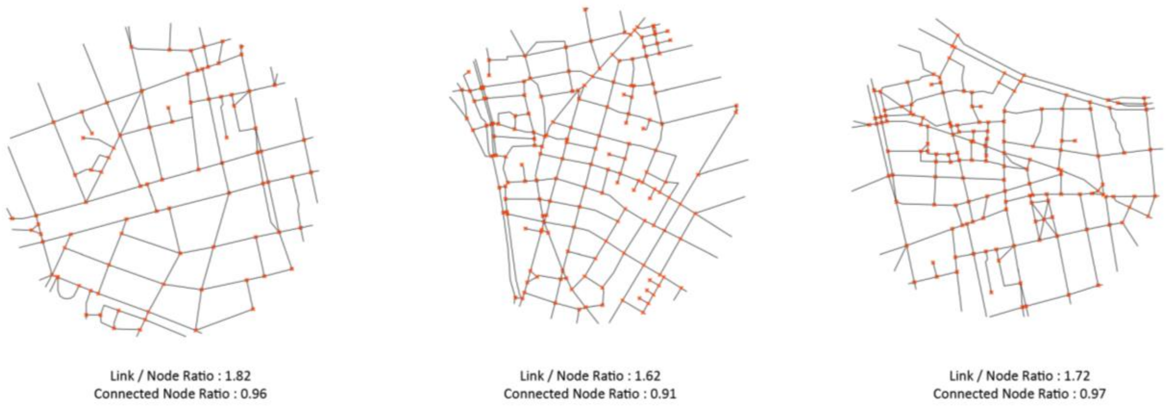


Figure 72: Node density mapping of Offenbach Hauptbahnhof (left), Bürgel (centre), and Marktplatz (right) within 1 sq. km. area

The spatial layout of the main railway station i.e. Hauptbahnhof in Offenbach am Main is continuous in nature, which is similar to Darmstadt Hauptbahnhof, but in contrast to the on-ground terminal spatial layout of Frankfurt Hauptbahnhof. The street network surrounding the main railway station in Offenbach am Main recorded an overall link density of 160 per square kilometre, with the nodal density (or intersection density) being 88 per square kilometre. Majority of the cul-de-sacs were located on the north of the main entrance of the railway station (see Fig 72). In regards to the street network corresponding to the residential area of Bürgel in Offenbach am Main, comparatively higher link and nodal densities were observed per unit area (i.e. square kilometre), which is 274 and 169 respectively. The Main river towards the west of the residential area along with the old segregated residential units, had an influence on the frequency of links and nodes leading towards a dense street network in its proximity. The cul-de-sacs in the residential area of Bürgel recorded the highest amongst the three selected urban areas in Offenbach am Main, i.e. 16 per square kilometre, with many situated on the eastern end of the network structure.

The Main river also had an impact on the configuration of links and nodes in the city centre, with Marktplatz recording 261 links and 152 nodes within 1 sq. km. Unlike the residential area, it recorded lower cul-de-sac density (similar to the transit area of Hauptbahnhof). The selected urban areas depict a walkable network, with lowest link-node ratio of 1.62 in Bürgel which addressed the minimum margin of 1.4. The highest ratio of 1.82 was observed around Hauptbahnhof, similar to that of Frankfurt am Main, followed by 1.72 in the city centre. The density of links and nodes tend to shift towards the Main river in the city centre and the residential area, which might have an impact on the immediate spatial characteristic. Similar to previous studies, the residential area had high cul-de-sac density which restricts the overall potential of a walkable network, in turn influencing the intelligibility of the area. Unlike other cities in the study, Offenbach had case study areas which were directly influenced by a water body i.e. Main river within observation limits, which restricts the potential density of links and nodes. This still resulted in similar hierarchy of walkable street network in Offenbach, as was observed in Frankfurt, while in Darmstadt the industrial and commercial area adjacent to Hauptbahnhof influenced the street network leading to a different hierarchy of connected spaces.

4.8.2 Intelligibility

The axial maps of selected case study areas were analysed through the DepthmapX following the Space Syntax theory, similar to the studies in Frankfurt am Main and Darmstadt. The axial maps were revised for spaces which had bridges, or underway passage to have correct representation of the areas (for e.g. the pedestrian bridge in city centre, tunnel adjacent to Hauptbahnhof etc). Following maps were generated post spatial analysis of the three urban areas through axial integration on global level:

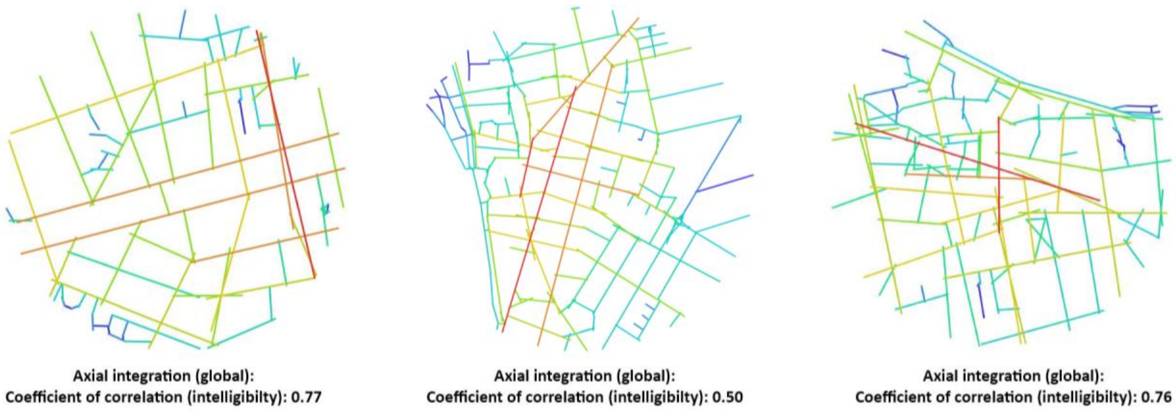


Figure 73: Global axial integration and relative intelligibility coefficient of axial lines surrounding Offenbach Hauptbahnhof (left), Bürgel (centre) and Marktplatz (right) within 1 sq. km.

The axial network surrounding Hauptbahnhof showed high intelligibility characteristic, with immediate streets located north (i.e. Bismarckstrasse) and south (i.e. Marienstrasse) of it being highly integrated within the network (see Fig. 73 and 40). The underpass in the east between Gross-Hassenbach-Strasse and Senefelderstrasse also showed strong connectivity and integration (r=n) values. Overall, the intelligibility factor had a correlation coefficient of 0.77 for the transit area of Hauptbahnhof (Fig. 74). The integral core of the overall network was more prominent in the east, than central as observed in city centre and residential area.

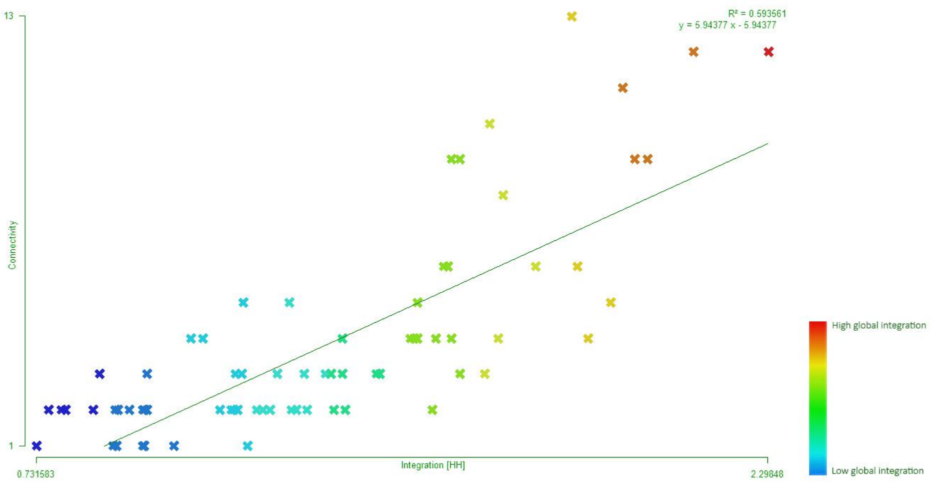


Figure 74: Scatterplot: Connectivity (r=1) vs Global Integration (r=n) of axial lines surrounding Hauptbahnhof [1 sq. km.] in Offenbach am Main

With respect to the residential area of Bürgel, the weak integrated axial streets were observed along the cul-de-sacs which led to overall low intelligibility characteristic. Major integrated streets were observed along central core of the axial network including the street of Langstrasse, which was also directly connected to majority of streets. The location of retail shops and restaurants on the ground level along the street, supports the high integration characteristic of the space where people would tend to go. While the Offenbacher Strasse (opposite the open space of Bürgerplatz in Fig. 42) showed high integration value in the west (in Fig. 73), similar to the adjacent street of Langstrasse, it showed low connectivity which contributes to an overall intelligibility with a correlation coefficient of 0.50.

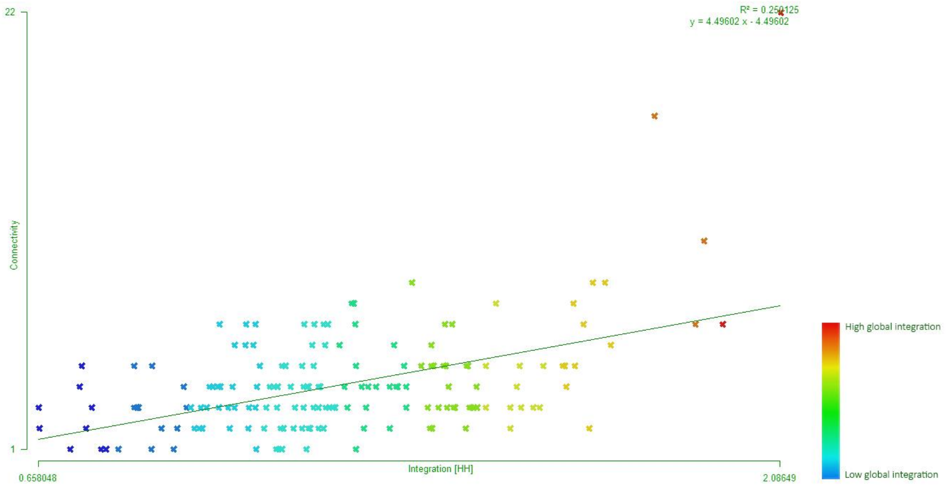


Figure 75: Scatterplot: Connectivity (r=1) vs Global Integration (r=n) of axial lines surrounding the residential area of Bürgel [1 sq. km.] in Offenbach am Main

Similar to area surrounding the city centres in Darmstadt and Frankfurt am Main, the city centre in Offenbach recorded high network of integrated streets (r=n) in the central core through Marktplatz along the street of Berliner Strasse. The axial line through the street of Berliner strasse also showed high frequency of streets directly connected to it. The junction of highly integrated streets on Marktplatz (in Fig. 73) replicates its landmark nature surrounding the pedestrian zone in the city centre (in Fig. 38). The street of Frankfurter Strasse, adjacent to the integrated cross-junction in the centre, also showed high integration value (r=n) where the high-street filled with markets and shopping plazas compliment the highly integrated axial street. The overall high intelligibility was reflected through correlation coefficient of 0.76 in the city centre of Offenbach (see Fig. 76), which was in proximity to the intelligibility characteristic of the Hauptbahnhof network. With respect to the Masterplan 2030 for the city of Offenbach am Main, one of the urban development measures include connecting the northern side of river Main (which falls within the jurisdiction of Frankfurt am Main) with the city of Offenbach through a bridge for pedestrians and cyclists. This bridge in close proximity to the north of the axially integrated junction in the city centre, would alter the existing street network in future and have an influence on the way people move around the space in future. Its proximity to the integrated street junction near Marktplatz will contribute further to the central integrated network, leading towards more influx of active user-groups using the space.

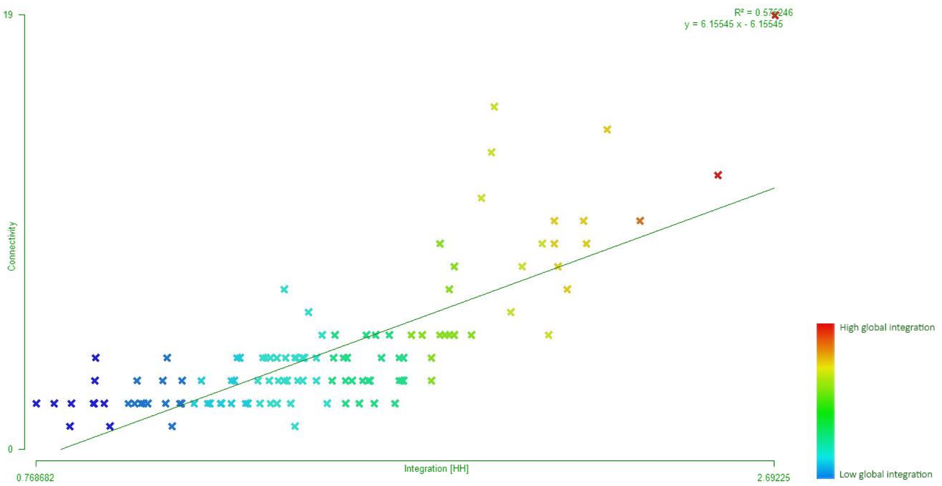


Figure 76: Scatterplot: Connectivity (r=1) vs Global Integration (r=n) of axial lines surrounding the city centre i.e. Marktplatz [1 sq. km.] in Offenbach am Main

Overall, the hierarchy of intelligible areas in Offenbach from low to high is Bürgel, Marktplatz and Hauptbahnhof respectively. This is similar to the intelligibility characteristic of similar urban areas in Frankfurt, while in Darmstadt the city centre showed highest intelligibility. With respect to all the areas and their mean intelligibility values, Frankfurt performed better which was followed by Offenbach and Darmstadt. The structural configuration due to river Main in Offenbach had less impact on the intelligibility characteristic as compared to Darmstadt, where the industrial land-use in close proximity to Darmstadt Hauptbahnhof and the non-terminal nature of the rail service, i.e. rail tracks running in between the urban area leading to less street networks connecting the opposite ends, resulted in the space being less intelligible for a person to navigate based on axial nature of the streets.

4.8.3 Public Transport Accessibility Level

The PTAL index for the selected urban areas in Offenbach am Main is recorded within similar observation limits (as in the pilot study) for buses i.e. 640 metres of radius, and trains within the maximum radius of 960 metres. The data collection for every service station was recorded within the same time interval of morning peak hours between 08:15 - 09:15, during the weekdays in the month of January 2021. In contrast to Frankfurt am Main and Darmstadt, the city of Offenbach lacked the infrastructure for trams. The absence of tram services could lead to lower PTAL value for the selected urban areas, but as noticed in the city centres of Darmstadt and Frankfurt, Luisenplatz recorded a higher PTAL value despite lacking additional train services which were available in the city centre of Frankfurt am Main.

Within the area surrounding Offenbach Hauptbahnhof, the farthest service station with different route of transport was located approximately 400 metres away from the point of interest in Bahnüberführung in the east (in Fig. 77). Diverse routes of buses and trains were recorded, with maximum frequency of 7 by the bus services within the peak hour interval (in Table 22). The train services were closest from the point of origin, though the diversity and frequency of train services recorded were low as compared to similar urban areas in other cities of Frankfurt am Main and Darmstadt.

Figure 77: Shortest pedestrian access between the point of interest A in Offenbach Hauptbahnhof and B at Bahnüberführung service station

The PTAL indexes for respective service stations and modes in the observational area surrounding Offenbach Hauptbahnhof were recorded as follows:

Site	Service	Stop	Route	Distance	Frequency	Weight	Walktime	SWT	Access	EDF	Index
Offenbach Hbf	Bus	Hauptbahnhof	102	110	5	0.5	1.38	8.00	9.38	3.20	1.60
			104	110	4	0.5	1.38	9.50	10.88	2.76	1.38
			106	110	4	0.5	1.38	9.50	10.88	2.76	1.38
			41	110	2	0.5	1.38	17.00	18.38	1.63	0.82
			551	110	1	0.5	1.38	32.00	33.38	0.90	0.45
			X83	110	2	0.5	1.38	17.00	18.38	1.63	0.82
			X97	110	2	0.5	1.38	17.00	18.38	1.63	0.82
		Bahnüberführung	101	405	5	0.5	5.06	8.00	13.06	2.30	1.15
			105	405	7	1	5.06	6.29	11.35	2.64	2.64
			551	405	2	0.5	5.06	17.00	22.06	1.36	0.68
			OF-30	405	2	0.5	5.06	17.00	22.06	1.36	0.68
	Train	Hauptbahnhof	RB51	50	1	1	0.63	30.75	31.38	0.96	0.96
			RE50	50	1	0.5	0.63	30.75	31.38	0.96	0.48
			RE55	50	1	0.5	0.63	30.75	31.38	0.96	0.48
			RE85	50	1	0.5	0.63	30.75	31.38	0.96	0.48
										PTAL:	14.80

Table 22: PTAL for area surrounding Offenbach Hauptbahnhof through different public transport services

The area surrounding Hauptbahnhof in Offenbach recorded an overall PTAL value of 14.80, which fell within the range of 10.01-15.00 of group 3 denoting an average level of access. The bus services contributed 84% of the overall PTAL with an index value of 12.41, followed by train services through 2.39 index value (in Table 22). The proximal locations of bus stops and their respective peak hour frequencies contribute majorly to the overall PTAL, though the lower frequency of trains and absence of tram services led to a low index value.

The selected residential area in Offenbach i.e. Bürgel is served by buses, with farthest service route located approximately 360 metres from the point of origin (in Fig. 78). In contrast to other selected urban areas where only the closest service stop to a particular route was considered for the index calculation, the service stops in Bürgel with similar routes had to be considered twice as the direction of the service was different at two stops (in Table 23). For example, the bus route 101 had two service stops where Bürgerplatz only had one-way direction of services and Hessenstrasse had the opposite direction of bus service. This was mostly due to narrow width of streets, where the two-way directional movement of bus services on same street was not possible. The bus services recorded the highest frequency of 5 during the peak hours.

Figure 78: Shortest pedestrian access between the point of interest A in Bürgel and B at Hessenstrasse service station

The PTAL indexes for respective service stations and modes within the residential area of Bürgel were recorded as follows:

Site	Service	Stop	Route	Distance	Frequency	Weight	Walktime	SWT	Access	EDF	Index
Bürgel	Bus	Bürgerplatz	101	245	4	0.5	3.06	9.50	12.56	2.39	1.19
			107	245	2	0.5	3.06	17.00	20.06	1.50	0.75
		Hessenstrasse	101	365	5	1	4.56	8.00	12.56	2.39	2.39

			107	365	2	0.5	4.56	17.00	21.56	1.39	0.70
										PTAL:	5.03

Table 23: PTAL for the residential area in Bürgel through different public transport services

The residential area of Bürgel recorded an overall PTAL value of 5.03, falling within the designated index range of 5.01-10.00 of group 2, denoting a below average accessibility index. While the bus services contributed to the overall index, the absence of other modes of public transport along with low service frequency led to weak access to public transport in comparison to area surrounding city centre and Hauptbahnhof in the city of Offenbach.

The city centre in Offenbach, i.e. Marktplatz, is served by public transport services of buses and underground trains. The farthest service station is located at 510 metres on Kaiserstrasse (in Fig. 79) from the point of origin, with maximum service frequency of 4 shared by both bus and train services during the peak hours (in Table 24). The bus services were closest to access from the point of origin in comparison to trains, and contributed to the overall high index value amongst the three selected areas.

Figure 79: Shortest pedestrian access between the point of interest A in Marktplatz and B at Kaiserstrasse service station

The PTAL indexes for respective service stations and modes within Marktplatz were recorded as follows:

Site	Service	Stop	Route	Distance	Frequency	Weight	Walktime	SWT	Access	EDF	Index
Marktplatz	Bus	Frankfurter Str.	101	15	4	1	0.19	9.50	9.69	3.10	3.10
			103	15	2	0.5	0.19	17.00	17.19	1.75	0.87

		104	15	4	0.5	0.19	9.50	9.69	3.10	1.55
		105	15	4	0.5	0.19	9.50	9.69	3.10	1.55
		106	15	4	0.5	0.19	9.50	9.69	3.10	1.55
		120	15	2	0.5	0.19	17.00	17.19	1.75	0.87
		41	15	2	0.5	0.19	17.00	17.19	1.75	0.87
		551	15	2	0.5	0.19	17.00	17.19	1.75	0.87
		X83	15	2	0.5	0.19	17.00	17.19	1.75	0.87
		OF-30	15	1	0.5	0.19	32.00	32.19	0.93	0.47
	Berliner Str.	103	155	2	0.5	1.94	17.00	18.94	1.58	0.79
		108	155	4	0.5	1.94	9.50	11.44	2.62	1.31
		120	155	2	0.5	1.94	17.00	18.94	1.58	0.79
	Kaiserstrasse	102	510	4	0.5	6.38	9.50	15.88	1.89	0.94
Train	Marktplatz	S1	170	4	1	2.13	8.25	10.38	2.89	2.89
		S2	170	4	0.5	2.13	8.25	10.38	2.89	1.45
		S8	170	2	0.5	2.13	15.75	17.88	1.68	0.84
		S9	170	3	0.5	2.13	10.75	12.88	2.33	1.17
									PTAL:	22.75

Table 24: PTAL for area surrounding Marktplatz in Offenbach through different public transport services

The city centre in Offenbach recorded a PTAL value of 22.75 within the range of 20.01-25.00 under group 5 denoting a good level of public transport access. The bus services contributed 72% of the overall PTAL, with a resulting index of 16.41 followed by train services (with an index value of 6.34). While the train services had similar number of different routes (i.e. four) during peak hours as observed in main transit area of Hauptbahnhof, the higher frequency along with bus services in Marktplatz assisted in higher PTAL value.

4.8.3.1 Added perspective through reduced mobility

In order to reflect the perspectives of users with reduced mobility, the PTAL index was revised similar to the studies in Darmstadt and Frankfurt am Main. The revised indexes for the three selected urban areas within the study in Offenbach can be observed as follows:

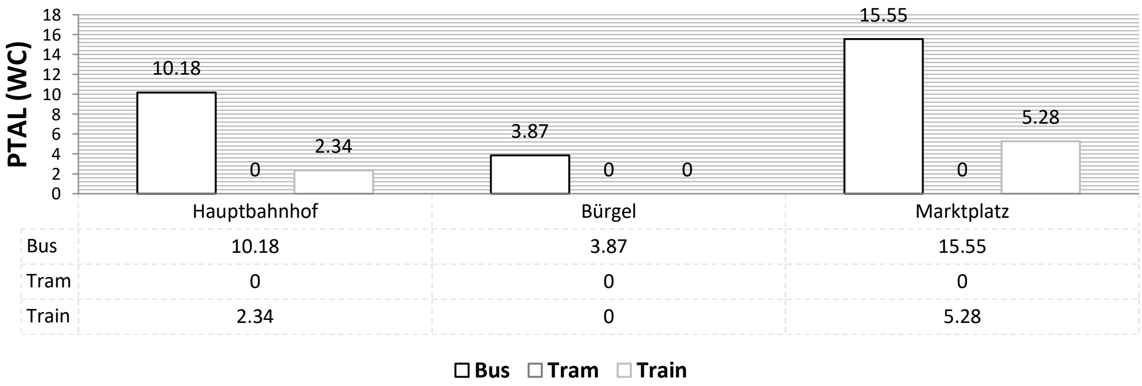


Table 25: Revised PTAL for selected urban areas in Offenbach am Main focusing on users with reduced mobility (i.e. wheelchair users)

With respect to the revised PTAL indexes, a 15% decrease was observed in Hauptbahnhof region, 23% decrease in the index value of residential area of Bürgel and 8% decrease of index value in the area surrounding city centre i.e. Marktplatz (see Table 25 and 24). Similar to the three selected areas in Frankfurt, the revised PTAL group range for the area surrounding the main transit station i.e. Hauptbahnhof and the city centre remained the same, while with respect to residential area, it dropped lower to access group of 1b i.e. within the range of 2.51 - 5.00. The lower access levels with respect to public transport, especially in residential areas, reflect the lack of equity in accessibility levels for the user-group with reduced mobility, and assists in prioritizing areas to improve the present level of accessibility for public transport.

4.8.4 NACH

The network of segments was analysed, similar to previous studies in Frankfurt and Darmstadt, through normalisation of angular choice (i.e. NACH) measure utilizing space syntax theory. The observation boundaries varied through different perspectives, i.e. 565m (~1 sq. km) for the selected areas in a small-scale perspective and 2500m for the overall city in a large-scale perspective, as follows:

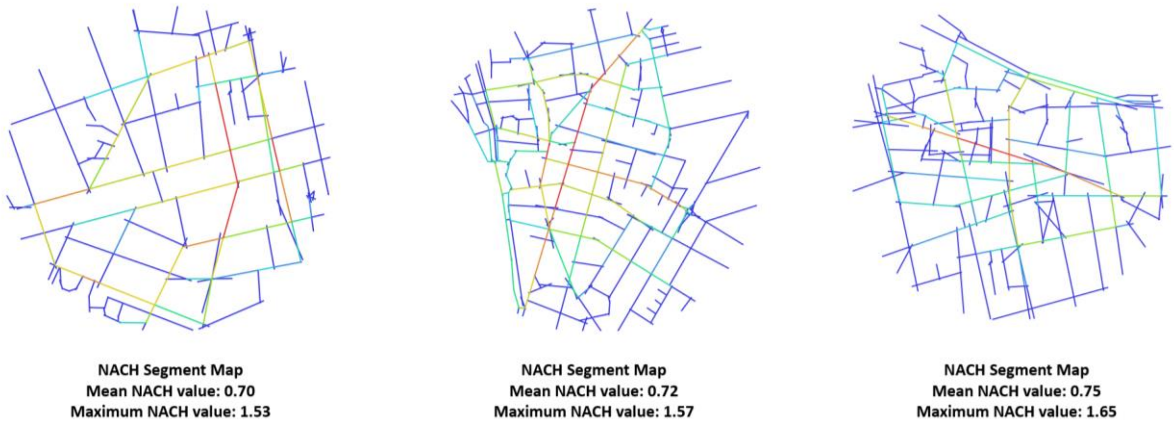


Figure 80: Segment maps showing normalisation of angular choice through Offenbach Hauptbahnhof (left), Bürgel (centre) and Marktplatz (right) within the limited boundary of 1 sq. km.

Small scale perspective

Within the main transit area, majority of street segments with high NACH values were located on the east of the Hauptbahnhof entrance, with an overall mean value of 0.70 per square kilometre (in Fig. 80). The segment with highest NACH value was recorded along the tunnel, adjacent to the bus transit station, connecting Senefelderstrasse and Gross-Hasenbach-Strasse (in Fig. 80 and 40). The parallel streets of Bismarckstrasse and Marienstrasse recorded relatively high NACH value over 1.20, showcasing high potential of bicycle pathways. The residential area of Bürgel recorded a mean NACH value of 0.72, with many street segments with high NACH value falling in close proximity to the centre of the overall network. Majority of these direct segments fell along the Langstrasse street, followed by Offenbacher strasse in close proximity (in Fig. 80 and 42). Marktplatz, within the city centre of Offenbach, recorded highest overall mean NACH value of 0.75 with Berliner Strasse playing a major role in the centre (in Fig. 80 and 38). Similar to Hauptwache in Frankfurt, Marktplatz in Offenbach includes a set of high-streets which fall within the pedestrian zone where pedestrians have a right of way as compared to other user-groups. This leads to prioritization of segments with relatively low NACH values around Marktplatz for direct bicycle pathways.

Considering the frequency of segments falling higher than the 1.20 NACH value, lowest number was reflected around Hauptbahnhof with 108 segments, followed by 214 segments in the city centre i.e. Marktplatz. The residential area of Bürgel recorded the highest number of segments showing NACH values greater than 1.20 value i.e. 278. The areas indicate potential for direct bicycle routes, with Marktplatz and Bürgel showing concentration of high NACH segments in the central core of the network whereas the Hauptbahnhof shows a shift towards the east with respect to the central core. Contrary to the pilot study, the residential area showed network of streets with higher number of direct routes for cyclists as compared to the other urban areas within the respective city. The study shows while the city centre of Offenbach had the network of street segments leading to high mean NACH value, it was the residential area which resulted in higher frequency of segments having potential for cyclists using the street, although the overall mean NACH value of streets in Bürgel was marginally low. This indicates the importance of reflecting every street segment in a network, to implement and improve the set of bicycle pathways in different urban areas.

Large scale perspective

Similar to the pilot study, a larger observation boundary of 2500m radius is taken into consideration to digitize the map through a network of axial lines (later converted into segment network). This is done to prioritize potential bicycle routes through a long-term perspective, irrespective of the selected urban areas, utilizing daily cycling trip boundaries via other accessibility parameters.

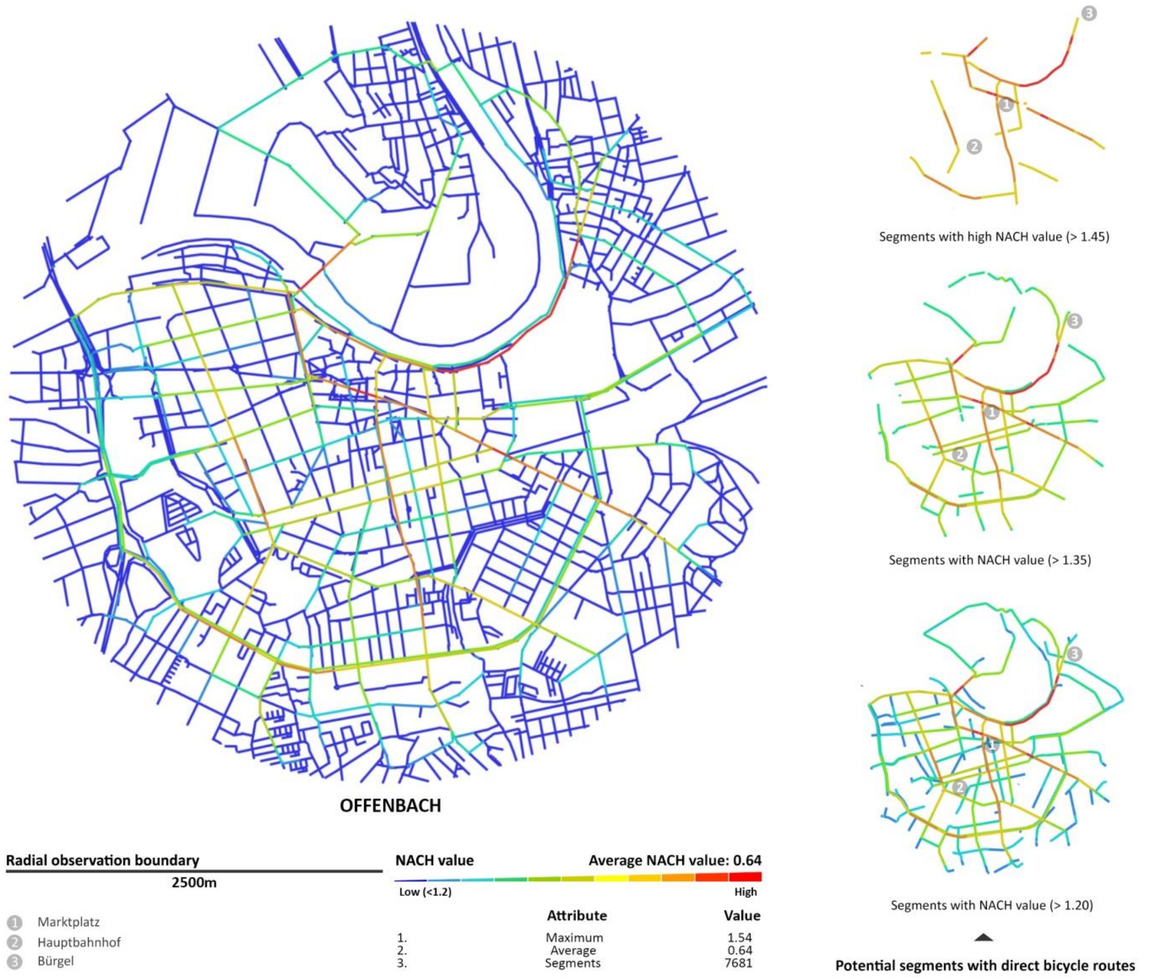


Figure 81: Segment maps showing normalisation of angular choice (NACH) through Offenbach within an observational radius of 2500m from the city centre i.e. Marktplatz

The highest NACH value recorded within the segment network was 1.5394 (~1.54) along the street segment Mainstrasse, connecting the city centre to the residential area of Bürgel adjacent to Main river (in Fig. 81). This was followed by Berliner Strasse in the city centre, leading towards Bieberer Strasse in east and Waldstrasse in the south. The Carl-Ulrich-Brücke, i.e. the bridge connecting eastern peripheral area of Frankfurt to Offenbach city plays an integral role contributing towards the continuous network of favourable bicycle pathways around the immediate areas. While some streets have the dedicated bicycle lanes along the high NACH segments, there were exceptions like Waldstrasse which lacked a continuous network of bicycle pathways. With cars being dominant on the NACH favoured segments like Waldstrasse and Berliner Strasse, the street segments without dedicated pathway might attract less cyclists. A study combining different parameters will reflect upon better understanding of the utility of the directness of streets (addressed in Chapter 5).

In Offenbach, while the most direct routes fall along the Mainstrasse, a primary lane for cyclists falls adjacent to the street along the Main river with no automobiles (in Fig. 39). This impacts the frequency of users using the space, which might not favour the hierarchy of high NACH segments. Overall, the set of direct routes for cyclists favour the network on the south of Main river, with industrial area located on the northern end. The cross junction at Marktplatz through Berliner Strasse and Waldstrasse, acts as an important area for direct route connectivity followed by Mainstrasse in east, Körnerstrasse in west and Bundestrasse 43 in south with respect to short-distance mobility. The street segments which showed similar direct route potential for cyclists in both small-scale and large-scale perspectives favours the prioritization for direct bicycle routes, if not already present on-site.

4.8.5 Crowding and movement restriction

Considering the crowding and movement restriction aspect, the pedestrian and other user-group's data was collected on the designated timelines based on the different typology of areas in Offenbach am Main. With respect to different typology of areas, Marktplatz fell within the 'High Street' category, Bürgel was the 'residential' area within 2500m peripheral distance from the city centre, and Hauptbahnhof was the 'Transit' area which was undertaken for data collection during respective timelines based on the pilot study. The available street widths for movement were measured (see Appendix) with respect to each selected gateway, and buffer widths were considered corresponding to the street elements and immediate environment.

The residential area of Bürgel included 15 control gateways (in Fig. 82 and Table 26) which were utilized for peak hour data collection, recording least mean peak hour crowding amongst the three case study areas in the city. Amongst the three selected residential areas in the cities of Darmstadt, Offenbach and Frankfurt, Bürgel had the least mean width of pathway for pedestrians and cyclists through selected gateways. This favours high movement restriction due to less space available for different active user-groups to move. The peak hour flows for pedestrians, cyclists and vehicles through the selected control gateways in Offenbach were recorded, with sub-categories of users with reduced mobility (i.e. wheelchair users, walkers etc) and baby strollers under pedestrian category, along with users using electronic (or manual) scooter and boards (i.e. longboards or skateboards); four- and two-wheeler automotive vehicles under non-active mode of transport.

The frequency of pedestrians peaked 222 and 216 in numbers along the Langstrasse gateways i.e. 12 and 2 respectively (in Table 26 and Fig. 82). Contrary to the overall network of gateways around Bürgel, gateway 7 fell alongside the cycling boulevard adjacent to river Main which resulted in highest peak of 156 cyclists in the residential area. This cycling pathway runs south along the river Main towards the city centre, creating a parallel route for cyclists next to Mainstrasse, which is dominated by motorized vehicles. The residential area also had a dedicated street intervention for cyclists along gateway 14, i.e. Von-Behring-Strasse, which recorded average frequency of cyclists among the 15 gateways in Bürgel. The Langstrasse was dominated with cars with peak frequency of 474 and 402 along the gateways 1 and 12 respectively, showing mix of both slow- and fast-moving user-groups in the residential area. On an average, the gateways in the Bürgel resulted in least available space of 2.82 metres for active user-groups.

Gateways:	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Pedestrians	144	216	36	66	156	30	78	18	192	108	18	222	30	24	84
Cyclists	42	72	36	30	66	0	156	48	48	36	6	102	12	42	36
URM	0	0	0	6	6	0	0	0	0	0	0	6	0	0	0
Baby strollers	6	18	0	0	12	0	6	0	0	6	0	6	0	0	6
Boards / Scooters	6	6	0	6	6	0	0	0	0	0	0	0	0	6	0
Four-wheelers	474	372	18	60	384	18	0	12	228	252	6	402	72	48	36
Two-wheelers	6	6	0	6	6	6	0	0	6	6	0	6	0	0	0
Total	192	294	72	102	228	30	234	66	240	144	24	324	42	72	120
Footway width (m)	3.13	2.48	1.18	3.22	4.63	1.11	3.1	3.42	3.07	2.92	0.93	2.45	3.05	5.83	1.81
ppm	61.34	118.55	61.02	31.68	49.24	27.03	75.48	19.30	78.18	49.32	25.81	132.24	13.77	12.35	66.30
ppmm	1.02	1.98	1.02	0.53	0.82	0.45	1.26	0.32	1.30	0.82	0.43	2.20	0.23	0.21	1.10

Table 26: Peak hour frequency and associated variables with respect to selected gateways in Bürgel, Offenbach

Figure 82: Peak hour pedestrian crowding and movement restriction around residential area of Bürgel, Offenbach

The gateways in Bürgel fell within the category of least movement restriction (i.e. <3%) despite having lowest width of space amongst the selected urban areas. The highest peak hour crowding was observed along the Langstrasse, with 2.20 and 1.98 ppmm falling on gateways 12 and 2 respectively. The overall mean peak hour crowding for the gateways was 0.91 ppmm, which was relatively higher than the Komponistenviertel in Darmstadt, but lower than Bornheim in Frankfurt.

Gateways:	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Pedestrians	102	90	210	114	78	150	306	438	114	162	252	96	126	90	330
Cyclists	126	36	114	30	36	84	24	102	6	84	96	96	78	60	66
URM	0	0	0	0	0	12	0	6	0	12	0	0	0	6	18
Baby strollers	0	0	24	6	6	12	6	24	6	18	18	0	6	0	12
Boards / Scooters	0	0	6	0	6	0	0	0	0	0	6	0	0	0	0
Four-wheelers	126	282	438	336	90	0	204	834	18	0	990	24	174	204	0
Two-wheelers	6	6	12	0	0	0	6	6	0	0	6	0	6	6	72
Total	228	126	330	144	120	234	330	540	120	246	354	192	204	150	396
Footway width (m)	3.2	4.18	4.15	3.6	3.25	4.4	4.22	4.37	4.1	6.69	5.65	8.67	2.25	4.83	3.75
ppm	71.25	30.14	79.52	40.00	36.92	53.18	78.20	123.57	29.27	36.77	62.65	22.15	90.67	31.06	105.60
ppmm	1.19	0.50	1.33	0.67	0.62	0.89	1.30	2.06	0.49	0.61	1.04	0.37	1.51	0.52	1.76

Table 27: Peak hour frequency and associated variables with respect to selected gateways in area surrounding Hauptbahnhof, Offenbach

Figure 83: Peak hour pedestrian crowding and movement restriction around Hauptbahnhof, Offenbach

The transit station in Offenbach recorded pedestrians at its peak on the streets linking the entrance and exit to Hauptbahnhof along gateways 8 and 15 (in Fig. 83 and Table 27), through the streets of Bismarckstrasse and Schäferstrasse respectively. The highest number of pedestrians peaked at 438 during the peak hours on Bismarckstrasse in the north. Unlike the city centre and residential area of Bürgel, the Hauptbahnhof is situated away from the river Main with no dedicated riverside cycling boulevard which resulted in lowest peak frequency of 126 cyclists amongst the three urban areas in Offenbach. This was observed along gateway 1 on Tulpenhofstrasse (which also acts as one of the direct routes with respect to NACH). Bismarckstrasse also saw high number of slow-moving user-groups (e.g. baby strollers) through gateways 3 and 8, followed by fast moving traffic of cars. The 'transit' area provided an average width of 4.49 metres of space for active user-groups, which was the least amongst the transit stations in the selected three cities.

Similar to Bürgel, the Hauptbahnhof area in Offenbach am Main recorded the peak hour crowding and movement restriction within the comfortable limits of <3ppmm and <3% respectively. The highest peak hour crowding of 2.06 ppmm was recorded along the Bismarckstrasse on the north of Hauptbahnhof entrance, with an overall mean crowding of 0.99 ppmm for the selected transit area.

Gateways:	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Pedestrians	216	222	696	1752	1836	1026	846	852	834	798	552	90	318	102	192
Cyclists	36	42	276	132	114	66	72	186	114	216	90	18	108	30	558
URM	0	0	12	12	6	36	0	0	6	6	0	0	0	0	18
Baby strollers	6	6	36	48	90	48	12	48	42	30	12	0	12	0	6
Boards / Scooters	0	0	0	12	6	6	6	0	0	6	0	0	6	0	6
Four-wheelers	150	60	924	606	0	0	318	906	486	1068	0	0	336	1032	0
Two-wheelers	0	0	18	18	0	0	12	24	18	12	0	0	12	24	0
Total	252	264	972	1896	1956	1098	924	1038	948	1020	642	108	432	132	756
Footway width (m)	3.15	1.26	10.85	10.97	9.42	5.2	5.3	7.8	7.08	12.4	4	2.6	4.85	8.93	2.7
ppm	80.00	209.52	89.59	172.84	207.64	211.15	174.34	133.08	133.90	82.26	160.50	41.54	89.07	14.78	280.00
ppmm	1.33	3.49	1.49	2.88	3.46	3.52	2.91	2.22	2.23	1.37	2.68	0.69	1.48	0.25	4.67

Table 28: Peak hour frequency and associated variables with respect to selected gateways around Marktplatz, Offenbach

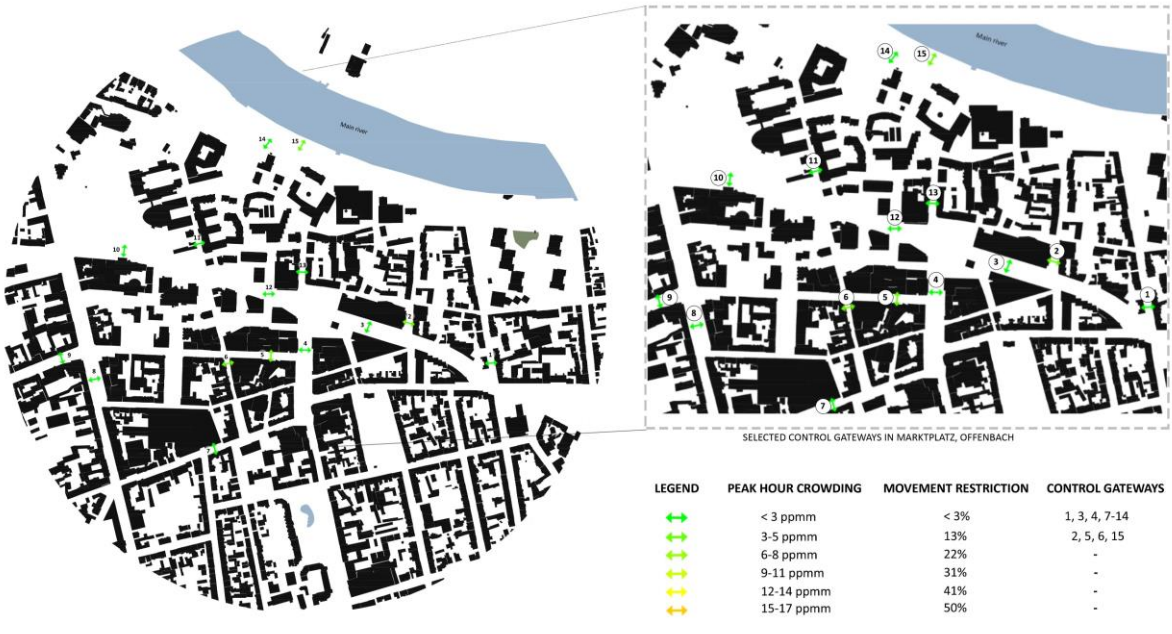


Figure 84: Peak hour pedestrian crowding and movement restriction around Marktplatz, Offenbach

With Marktplatz falling within the pedestrian zone of the city centre, the highest frequency of pedestrians was recorded as 1836 along the Frankfurter Strasse (i.e. Gateway 5), followed by adjacent Marktplatz street (i.e. Gateway 4) which recorded a close pedestrian frequency of 1752 (in Table 28 and Fig. 84). With cycling boulevard situated in the north next to the Main river, the peak frequency of 558 cyclists was recorded along the gateway 15, which was followed by 276 cyclists observed on Berliner Strasse (also being one of the direct routes within NACH parameter). The street also recorded high frequency of four-wheeler traffic i.e. 1068 along gateway 10 in the west. The slow-moving user groups mostly dominated along the pedestrian zone of Marktplatz along gateways 4, 5 and 6. On an average the city centre provided a mean moving space of 6.43 metres for active user-groups, which was the highest amongst the three case study areas in Offenbach. Unlike the selected transit and residential areas in Offenbach, the gateways in the city centre recorded movement restrictions and crowding beyond the least comfortable range. The city centre had an average peak hour crowding of 2.31 ppmm, with the highest being 4.67 ppmm along the cycling boulevard alongside river Main in the north. Considering the Masterplan of the city of Offenbach am Main, the construction of pedestrian bridge connecting the riverside boulevard to the street across Main river in Frankfurt am Main will impact the existing spatial configuration and contribute to further crowding.

4.9 Summary

This chapter initiates the spatial study of selected urban areas through the pilot study in one of the cities forming the urban agglomeration. The pilot study assists in understanding the overall timeline for analysing the selected spatial configuration of spaces through different attributes (i.e. identified parameters). While the data was collected and utilized before the onset of COVID-19 pandemic, in order to have a fair comparison of certain attributes (like PTAL, where the frequency of public transport had an impact) with other urban areas (i.e. whose data was collected during COVID-19 pandemic), the data for pilot study was revised. The pandemic influenced the accessibility characteristics of the urban areas, for example, the PTAL for an area surrounding the city centre and main transit station i.e. Hauptbahnhof was higher prior to the pandemic (Pandit & Knöll 2019) than during the pandemic, while both values fell within similar (i.e. highest) range of PTAL. The added perspective through users with reduced mobility introduces improvements within the existing parameter which assist in presenting a perspective which prioritizes the user-group.

The initial diagnosis for the pilot study in Darmstadt (based on the selected five parameters) puts the urban area surrounding the main transit station i.e. Hauptbahnhof higher in the hierarchy with respect to the city centre area and the residential area. This also gives an outlook of how the multi-criteria decision analytic tool can be utilized by urban planning and design professionals for prioritizing different urban areas based on their overall performance (through accessibility parameters). Different accessibility characteristics of an urban area play a crucial role in determining an urban area’s mobility characteristic. For instance, the residential area of Komponistenviertel in Darmstadt shows potential advantages over direct routes (through NACH), which is similar to that of the transit area surrounding Darmstadt Hauptbahnhof, but has lower access to public transport modes (through PTAL). The high connectivity of the city centre in pilot study, followed by its strong intelligibility, direct routes for cycling and strong PTAL range invites different user-groups supporting a multimodal area. This in turn, also makes it a priority to address the movement of different user-groups (including comfortable crowding and less movement restriction) and have less conflict spaces where intermodal accessibility plays a crucial role. These factors influence the choice of mode people prioritize based on the existing infrastructure which has an impact on the way people move, either through active means of transport or through motorized vehicles. Following the pilot study, the selected urban areas in Frankfurt am Main and Offenbach am Main were analysed through intra-parametric perspective for different urban areas within the city (with brief inter-city perspectives). The spatial configuration of open spaces, natural boundaries and built infrastructure dictated the unique parametric characteristics of the urban

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Pandit, L. & Knöll, M. (2019), Understanding multimodal accessibility parameters in diverse urban environments: A pilot study in Darmstadt, International Journal of Transport Development and Integration, Vol. 3, No. 4, pp. 317–330.

areas. For example, the NACH network (on a large-scale perspective) showed a unique centrality of streets with potential direct routes in Darmstadt, which was concentrated towards the eastern side of the city in comparison to the cities of Offenbach or Frankfurt am Main, where the streets with high NACH values crossed through the centre of the city. In addition, though the city centre of Offenbach had the network of street segments leading to an overall high mean NACH value, it was the residential area of Bürgel which resulted in higher frequency of segments having potential for cyclists using directness of the streets. This shows how individual street characteristics can also play a crucial role for active mobility planning. With respect to the public transit services, the access to public transport showed diverse accessibility levels which was influenced by both the mode of travel and the location of the service stations. For instance, despite lacking the underground rail services which were available in the city centre of Frankfurt, the distance to the service stations played a major role which resulted in city centre in Darmstadt recording higher PTAL value. In addition, the transit area surrounding Hauptbahnhof in Darmstadt showed comparatively low intelligibility and connectivity (in comparison to Offenbach Hauptbahnhof) but high access to public transport. Frankfurt am Main's selected transit area, on the other hand, shows high access to public transport, along with high connectivity and intelligibility. The comparatively low access to public transport services in Offenbach am Main Hauptbahnhof, along with low connectivity and intelligibility around Darmstadt Hauptbahnhof portray some of the barriers towards establishing an accessible transit-oriented development. In regards to the connectivity, the high concentration of cul-de-sacs in the residential areas restricted the overall potential of a walkable network, which in turn influences the intelligibility of the area. These outcomes address how spatial configurations in different urban areas contribute towards its multimodal accessibility characteristics through intra-city and brief inter-city perspectives.

The in-depth inter-city perspective of multimodal accessibility (discussed in Chapter 5) through selected parameters produces a comparative approach, adding to the intra-city perspective in this chapter. This assists in understanding similar urban areas in the selected cities and also presents an opportunity to see the urban mobility and accessibility characteristics of cities with different sizes through the combination of parameters.

CHAPTER 5

COMPARATIVE ANALYSIS

Preface

This chapter deals with comparison of selected urban areas in the cities forming the Rhein-Main urban agglomeration through inter-city parametric perspectives with corresponding mobility strategies and spatial configurations. This initiates the process of comparing different urban areas in different cities and helps in understanding how the current state of accessibility through different modes is and how it can be improved through a macro-level study assisting in micro-level urban interventions and strategies. The comparison of the selected urban areas helps in assessing different accessibility parameters within geographic boundary limitations based on the literature and also leads to adjustments, which is later discussed in this chapter, to have an overall outlook on the existing urban fabric. This also includes combined use of different identified parameters to understand different mobility characteristics of a city or an urban area. Following the inter and intra-city comparison based on each selected parameter in the study, the identified urban areas in the cities of Darmstadt, Frankfurt am Main and Offenbach am Main are later ranked with equal weightage given to the selected five parameters. While this produces a more data-driven outcome, involving public perception through surveys (discussed in Chapter 6) enables a data-informed approach where the data is used as a check for varying priorities.

5.1 Parametric Comparison

With the selected urban areas surrounding city centre, transit station and a residential area within the three cities of Darmstadt, Frankfurt am Main and Offenbach am Main being analysed through the identified accessibility parameters, a categorical comparison through each parameter would assist in understanding different accessibility aspects of a similar typology of urban area. Some parameters have been explored further through added perspectives in previous chapters. These include perspective of user-groups with reduced mobility in Public Transport Accessibility Level (i.e. PTAL) for each urban area, or the large-scale (or citywide) perspective of potential direct routes favouring cycling through Normalised Angular Choice (i.e. NACH) measure involving Space Syntax methodology). Added observations based on the relationships between parameters have been further explored in this chapter, which include NACH, Integration values (local and global) and the respective characteristics involving movement of cyclists' data from crowding and movement in cities. This assists in understanding how different parametric characteristics of an urban area or a city, interact and influence the accessibility of a space. The inter-city parametric comparison through the three cities forming the Rhein-Main urban agglomeration is undertaken as follows:

5.1.1 Connectivity of street network

A good connectivity of a street network (not to be confused with the 'connectivity' attribute in Space Syntax theory) forming a particular urban area, showcases a favourable walking environment. The density of streets and street-junctions along with cul-de-sacs, due to the respective spatial configuration of an area, offers corresponding freedom of choice for a person to move in a space. The different urban areas in the study, have shown varying network of streets. These range from the streets being distributed or non-distributed in nature (Hillier & Hanson 1984). Distributed streets have a network of streets which generate different movement possibilities, while non-distributed streets often have cul-de-sacs (or dead ends) which lead to less diverse movement patterns (also acting as a barrier for active mobility planning involving walking).

The varying configuration of streets and spaces based on different typology of nine urban areas, especially through the network of links (or streets), nodes (or street junctions), and cul-de-sacs were observed, which showcased their respective connectivity ratios (or link-node ratio) as follows:

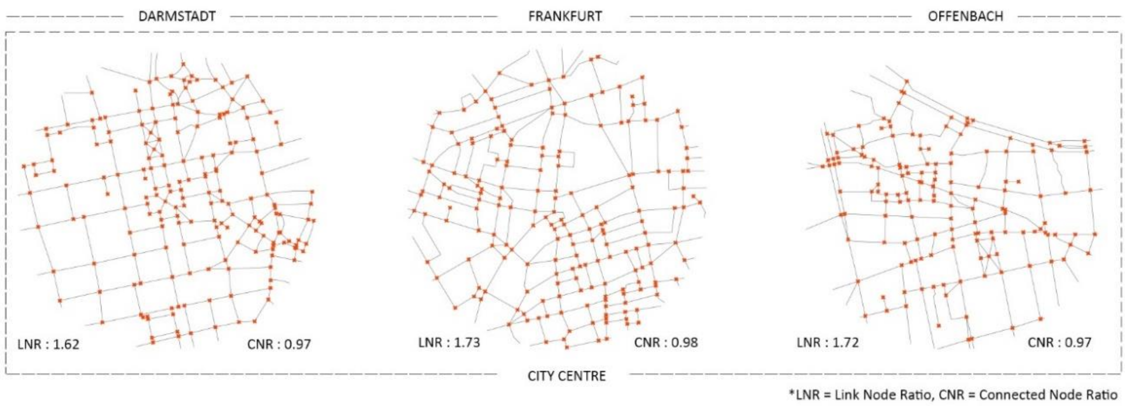
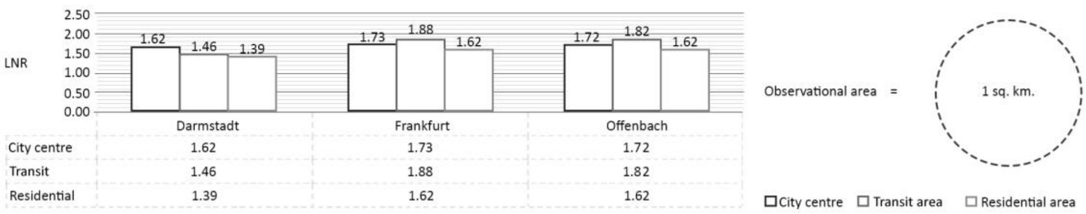


Figure 85: Street network with node density of area surrounding city centre in the respective cities of Darmstadt, Frankfurt am Main and Offenbach am Main (corresponding to 1 sq. km. area of observation)



	Darmstadt	Frankfurt	Offenbach
City centre	1.62	1.73	1.72
Transit	1.46	1.88	1.82
Residential	1.39	1.62	1.62

Table 29: Link-node ratio of areas surrounding city centre (also represented in maps), transit station (i.e. railway station), and selected residential areas in the respective cities of Darmstadt, Frankfurt am Main and Offenbach am Main (within 1 sq. km. area of observation)

Hillier, B. and Hanson, J. (1984), The social logic of space, Cambridge University Press, Cambridge, UK.

The network of streets in nine selected urban areas showcased link-node ratio to be greater or in close proximity to the value of 1.40 (see Table 29 and Fig. 85), which denotes a bare minimum for a walking network and a good ratio for a network planning process (Ewing 1996). Within the three cities, the area surrounding the city centres and the main transit stations (i.e. Hauptbahnhof) showed better link-node ratios as compared to the residential area which usually had a low connectivity. The residential areas had more spaces which were subject to non-distributed network of streets with higher frequency of cul-de-sacs in the urban area.

Considering the 'city centres', while the area in Darmstadt showed majority of streets following a linear pattern in the west, there was more angularity in the street network of the other two cities of Frankfurt and Offenbach. This angularity of streets is also observed towards the east in the city centre of Darmstadt, which usually denotes the old parts of the cities combined with variety of directional streets. This was also observed in Frankfurt am Main and Offenbach am Main, where the old part of the cities had denser network of streets with a certain angular characteristic in its network. The immediate streets around the central plaza in Luisenplatz act as a transitional space between the linear pattern in the west, and more angular pattern in the east (in Fig. 85); this is also observed in the area surrounding Hauptwache where the network of streets towards the district of Altstadt showcase denser network of streets with different directional streets in the southern area. The area around the city centre in Offenbach am Main showed a dense network of streets in proximity to river Main and castle, with more linear pattern and large block sizes towards the south. The nucleus of the old city centres has shown a certain relationship of dense network of streets which have led to a good walking network and also supported the high streets which are characterized by shopping areas, restaurants and mixed-use spaces.

The selected 'transit areas' in the two cities of Frankfurt am Main and Offenbach am Main have shown one of the most favourable walking networks in the cities, with more streets and junctions supporting freedom of movement and less cul-de-sacs which deter it. The large commercial and industrial space in proximity to the main railway station in Darmstadt reduced the density of streets and junctions in the corresponding area. Unlike the two transit stations in Darmstadt and Offenbach, the Hauptbahnhof in Frankfurt am Main is a terminal station with majority of its street network (within the observation area) in the east. This orthogonal network (see Fig. 58) includes a linear pattern of organized blocks and streets which form the neighbouring district and include more X-type junctions (i.e. 4 links for one node), which leads to higher link-node ratio and increased choice for movement as compared to T-or Y-type of junctions (unless one of the links is a cul-de-sac). The linking of streets across the rail tracks in the area also assisted in maintaining a good walkable network in the cities around railway stations. This includes the peripheral parallel bridges over the rail tracks in Darmstadt, or set of underpasses in the area surrounding Offenbach Hauptbahnhof.

The connectivity characteristic of the three selected 'residential areas' through the cities followed a similar hierarchy, which showed lower link-node ratio. With respect to the typology of case study areas, the residential areas of Frankfurt am Main and Offenbach showed similar link-node ratios as compared to the area surrounding the city centre in Darmstadt. This shows how different street environments can showcase similar walking network of streets. A downtown area (for e.g. Luisenplatz in Darmstadt) can have a network of streets which shows a similar characteristic to a suburban residential settlement (like that of Bürgel in Offenbach am Main). The residential area of Komponistenviertel with its detached housing and cul-de-sacs showed the least connectivity through its street network amongst the selected nine urban areas. While it still showed a good network of connectivity (or link-node ratio), the network could be improved on a large-scale perspective through better connections and limiting the density of cul-de-sacs where possible. With densification of the residential areas being planned under several urban development planning concepts, the residential planning when done with a good network of streets favouring walking environment would enhance the quality of stay and also assist in favouring the short-distance mobility in a long-term perspective.

5.1.2 Intelligibility and ease of navigation

Following a good network of streets favouring walking, an ease of navigation to move around through a configuration of open spaces further assists in accessing a particular destination in an area. In generic terms on a large-scale perspective, a maze-like network of streets would be difficult to navigate through as compared to an intelligible area. In order to understand the intelligibility of spaces through different urban areas in the study, the methodology involves utilization of the Space Syntax theory and its attributes via DepthmapX platform. The 'intelligibility' characteristic of an urban area is represented through the scatterplot of two attributes within Space Syntax i.e. Connectivity and Global integration. The higher the correlation between the two attributes is, the more intelligible and easier to orient through a built environment it is. The weak correlation interprets more segregation between the local streets and the main streets which are integral to the overall mobility of the area.

All three urban areas in the cities of Darmstadt, Frankfurt am Main and Offenbach am Main were mapped manually through a network of axial lines, which showcase the longest line of sight through an open space in a spatial configuration. The two attributes of Connectivity and Global integration (also represented in the Fig. 86) are correlated through scatterplots, leading to the coefficient of correlation of the selected nine urban areas as follows:

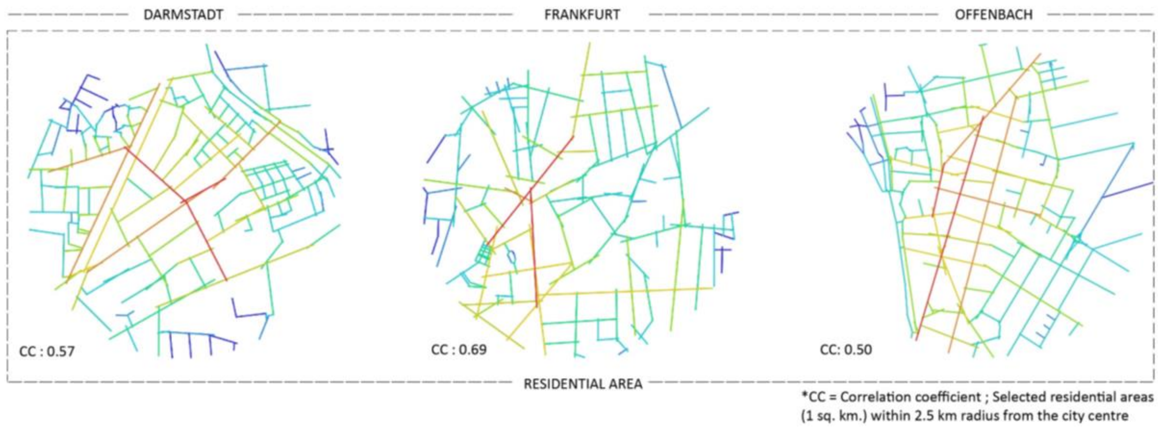
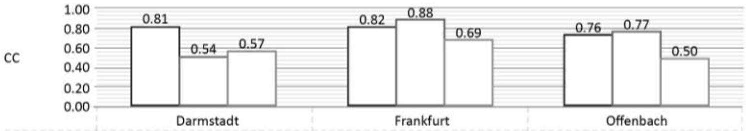


Figure 86: Street network representing global integration with corresponding intelligibility (via CC) of selected residential areas in the cities of Darmstadt, Frankfurt am Main and Offenbach am Main (within 1 sq. km. area of observation)



	Darmstadt	Frankfurt	Offenbach
City centre	0.81	0.82	0.76
Transit	0.54	0.88	0.77
Residential	0.57	0.69	0.50

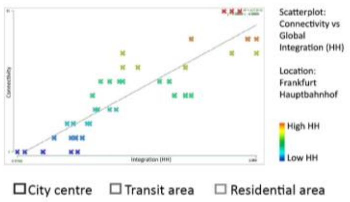


Table 30: Intelligibility characteristic (through correlation coefficient i.e. CC) of city centre, transit area, and selected residential areas (also represented in maps) in the cities of Darmstadt, Frankfurt am Main and Offenbach am Main

The network of streets in the selected nine urban areas showed varying intelligibility characteristic, with high (0.70 to 0.90) and moderate (0.50 to 0.70) correlation coefficient values (Hinkle et al. 2003). Within the three cities, the residential areas usually showed lower intelligibility characteristic (which also showed low link-node ratio in the hierarchy of areas), with an exception of transit area surrounding Darmstadt Hauptbahnhof, having a lower intelligibility than the residential area in Komponistenviertel (in Table 30).

The area surrounding the 'city centres' showed a high intelligibility characteristic. With respect to the city centre of Darmstadt, the network of streets with high integration values were in close proximity to the streets with low integration values. For example, the pedestrian pathways through the green open space in Herrngarten in the north-east from the central pedestrian plaza of Luisenplatz had multiple highly integrated streets (for e.g. the street of Bismarkstrasse being one of them) in close proximity to it. This enables a good connectivity of diverse open spaces ranging from the open pedestrian plaza including high street with shopping areas (like Ludwigsplatz), to the green open public spaces (like Herrngarten) through the integrated streets (in Fig. 31 and 46). In comparison to the network of highly integrated streets through the city centre in Frankfurt am Main, the set of axial streets formed a star-shaped network running in different directions from the central pedestrian plaza. Moderately integrated streets connected the Zeil shopping area through the old city towards the river Main in the south (in Fig. 59). Multiple integrated running streets in different directions around the pedestrian plaza in Hauptwache ensured a high connectivity to low-integrated streets resulting in high intelligibility. The city centre in Offenbach am Main had lower number of highly integrated streets in comparison to the similar areas in Frankfurt am Main and Darmstadt. The set of highly integrated streets in the street network ensured a better reach to low integrated ones, which in a way assisted in improving the intelligibility characteristics of the network of streets surrounding the city centres.

The selected 'transit areas' in the cities of Frankfurt am Main and Offenbach am Main showed a close proximity to the intelligibility characteristic of the city centres. This was different for the area surrounding the main transit station in Darmstadt. While the two parallel streets in the north and south of the main transit station in Darmstadt showed high integration values, the street network with low integration values were segregated in between (in Fig. 32 and 46) (for example, the streets towards the west of Hauptbahnhof had low integration, which also acted as cul-de-sacs). This led to the transit area having the lowest intelligibility characteristic in comparison to the similar areas in the cities of Frankfurt am Main and Offenbach am Main. The orthogonal street network in close proximity to the Frankfurt Hauptbahnhof assisted in its high intelligibility characteristic, as it helps in the understanding of the immediate neighbourhood following a similar logic of street pattern. The similar pattern through parallel streets on the north and south of Offenbach Hauptbahnhof, along with the set of highly integrated streets, reflected in the high intelligibility of spaces.

The selected 'residential areas' in the three cities showed a moderate intelligibility characteristic. The higher frequency of cul-de-sacs in the residential areas contributed to the high number of streets having low integration values in different areas. This in turn led to lesser reach of highly integrated streets in the residential area. Amongst the selected residential areas, Bornheim in Frankfurt am Main showed highly integrated streets running in different directions, which led to more opportunity of streets (especially the ones showing low integration) being in close proximity to the high integrated streets. This was reflected in its high intelligibility characteristic as compared to the other residential areas in the study. In general, the segregation of local streets from the highly integrated streets in turn

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Hinkle, D. E., Wiersma, W. and Jurs S. G. (2003), Applied statistics for the behavioral sciences, 5th Edition, Houghton Mifflin, Boston

supports the nature of privacy in the residential area, which has a negative impact on the navigable environment of the network of streets.

The large city of Frankfurt am Main dominated the intelligibility characteristic through the selected areas as compared to the comparatively smaller cities of Darmstadt and Offenbach am Main. Development of the urban areas with spatial configuration leading to multiple highly integrated streets in different directions and less cul-de-sacs are one of the contributing factors. On a large-scale perspective, the intelligibility of spaces could be improved through extension of highly integrated streets (where possible) to other streets in the network, which brings the main street closer to the segregated ones. While it is difficult to change the existing urban configuration of street network for brownfield projects, new street network (including pedestrian or cycling pathways) for new development projects can contribute to integration values of the streets (which influences intelligibility). For instance, based on the Integriertes Entwicklungskonzept Bürgel (Stadt Offenbach am Main 2018) the new network of streets around planned development projects in the east contribute positively to its intelligibility characteristic (see Fig. 87). Supporting the walking network through lower frequency of cul-de-sacs would assist in avoiding streets which show low integration values towards the immediate network of streets, and would help in reflecting better intelligibility of the space. With respect to the short-term goals of improving the ease of navigation through a street network, the utilization of signages especially in streets which are segregated from the highly integrated streets would be beneficial, which can also cater to different user-groups (for e.g. cyclists). An alternative route would be to locate distinct landmarks (e.g. street elements like benches, sculptures, urban landscape etc.) on streets with moderate or weak integration values, which brings a unique sense of belonging and addresses the immediate surrounding with better ease of navigation.

Figure 87: Influence of new street network on the intelligibility of the residential area of Bürgel in Offenbach am Main based on its Intergriertes Entwicklungskonzept (2018)

5.1.3 Access to Public Transport

The access to public transport via PTAL (i.e. Public Transport Accessibility Level) was undertaken through the selected urban areas in the three cities following a similar timeline. The accessibility levels determine how close or how frequent the public transport services are in an observational area, which leads to less waiting time and contributes towards a more robust mobility system in a city. A good range of PTAL encourages more people to utilize the public transport services in an area as compared

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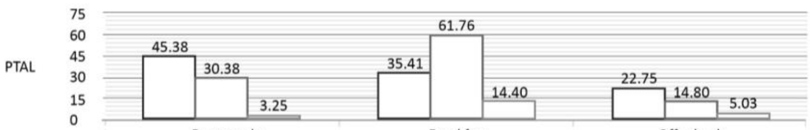
Stadt Offenbach am Main (2018), Bürgel Integriertes Entwicklungskonzept, Amt für Stadtplanung, Offenbach am Main, pp. 15-24.

to the one with lower PTAL value. The PTAL values in the three cities forming the Rhein-Main agglomeration were mainly contributed by the public transport services of buses, trams and trains (which included both underground and on-ground intra-and inter-city trains). As mentioned in the previous chapters, the observational radius for the public transport services was different. With respect to the methodology, 640 metres (i.e. approximate walk time of 8 minutes) was the maximum distance for bus services, while 960 metres (i.e. approximate walk time of 12 minutes) was the maximum distance for train (or tram) services. The information of the peak hour services was taken from the Rhein-Main-Verkehrsverbund (RMV) (2021) website. During the calculation of the respective urban area's PTAL value, a normal human walking speed i.e. 4.8 kph was considered to calculate the walking time to reach the service station (for example, a bus stop). The perspective of user-group with reduced mobility was undertaken in previous chapters (in 4.3.3.1, 4.6.3.1 and 4.8.3.1) to examine the prioritization of services resulting in lower PTAL values. For more details on the methodology, Chapter 3 (in 3.1.3) discusses the approach for calculating PTAL value within an observational area.

The PTAL for the three selected areas in the cities of Darmstadt, Frankfurt am Main and Offenbach am Main were calculated (in Table 31) resulting in following values:

Figure 88: Figure ground maps of the city centres in Darmstadt, Frankfurt am Main and Offenbach am Main with corresponding PTAL values



	Darmstadt	Frankfurt	Offenbach
City centre	45.38	35.41	22.75
Transit	30.38	61.76	14.80
Residential	3.25	14.40	5.03

PTAL INDEX

GROUP	RANGE
6 B (HIGH ACCESS)	40.01 +
6 A	25.01 - 40.00
5	20.01 - 25.00
4	15.01 - 20.00
3	10.01 - 15.00
2	5.01 - 10.00
1 B	2.51 - 5.00
1 A (LOW ACCESS)	0.01 - 2.50

☐ City centre ☐ Transit area ☐ Residential area

Table 31: Public Transport Accessibility Level of areas surrounding city centre, transit area, and selected residential areas within the respective cities of Darmstadt, Frankfurt am Main and Offenbach am Main

The hierarchy of urban areas showing their respective PTAL values was similar within the cities of Darmstadt and Offenbach am Main, where the city centres showed a higher access to public transport

Rhein-Main-Verkehrsverbindung (2021), Timetables, Frankfurt. Retrieved from https://www.rmv.de (01-01-21) services followed by areas surrounding the railway station and the residential area. The selected residential areas in all three cities showed lower PTAL values reflecting lack of diverse means of public transport with low frequency of services. With respect to the diversity of public transport services, the city of Offenbach did not have a network of trams which was present in Darmstadt and Frankfurt am Main.

Access to public transport services in city centres fell within the high access range above group 5 (i.e. above PTAL value of 20.01) in the PTAL index, with the city centre in Darmstadt dominating over the city centres in Frankfurt am Main and Offenbach am Main. With Frankfurt being a larger city and having train, bus and tram services within the area surrounding of its city centre in Hauptwache, the area around Luisenplatz in Darmstadt had higher access level with only bus and tram services (see Table 31), as it lacked train services in proximity. The on-ground level access to buses and trams being in the central plaza of the city centre in Darmstadt, with group of close service stations, contributed to its higher access while in Frankfurt the services in proximity to the city centre were mostly underground, which took longer travel time. The area around Marktplatz in Offenbach am Main showed a good access to public transport via underground train and on-ground bus services, but had a lower access in comparison to the city centres of Darmstadt and Frankfurt am Main.

The selected transit area in Frankfurt am Main showed the highest level of access to public transport services as compared to the city centre and the residential areas. The high frequency of train services contributed to more than 50% of the overall PTAL value in the area surrounding Frankfurt Hauptbahnhof, which itself was higher than the overall PTAL values in the transit areas of Darmstadt and Offenbach am Main. With respect to the range of PTAL values, the area surrounding main railway stations in Frankfurt am Main and Darmstadt fell within the high access range group 6 (B and A respectively) (see Table 31). The area surrounding Offenbach am Main Hauptbahnhof included public transport services of trains and buses, where the bus services contributed to more than 80% of the overall PTAL value. This showed the poor contribution of train services in the Offenbach Hauptbahnhof area, which could also be reflected through the absence of S-Bahn train services, which were present in the city centre of Offenbach am Main i.e. Marktplatz. While the contribution by bus services towards the PTAL of area surrounding Darmstadt Hauptbahnhof was similar to that of Offenbach Hauptbahnhof, the added frequency of trains and presence of tram services in Darmstadt contributed to its higher access levels to public transport as compared to Offenbach am Main Hauptbahnhof.

The PTAL values of the selected residential areas reflected low access to public transport services especially in Darmstadt and Offenbach am Main (in Table 31). The residential area of Bornheim in Frankfurt am Main had access to all three services of trams, trains and buses within the observational radius of the respective transport services, which resulted in a comparatively higher PTAL value (this was similar to the PTAL value of transit area surrounding Hauptbahnhof in Offenbach am Main). The public service stations in the residential areas, i.e. bus stops, of Offenbach am Main and Darmstadt were positioned differently, which also had an impact on the area's PTAL. While the bus stops were positioned on the streets forming the inner parts of the residential area in Bürgel; in Komponistenviertel, they were placed on the peripheral roads of the residential area. This resulted in longer walking time from the central landmark of the residential area in Darmstadt as compared to that of Offenbach am Main, which contributes to a lower PTAL in Komponistenviertel.

With many urban development plans through the selected cities focusing on densification of residential settlements (for example, the identification of potential areas in the residential neighbourhoods of Bürgel in Offenbach am Main or Komponistenviertel in Darmstadt), a higher level of access to the public service stations would be required. The positioning of the public service stations plays an important role in reducing the overall movement time, as observed in the study involving the two residential areas in Darmstadt and Offenbach am Main. The study also showcases how a city centre in a comparatively smaller city has a better access to public transport services as compared to a city centre in a large city within the same urban agglomeration (even with less diverse public transport services). At the same time, the highest PTAL value was also observed in the selected urban area of the largest city in the study i.e. Frankfurt am Main, followed by the neighbouring city of Darmstadt. Improving the access levels by increasing peak hour frequency of public transport services, or through better placement of the stations with respect to the urban configuration of an urban area assists in providing a fast-mobile network considering the priority is also given to the user-groups with reduced mobility.

5.1.4 Potential of Direct Routes

The network of streets within an urban space showcase certain attributes which favour particular user-groups with their mode of movement. Cyclists are a user-group which can transition from a pedestrian view-point of movement in space to a fast-moving group often sharing the space with motorized vehicles in cities. Within the network of streets, there are certain routes which favour the cyclists with respect to least deviation of movement, and at the same time being the shortest route between an origin and a destination point. The Normalised Angular Choice (i.e. NACH) measure within the Space Syntax theory, assists in producing a more visual perspective of routes having the potential of directness for cycling. Considering the nine urban areas in the selected cities forming the Rhein-Main urban agglomeration, the streets were mapped based on two perspectives i.e. small-scale and large-scale. For the comparison of street network within the selected urban area, small-scale perspective is utilized while the citywide scale with 2.5-kilometre observation radius helps in understanding a larger network of streets. This assists in understanding how the main network of potential cycling routes integrate on different scales for implementing long-term active mobility plans for a city.

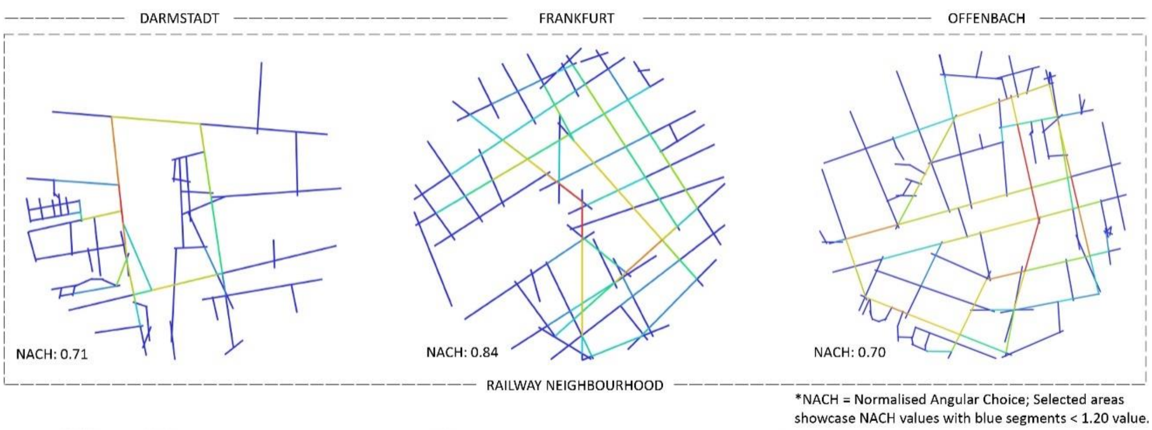
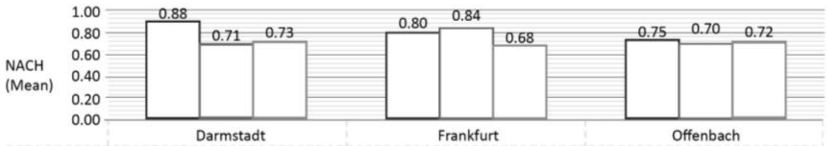


Figure 89: Segment maps showing mean NACH values for the selected transit areas in Darmstadt, Frankfurt am Main and Offenbach am Main

The Normalised Angular Choice (NACH) network for the nine urban areas in the cities of Darmstadt, Frankfurt am Main and Offenbach am Main were produced with following values on a small-scale perspective:



	Darmstadt	Frankfurt	Offenbach
City centre	0.88	0.80	0.75
Transit	0.71	0.84	0.70
Residential	0.73	0.68	0.72

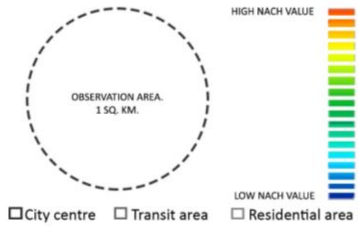


Table 32: Mean NACH values of area surrounding city centre, transit area, and selected residential areas in the respective cities of Darmstadt, Frankfurt am Main and Offenbach am Main

The street network of area surrounding the city centres in Darmstadt and Offenbach am Main showed maximum mean NACH values in comparison to the other residential and main transit area within their cities. While in Frankfurt am Main, the street network surrounding the main transit station showed maximum mean NACH value in the city (within the three selected urban areas). The network of streets within the small-scale perspective through areas showcased their potential for having direct routes for cycling, and later the combined understanding along with the on-site frequency of cyclists through different points in the areas (via crowding and movement restriction methodology) helped in reflecting how the streets were utilized by the user-group.

The city centres generally showed a high range of mean NACH values within the cities of Darmstadt, Frankfurt am Main and Offenbach am Main. The network of direct bicycle routes through the city centres showed different patterns based on their spatial configuration. The city centre in Darmstadt i.e. Luisenplatz showed direct routes with high NACH values around the central landmark and the peripheral areas in the east, with a buffer of street network with low NACH values in between (see Fig. 52 and 31). This pattern was unique in comparison to the street network surrounding the city centres in Frankfurt am Main and Offenbach am Main, where the street segments with high NACH value were present in proximity to the central landmark of the urban area. This in turn reflected towards the city centre in Darmstadt having the highest mean NACH value through its immediate network of surrounding streets, even in comparison to the large city of Frankfurt am Main. With respect to the street network around Hauptwache, the streets merging towards the central open plaza had high NACH values, with two routes moving towards the south via Altstadt showing the potential for directness linking the central pedestrian plaza to the river Main in south (see Fig. 66 and 23). These would be beneficial with the agenda of linking the two areas within the urban development plans of Frankfurt in the city centre. The Marktplatz in Offenbach am Main, had a similar scenario with the central street of Berlinerstrasse playing a major role for cycling in east-west direction. With river Main in the north, the street through the HfG connecting the riverside with the central landmark showed high potential for cyclists (see Fig. 80 and 38). This would also be an important street segment considering the future urban development plans of the city of Offenbach am Main, which focuses on a potential bridge for pedestrians and cyclists over Main river falling on the northern end of the segment.

The segment analysis via NACH on the spatial configuration surrounding the main transit stations with consequent street network, resulted in the area surrounding Frankfurt Hauptbahnhof showing the highest mean NACH value. The high density of orthogonal street network in the east of the main transit station (see Fig. 25) along with street segments with high NACH value in front of the Hauptbahnhof entrance (in Fig. 89) supported its high potential with direct routes for cycling in the immediate area. With respect to Darmstadt and Offenbach am Main, their transit area showed similar mean NACH values with street segments with highest NACH values observed in area away from the main entrance to the central railway station. In Offenbach am Main, the street segments with highest NACH value also supported the new bicycle street situated on the southern end of the railway station through the Senefelderstrasse (in Fig. 40), although with respect to the highest NACH valued street segment in the area surrounding Darmstadt Hauptbahnhof, it lacked a dedicated bicycle pathway (for instance, the street adjacent to western end of Hauptbahnhof in Fig. 89 and 32). This example showcases the underutilization of a street's potential for cycling in different areas on a small-scale perspective.

The residential area of Bornheim in the city of Frankfurt am Main showed the least mean NACH value amongst the selected nine urban areas for the study. Considering the street network showing high potential for direct bicycle routes, the street segments with high NACH value passed through central areas of the residential street network. This assists in providing access to active mode of cycling through the central areas of the residential areas, which later have distributed streets to different housing units. With respect to the residential area of Bürgel in Offenbach am Main, the riverside pathway for cyclists and pedestrians showed above-average NACH value (see Fig. 42 and 80) which was supported by the close street connectivity with the central Langstrasse street (showing high NACH value). The street parallel to Langstrasse in east is currently utilized as the new bicycle street, similar to Senefelderstrasse in proximity to southern end of the Offenbach Hauptbahnhof. While the street of Langstrasse has higher potential for cycling, it is subject to one-way traffic movement with narrow street network in the area. Within the future urban development plans of the city, the street of Langstrasse will be subject to less vehicular traffic with alternative street options via Mainzer Weg being identified to divert traffic flow, which alters the present functionality of the street and favours its potential for cycling.

Considering the large-scale perspective (with observational area of 2500 metres in radius), the segments showing potential for direct bicycle routes (higher NACH values), fell around the city centre in Frankfurt with an average and maximum value of 0.74 and 1.60 respectively (in Fig. 67). With respect to Darmstadt, the high potential segments showcased a shift towards the eastern end from the city centre with an average and maximum value of 0.68 and 1.58 respectively (in Fig. 53). In Offenbach am Main, the direct routes led to average NACH value of 0.64 with maximum 1.54 value along Mainstrasse connecting the city centre to the residential area of Bürgel (in Fig. 81). While the high-valued NACH segments passed through the central core of the city in Frankfurt and Offenbach, for Darmstadt the shift was observed towards east. The low density of network due to industrial land-use in west, shows the influence on the closeness of direct routes in Darmstadt. With ongoing inter-city bicycle highway projects, these potential streets with high NACH value can be utilized to identify a network of street segments responsible for continuous direct movement of cyclists which connect to existing cycling pathways.

The identification of potential streets favouring cycling is beneficial, especially with the urban development plans (like masterplans) being made, to understand and alter the characteristic of street network in continuum with urban experiments like Fahrradstrasse (i.e. bicycle street) as seen in the selected urban areas in the study (for e.g. in the transit and residential areas of Offenbach am Main). A street network of direct routes once connected and prioritized via dedicated bicycle pathways with large-scale perspective in place would assist in providing a robust cycling network. The identified street networks in the selected urban areas does not take into consideration the slope of the street segments. For a cycling lane, a preferred maximum slope between 6% (Ministerium für Verkehr 2018) to 10% (CROW 2007) should be prioritized (for example, a 10% slope relates to 10m drop or rise in 100m

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Ministerium für Verkehr (2018), Qualitätsstandards für Radschnellverbindungen in Baden-Württemberg, Baden-Württemberg, Germany.
CROW (2007), Design Manual for Bicycle Traffic, Utrecht, Netherlands.

length of lane). If a certain street segment with slope higher than the maximum permissible slope shows high NACH value, an alternative street with lower NACH value can be prioritized based on the on-site study through frequency of cyclists and tactical urbanism.

5.1.4.1 NACH vs Frequency of cyclists

The difference between the utilization of a space and its potential for specific user-groups can vary based on several factors. In the case of a specific user-group i.e. cyclists, they would usually prefer a network of streets which showcase directness with least deviation of movement based on shortest-route choice, considering the other factors (like quality and safety of dedicated lanes) are equal. With the frequency of cyclists available during the peak hours on selected street sections (based on the crowding aspect), the values were correlated with the corresponding NACH values which fell within the 2500m observation radius on the large-scale perspective. This helps in understanding how the cyclists in the cities, irrespective of the urban area, utilized the direct routes and which areas acted as a barrier if they did.

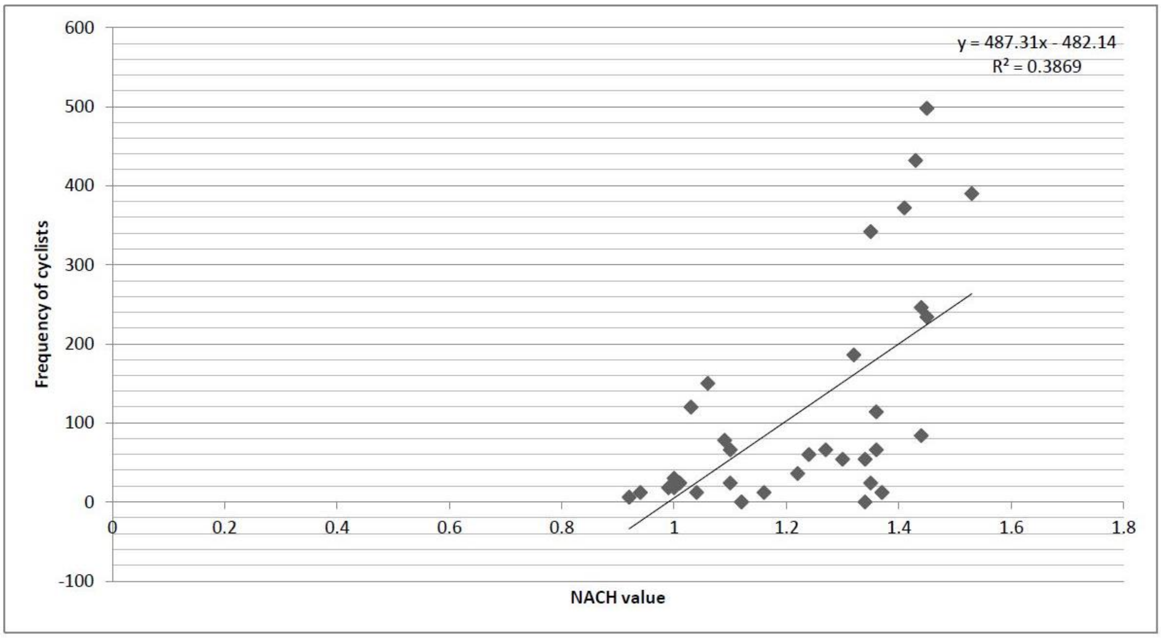


Figure 90: Scatterplot showing correlation between the NACH values of the selected street segments and their respective peak hour frequency of cyclists in the city of Darmstadt

In addition, if there were street sections which fell at the intersection of two segment lines carrying two NACH values, an average of the two segments was taken into consideration for the correlation. With respect to approximately 103 street data points (or selected street sections) through the selected urban areas in the three cities, positive correlation was observed between the frequency of cyclists and NACH values. With p-values (<0.05), i.e. the probability of the observed result occurring with no relation between the two parameters, the resulting correlation coefficients were statistically significant in nature. This means that there was a tendency of cyclists using the direct routes which had higher NACH values within the selected street network in the cities. While the positive correlation directs towards the mobility behaviour of the particular user-group (i.e. cyclists) using these street segments, the strength of correlation also presents a perspective on how different surrounding environments (via different cities) reflect its mobility culture (responding to the second research question).

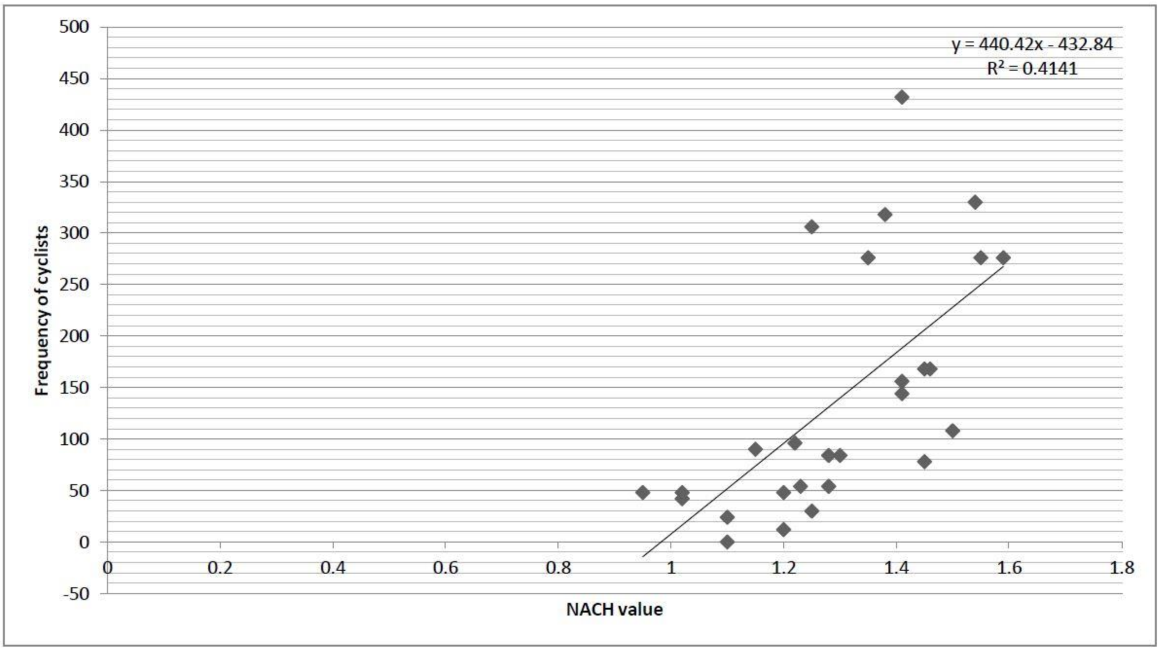


Figure 91: Scatterplot showing correlation between the NACH values of the selected street segments and their respective peak hour frequency of cyclists in the city of Frankfurt am Main

The cities of Darmstadt and Frankfurt am Main showed a moderate positive correlation with their correlation coefficients as 0.62 and 0.64 respectively (in Fig. 90 and 91). In contrast, the city of Offenbach am Main had a relatively low positive correlation with the correlation coefficient value of 0.31 (in Fig. 92). The p-values for the correlation between the NACH values of the street segments and the peak hour frequency of the cyclists in Darmstadt and Frankfurt were low i.e. 0.0001 and 0.0003 respectively. This showed the correlation and relation to be statistically significant. While the correlation was also significant in the city of Offenbach am Main, the p-value was close to the 0.05 value i.e. 0.0435. The low positive correlation in the city of Offenbach am Main suggests that the cyclists were not fully utilizing the potential of direct routes within the city, which often led to short routes and less deviation in movement. With northern riverside cycling boulevard and indirect connections to direct pathways, the streets having higher NACH values in the city were underutilized, i.e. underutilization of direct bicycle routes by the cyclists. One of the other reasons for the low correlation could be the cars dominating the direct routes in the city, which on certain segments also lacked dedicated bicycle pathways (for instance, the street adjacent to the eastern pedestrian boundary of Marktplatz (see Fig. 38 and 80)). These factors lead to the potential routes being less attractive to the cyclists and forcing them to choose alternative routes in the city. This acts as a barrier in facilitating accessibility to multimodal urban mobility system, where the potential of street segments is not utilized and has a negative impact.

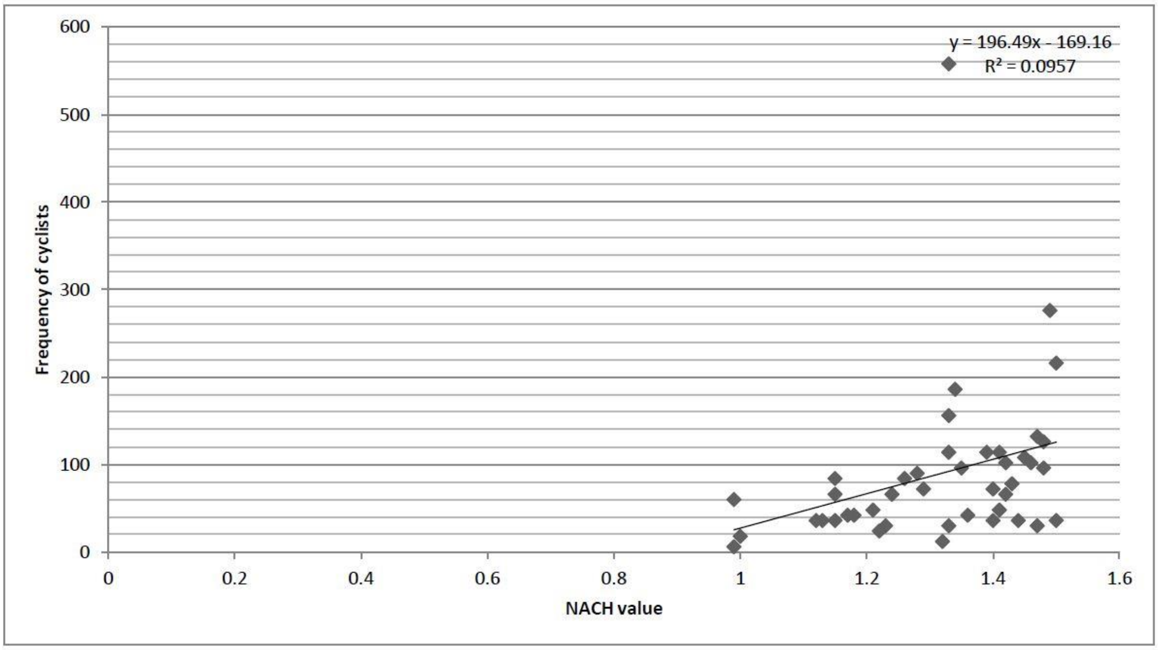


Figure 92: Scatterplot showing correlation between the NACH values of the selected street segments and their respective peak hour frequency of cyclists in the city of Offenbach am Main

With the selected street sections showing their resulting NACH values and peak hour cyclists' frequency (from on-site data collection), more street sections could be added in future research studies to have a wide collection of street data points and an in-depth correlation. This would assist in identifying a large domain of street segments which are being utilized by the cyclists and other user-groups on-site. The street sections selected for the correlation lie within the nine selected urban areas, which is more like an urban acupuncture study; and with more urban areas and on-site data points, it would assist in understanding the network routes and its on-site route utilization in depth.

5.1.5 Crowding and Movement Restriction

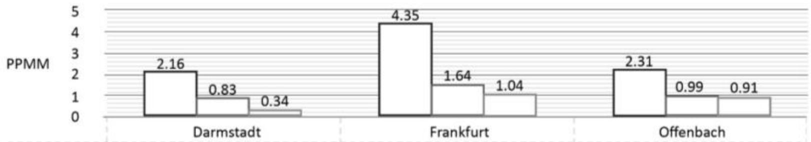
The ease of accessing an urban space can be characterized by the movement of people through different urban areas and the restrictions they may face while moving on street. Based on in-situ data collection through different peak hours during the day, reflecting different typology of urban areas, crowding and restriction of movement on a street was observed. This accessibility parameter looks into the movement restrictions caused by the street elements, which include (but are not limited to) on-street parking, signages, benches etc., and density of people through the available street space for pedestrians and cyclists. The crowding (measured in ppmm i.e. persons per metre minute) evaluates different areas through control gateways (see Fig. 19) based on different categories of spaces, which include high streets, office and retail, residential, tourist and transport interchange areas.

The control gateways were selected based on the reconnaissance study and street network characteristics from the previous accessibility measures. The measurements of the street sections (or control gateways) were carried forward prior to the on-site data collection of user-group frequency. Based on available footway width to move, after the buffer spaces from the street elements were deducted, the frequency of users was utilized in producing the crowding measure of the selected street sections through a mean value in selected urban areas as follows:

Gateways:	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Pedestrians	684	2268	1050	1470	684	3456	14190	3624	2706	1404	3642	12	2046	312
Cyclists	54	330	96	318	24	78	276	432	108	84	276	0	306	30
URM	0	6	6	6	6	6	48	18	6	0	12	0	6	0
Baby strollers	6	66	18	18	6	96	192	36	48	30	102	0	54	0
Boards/Scooters	36	24	0	36	12	0	54	36	6	24	24	0	30	12
Four Wheelers	486	186	78	138	0	0	0	96	0	510	0	0	30	396
Two Wheelers	12	30	18	24	0	0	0	12	0	12	0	0	0	6
Total	774	2622	1146	1824	720	3534	14520	4092	2820	1512	3942	12	2382	354
Footway Width	5.46	14.23	6.58	10.1	3.02	8.24	20.18	7.47	11.3	7.82	14.62	1.97	8.49	8.15
ppm	141.76	184.26	174.16	180.59	238.41	428.88	719.52	547.79	249.56	193.35	269.63	6.09	280.57	43.44
ppmm	2.36	3.07	2.90	3.01	3.97	7.15	11.99	9.13	4.16	3.22	4.49	0.10	4.68	0.72

Selected neighbourhood (1 sq. km.) with corresponding peak hour crowding through different streets.

Figure 93: Control gateway showcasing highest crowding (in ppmm) and corresponding movement restriction on the street of Zeil in the city centre of Frankfurt am Main



	Darmstadt	Frankfurt	Offenbach
City centre	2.16	4.35	2.31
Transit	0.83	1.64	0.99
Residential	0.34	1.04	0.91

PPMM (Persons Per Metre Minute)

GROUP	MOVEMENT RESTRICTION	RANGE
D (UNCOMFORTABLE)	100%	27.00 - 35.00
C	59%	19.00 - 26.00
B-	50%	15.00 - 18.00
B	41%	12.00 - 14.00
B+	31%	9.00 - 11.00
A-	22%	6.00 - 8.00
A	13%	3.00 - 5.00
A+ (COMFORTABLE)	<3%	<3 ppmm

☐ City centre ☐ Transit area ☐ Residential area

Table 33: Mean crowding values (in ppmm) of areas surrounding city centre, transit area, and selected residential areas in the respective cities of Darmstadt, Frankfurt am Main and Offenbach am Main

The hierarchy of crowding values through the three selected cities forming the Rhein-Main urban agglomeration was similar, with the city centres playing a dominant role, followed by areas surrounding the main transit station and the selected residential area. The selected residential areas in the three cities showcased lower crowding values, but they also represented lower mean pathway widths for movement as compared to city centre and transit areas. The overall mean crowding values remained in proximity to the comfortable range of movement restriction (i.e. 13%) and had mean crowding values within 5 ppmm.

The areas surrounding the city centres in Darmstadt, Frankfurt am Main and Offenbach am Main showed comparatively higher crowding values and associated movement restrictions. The city centre of Frankfurt had the highest individual and mean crowding values of 12 ppmm and 4.35 ppmm respectively (see Fig. 93 and Table 33). The mean crowding value of the city centre in the large city of Frankfurt am Main was almost double the value observed (in the city centre) in comparatively smaller city of Darmstadt (and Offenbach am Main). While the control gateways with highest crowding values were observed around the shopping streets (or high streets) in the city centre of Darmstadt and Frankfurt am Main, the northern cycling boulevard next to Main river in Offenbach had the highest crowding value in contrast (in Table 28). The high crowding on streets other than the ones surrounded by the shopping and retail areas in the city centre demonstrate the diversity of spaces which attract and propagate individual movement through different user-groups.

The main transit area around the Frankfurt Hauptbahnhof had the highest peak hour crowding and associated movement restriction, which stayed close to the comfortable range, in comparison to the selected transit areas in Darmstadt and Offenbach am Main. Although the transit area surrounding Offenbach Hauptbahnhof had low access to public transport (i.e. via PTAL) as compared to Darmstadt

Hauptbahnhof, the area in Offenbach recorded more movement within comfortable range which could be attributed to its close proximity to the city centre and dense urban settlement areas as compared to immediate area surrounding Darmstadt Hauptbahnhof (which had industrial area in proximity).

The peak hour crowding values of the selected residential areas were within the comfortable range in each city, with Komponistenviertel (i.e. the residential area in Darmstadt) showing the least crowding value and associated movement restriction as compared to Bornheim in Frankfurt am Main and Bürgel in Offenbach am Main. The higher population of inhabitants in the residential area of Frankfurt am Main influences the high crowding values, while the presence of detached housing units (for example, in Komponistenviertel residential area) and lower population density results in lower peak hour crowding in the cities of Darmstadt and Offenbach am Main. The narrow streets in the residential areas, also lead to low mean pathway widths available for movement, although the frequency of people moving was the least. With future urban development plans identifying residential areas (for example, potential for new housing units in Bürgel and Komponistenviertel based on master plans) to provide dense housing areas due to increasing population in the city, the peak hour crowding would increase but the narrow pedestrian pathways and absence of cycling lanes in some streets (see Appendix A3) would create a barrier in short-distance mobility.

Considering the available pathway widths for active user-group's movement, the streets in the residential area of Bürgel (through the selected gateways) had widths less than 3 metres, while the area of Komponistenviertel and Bornheim had much larger mean pathway widths (with Bornheim having the largest mean width of 5.25 metres). With residential areas being identified for future densification through housing projects, the narrow streets (especially in the selected residential areas of Darmstadt and Offenbach) would lead to higher crowding values and movement restriction. In contrast, the control gateways in the city centre of large city of Frankfurt showed the highest crowding values which was close to uncomfortable range of crowding values. While the street of Zeil and its surrounding network of neighbouring areas assisted in through movement, the overcrowding with increasing population and incoming tourists acts as a barrier for movement especially for vulnerable user-groups including users with reduced mobility, kids etc. Tactical urbanism and urban experiments would assist in understanding ways to improve the present condition of environment for active user-groups and identifying potential ways of supporting different modes of mobility. A similar case in Frankfurt Mainkai, in proximity to the city centre of Frankfurt, was seen as an opportunity to look through an urban area as a shared space and utilize some of the identified accessibility parameters in combination via practice-based research approach to see its potential leading to short-term and long-term recommendations favouring mobility.

5.2 Case of Frankfurt Mainkai road-closure experiment

The northern boulevard on the Mainkai stretch alongside river Main has had its share of dense vehicular traffic, few metres away from the pedestrian zone, which in contrast has a mixture of user groups using the space ranging from cyclists, e-scooter users, parents with baby strollers, to users with reduced mobility. Since August 2019, the Mainkai street was closed to vehicles temporarily for a year between the Untermainbrücke and Alte Brücke (which is the oldest bridge through the lower course of the river), bringing the vehicular traffic to a halt and encouraging pedestrians and cyclists to utilize the area (see Fig. 94). With the onset of the road-closure experiment, the research cooperation with the City of Frankfurt was undertaken by the Urban Health Games research group (now Urban Design and Planning Unit) at TU Darmstadt. The objective of cooperation was to reflect on the influence of the experiment on the movement of people using the space with conclusions and recommendations. This contributes towards the propagation of the research framework (in Fig. 1). This is done by utilizing some of the identified accessibility parameters, which assists in understanding the street configuration, and utilizing them for the urban development timeline.

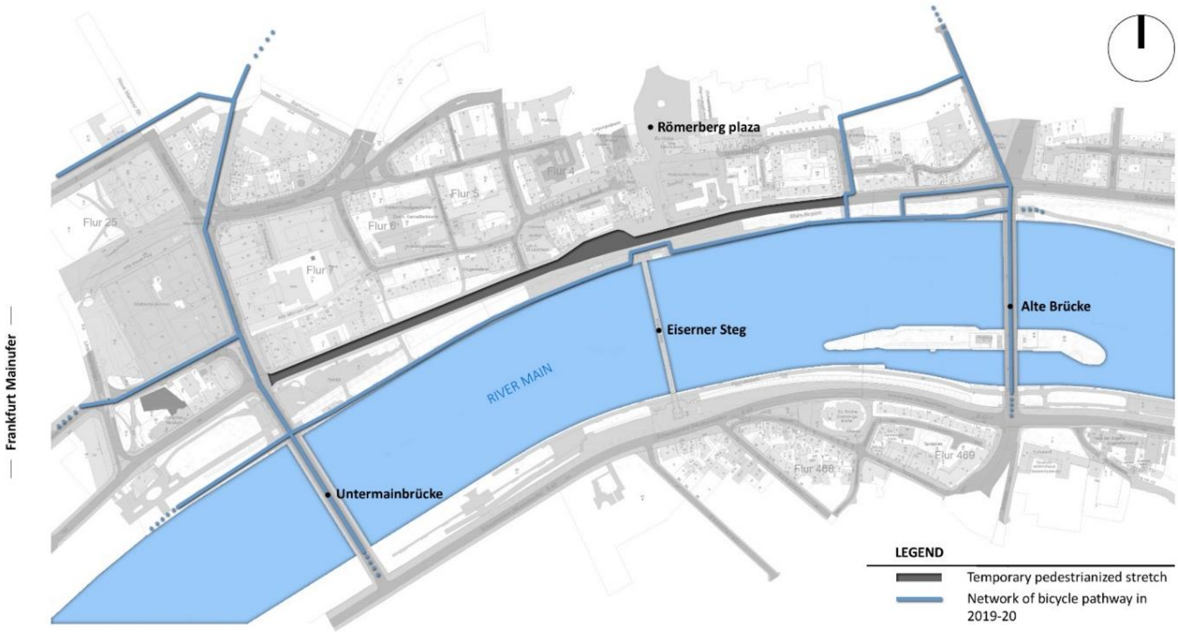


Figure 94: Frankfurt Mainkai and its surrounding areas with bicycle pathways and closed street of Mainkai for car-traffic in 2019-20 (Pandit et al. 2020)

On-site, between the two bridges, the Mainkai street is connected to the southern riverfront through a pedestrian bridge i.e. Eiserner Steg (see Fig. 94). The bicycle network during the road closure ran majorly through the two bridges i.e. Untermainbrücke and Alte Brücke, followed by peripheral street network leading through the Wallanlagen, i.e. the green ring of parks which run through the former footprint of the old walls of the city. The network was also present under the two bridges and ran around the entrance of Eiserner Steg, which shares the space with other pedestrian users. The bicycle pathways leading towards the Römerberg plaza gave priority to the pedestrians walking within the pedestrian zone, which initiates in front of the Eiserner Steg, and further expands in north towards the city centre i.e. Hauptwache. Following the road-closure, the traffic lights for the pedestrian crossing at several locations along the Mainkai streets were closed, though the physical infrastructure was still present at their respective locations with the temporary nature of the tactical urbanism experiment.

Methodology and analysis

The road-closure study was mainly divided into two categories i.e. crowding and movement restriction, which assists in understanding the on-site scenario of different user groups using the space through the pre-selected areas based on reconnaissance study; and spatial configuration and analysis, which involves utilizing Space Syntax measures in order to analyse and foresee different user group movements (mainly users walking and cycling) in pre- and post-road closure scenario.

The three-part analysis initiates with spatial analysis involving pre-and post-road closure scenario being axially mapped in order to lead towards the local integration network. The network is later converted into segment map for the normalisation of angular choice analysis. In order to distinguish

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Pandit, L., Fauggier, G.V., Gu, L. and Knöll, M. (2020), How do people use Frankfurt Mainkai riverfront during a road closure experiment? A snapshot of public space usage during the coronavirus lockdown in May 2020, Cities & Health, DOI: 10.1080/23748834.2020.1843127 between different horizontal layers of pedestrian movement through the two-dimensional map, post axial mapping of the network, the axial network was filtered again through bridge connections, i.e. the axial lines (pedestrian pathways) going under the bridge at Untermainbrücke and Alte Brücke were unlinked from the axial lines running through the bridge. This task was undertaken to rectify any errors caused during the local integration analysis in DepthmapX software. Similarly, with respect to pedestrian bridges over vehicular highways, the corresponding axial lines were unlinked along the B8 highway in Frankfurt am Main. In regards to the crowding and movement restriction analysis, on-site the data was collected during the morning (8:00-9:00), afternoon (14:00-15:00) and evening (17:00-18:00) peak hours for two weekdays and one weekend during the summer months for 3 years. Different control gateways were located on streets influencing the influx of different user-groups utilizing the Mainkai street. The planned undertaking of the on-site data collection was a group effort, led by the author, which has produced the data in this sub-chapter.

Figure 95: Pedestrian crossing adjacent to Eiserner Steg (on right), leading towards Römerberg plaza in Frankfurt (in 2019)

Local axial integration network

The local integration map for the Mainkai riverfront was generated, with higher values of integration (local) as red and lower values of integration (local) as blue. The high local integration values were observed in the north axial line passing through the Römerberg public plaza (see Fig. 96), which includes the picturesque timber houses on the old town square, leading towards the Eiserner Steg pedestrian bridge in the southern end. The high local integration values were followed by the axial lines on the north west transport junction of Willy-Brandt Platz. This predicts an overall high pedestrian flow along the Römerberg street, prior to the road closure on the Mainkai street. The parallel pedestrian pathways were present on the peripheral northern and southern edges of the Mainkai street, which had the vehicular traffic, with in-between pedestrian crossing through traffic lights (see Fig. 95). The streets with low integration values suggest a lower pedestrian traffic as compared to higher integration values, and can be utilized to divert or ease the overall pedestrian flow in order to have a comfortable pedestrian flow with least movement restrictions.

Figure 96: Local integration before the road closure of the Frankfurt Mainkai street

The post-road closure scenario was visualized through the adjacent axial map (see Fig. 97) and analysed through local integration measure. As compared to the earlier scenario, a shift of highly integrated axial line was observed over the intervention site, initiating from the western end adjacent to the Untermainbrücke. The intervention improved the earlier integration of the two parallel axial lines, which were the pedestrian pathways, now converted into one single and longer highly integrated axial line which has its ends connecting the streets leading towards the Römerberg plaza, followed by the adjacent street segments connecting the Alte Brücke. The pedestrian bridge i.e. Eiserner Steg now becomes more integrated (in Fig. 97) as compared to the earlier scenario (in Fig. 96).

Figure 97: Local integration depicting the post-road closure condition of the Frankfurt Mainkai street

Comparing the shared pathway between the pedestrians walking and cycling along the Mainkai riverside, the stretch becomes more integrated in the post-road closure scenario as compared to the pre-road closure. The intervention assists in integrating the pathway through the pedestrianized stretch, connecting the streets more closely, in turn integrating the network of streets between the city centre in the north and the Mainkai boulevard. This assists in generating an improved urban network for different user groups moving from city centre towards the riverfront area and vice versa (which is also one of the main objectives under the urban development plans around the city centre of Frankfurt am Main).

Normalisation of angular choice network

The normalised angular choice network of Frankfurt was generated with a radial distance of 2500 metre (similar to the large-scale perspective for NACH analysis in Frankfurt am Main), involving a total of 9220 segment lines where red segments have higher NACH values (highest recorded as 1.596) and blue segments have NACH values below 1.20 (see Fig. 98). Approximately 4% of the segment lines had NACH values greater than 1.44, with an overall mean value of .737996 (~.74). Considering the travel manoeuvre of cyclists, where their movements tend to have the least angular deviation along the travel path, the NACH network is observed around Frankfurt Mainkai.

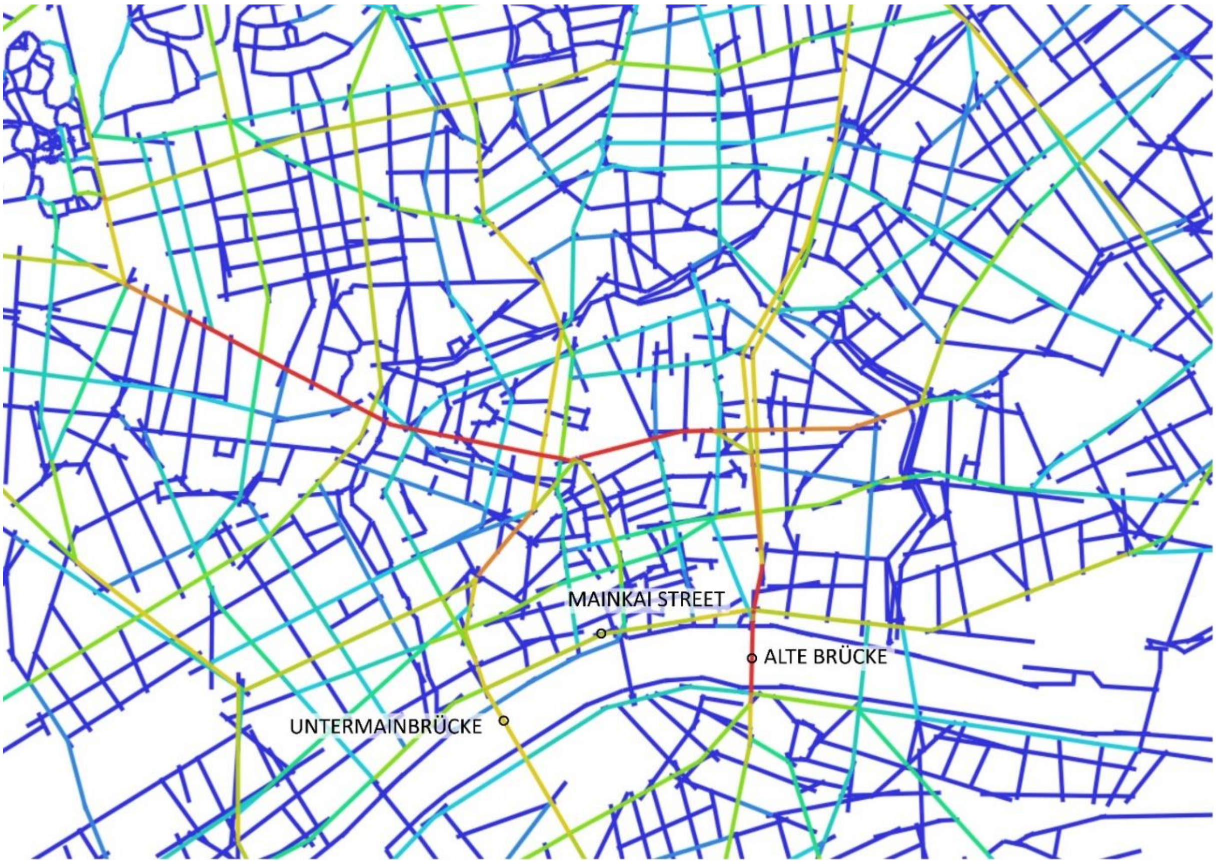


Figure 98: Direct routes with respect to normalised angular choice around Frankfurt Hauptwache (with Mainkai street in close proximity on the southern end) within a 2500m radii

The NACH network favours the closed Mainkai stretch (within the 4% high NACH valued segment lines) over the existing bicycle pathway with lower NACH value. The latter runs a few metres to the south of the pedestrianized Mainkai along the river bay, as a shared space between pedestrians (including users with baby strollers, kids, URM etc) and cyclists. The network also favours the two bridges (see Fig. 98) i.e. Untermainbrücke (yellow bridge segment) and Alte Brücke (red bridge segment), which in turn showed highest frequency of cyclists using the space within the peak hour crowding study, excluding the pedestrian bridge i.e. Eiserner Steg. Within the segment network, highest NACH value recorded was 1.5968 (~1.6) along the street segment Bockenheimer Landstrasse, leading towards Alte Oper (i.e. Opera House). The high NACH values around Hauptwache in the north exhibit higher potential, though the area is currently a pedestrian zone in which cars are banned and cyclists are obliged to dismount from the bikes. Before the road closure, the more direct routes along the Mainkai street were dominated by motorized vehicles with absence of dedicated bicycle pathway along the stretch. The prioritization of street space for motorized vehicles along the direct route forced the observed shared space between cyclists and pedestrians along the riverfront. Compared to the network of segments south to the river Main, the northern segments had higher potential of direct routes with respect to the overall network within the selected radius, reflecting the importance of the street.

Peak hour crowding and movement restriction

The on-site data was collected during the morning, afternoon and evening peak hours on 2 weekdays and a weekend in 2019, 2020 and 2021 (during similar months). Considering the peak hours during the day, the maximum frequency of pedestrians was recorded during the evening hours. As recorded during the pre-road closure scenario, the majority of pedestrians on the weekdays were observed around G12 (i.e. gateway 12), G13, and G14 (see Fig. 99 and Table 34) depicting the area around the high integrated (local) axial lines involving street from Römerberg plaza to the Mainkai street. High frequency of cyclists was observed along the two major bridges, i.e. Untermainbrücke and Alte Brücke, followed by the G13 and G10a (see Table 34 and 35) which lie in between the Mainkai street.

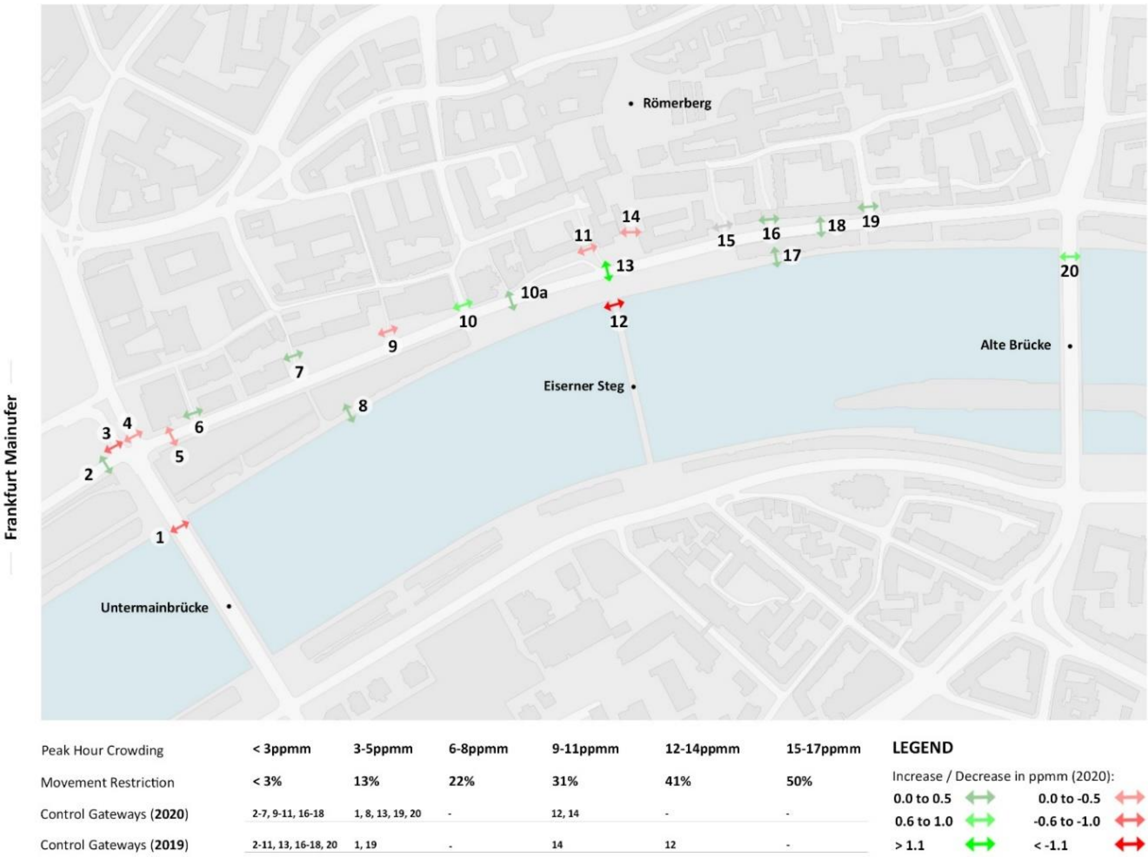
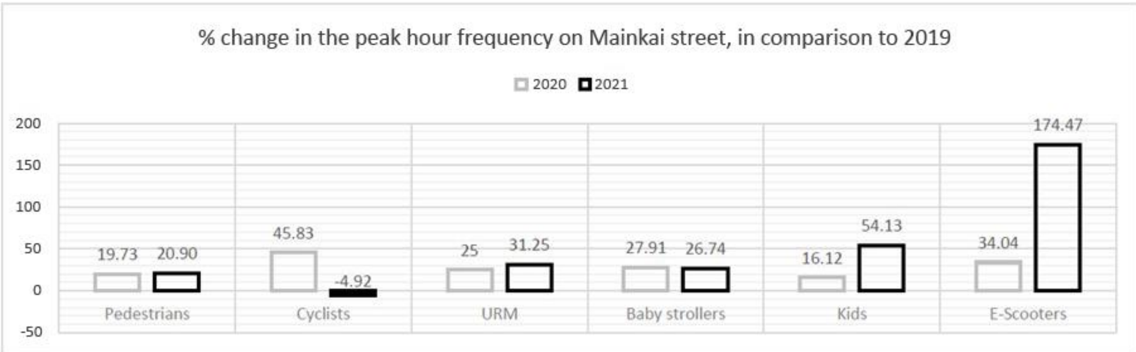


Figure 99: Peak hour crowding (in ppmm) and movement restriction (in %) on selected control gateways around Frankfurt Mainkai during 2019 and 2020 (Pandit et al. 2020)

With respect to the pace of movement, fast paced user groups (including cyclists) dominated around the opposite ends of the Mainkai street and were observed to be mixing with the slow-paced user groups (including kids, baby strollers, users with reduced mobility) along the riverside pedestrian pathway (through G8 and G17). Cyclists were often observed to have their speed of cycling reduced due to the shared space, as the street dominated by vehicles didn't have a dedicated bicycle pathway (in 2019). The high influx of pedestrians was observed around the high integrated axial lines (pre-road closure scenario), and when coupled with limited street width lead to further movement restriction, including higher peak hour crowding as high as 12-14 ppmm. The restriction tends to increase the closeness of walking space between pedestrians, in turn making the bi-directional movement more difficult. During the data collection, bicycle accidents were observed on the shared pedestrian pathway (more frequent on G13) mostly due to uneven surface near the pedestrian bridge (see Fig. 95), tram rails going through the open space and pedestrian obstruction.

In 2020, the Mainkai street saw an increase in the overall frequency of pedestrians, cyclists and e-scooter users using the new open space (in Fig. 100). With the Mainkai street closed, the additional street width was included for crowding calculations, providing more movement space. During the similar time period in 2021, with the Mainkai street open to vehicles, the street saw influence of road-closure experiment with increase in pedestrian density, but saw a reduction in cycling frequency (in Fig. 100). The riverside area had a greater reduction in the cycling frequency. This showcases a shift in the mobility pattern of cyclists who preferred the available space on the Mainkai street over riverside. The increase of E-scooter users on the street and riverside over the two-year period showed a new user-group's presence which would influence the overall mobility of other users in the same space.



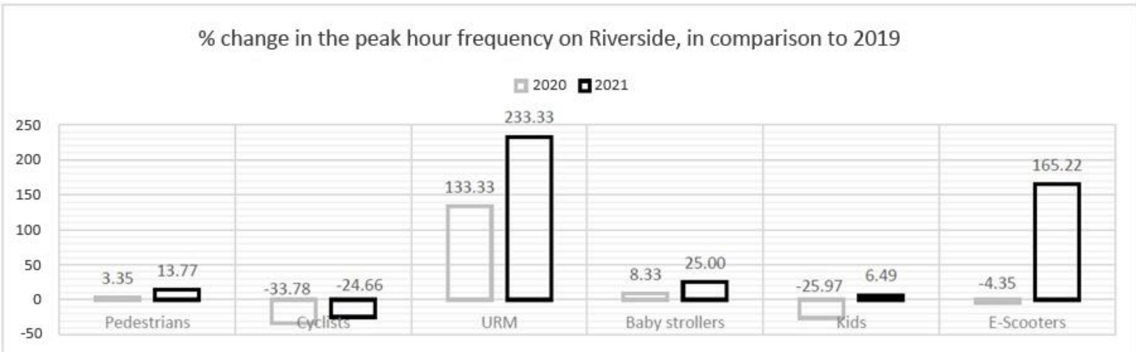
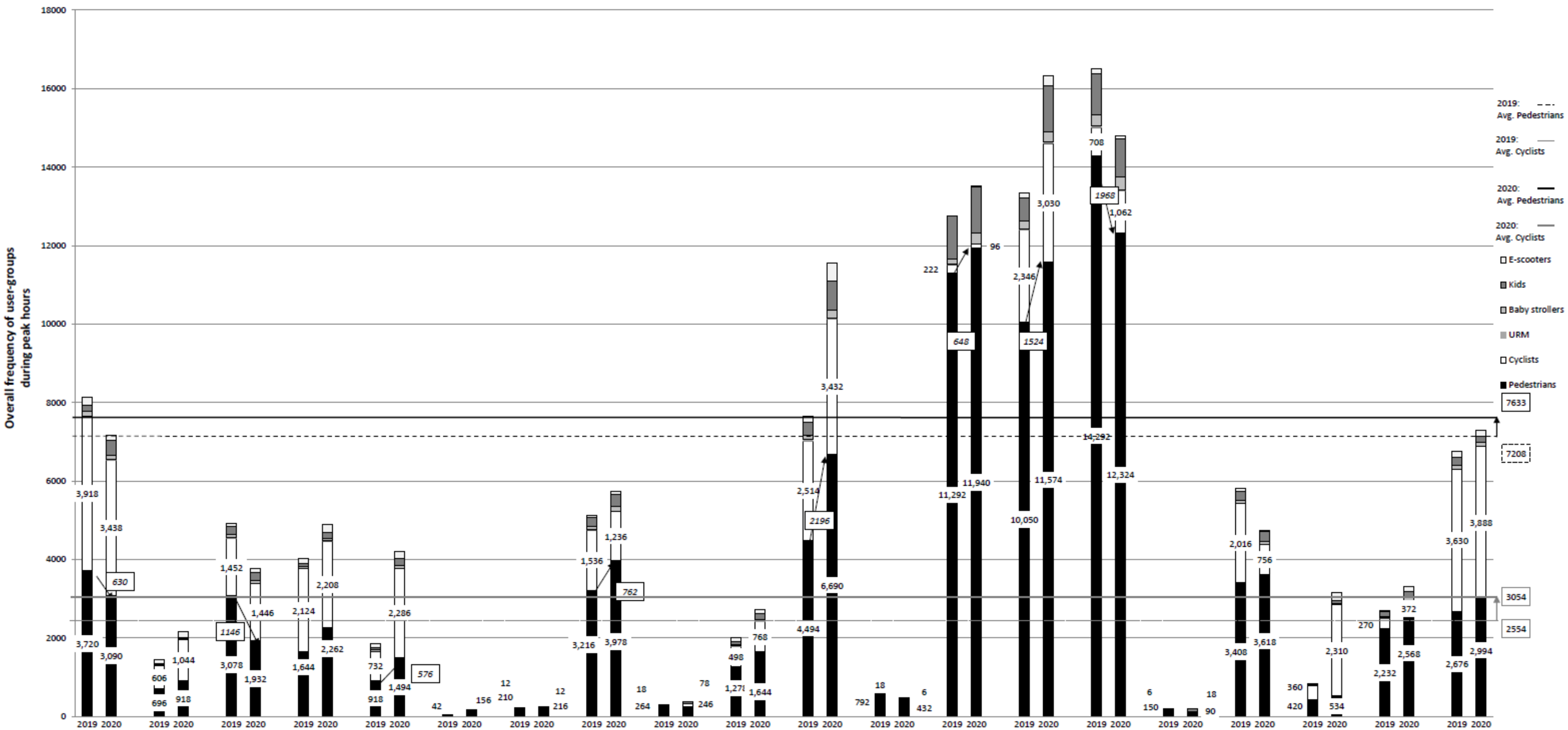


Figure 100: Change in peak hour frequency (in %) of different user-groups on Mainkai street and riverside in Frankfurt am Main in 2020 and 2021 (in comparison to 2019) (Pandit 2022)

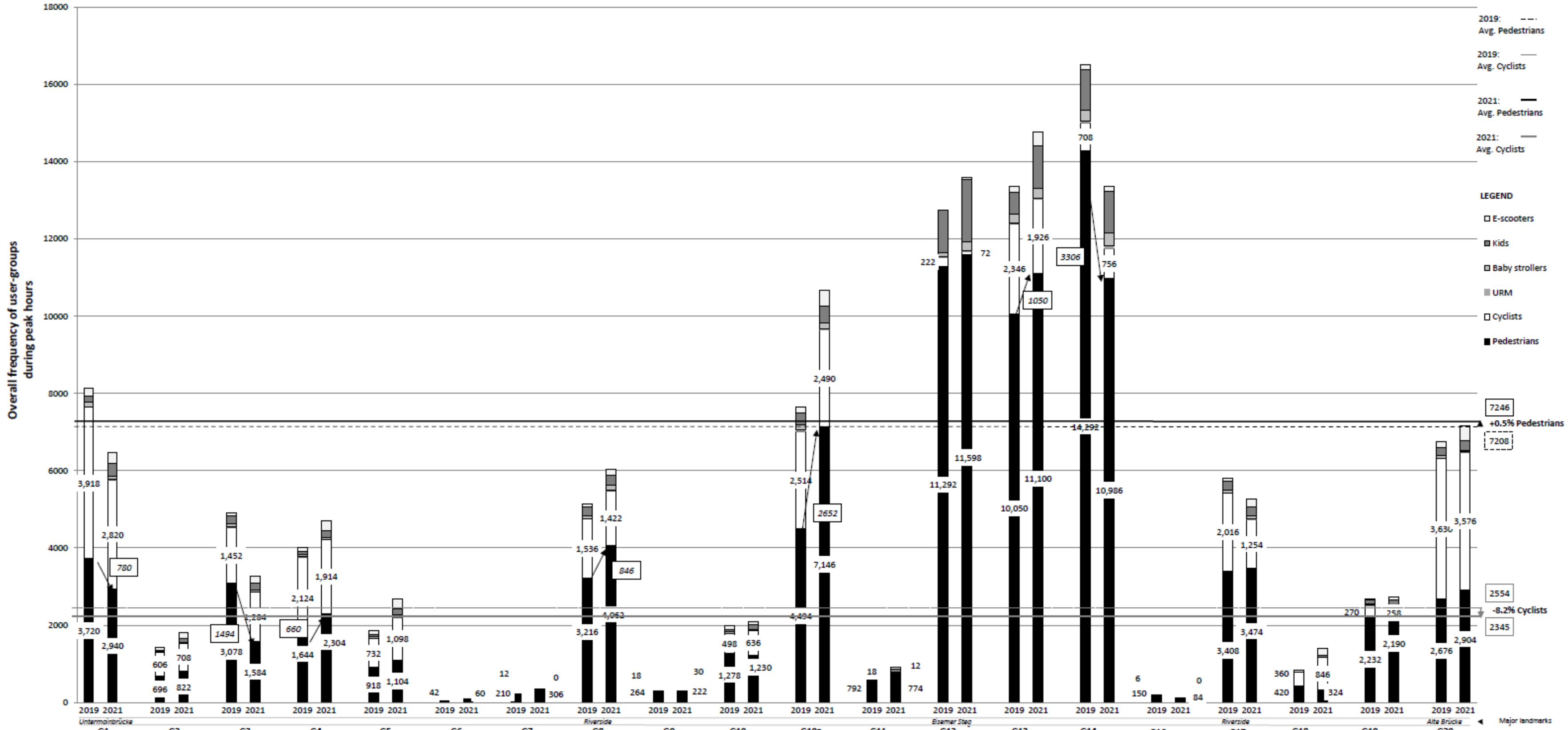
Pandit, L. (2022), Road Closure as an Experimental Urban Design Tool Fostering Active Mobility A Case of Frankfurt Mainkai Riverfront In: Vöckler, K., Eckart, P., Knöll, M., Lanzendorf, M. (2022), Mobility Design Die Zukunft der Mobilität gestalten, Bd. 2: Forschung, Berlin, pp. 178-184.



	G1 2019	G1 2020	G2 2019	G2 2020	G3 2019	G3 2020	G4 2019	G4 2020	G5 2019	G5 2020	G6 2019	G6 2020	G7 2019	G7 2020	G8 2019	G8 2020	G9 2019	G9 2020	G10 2019	G10 2020
E-scooters	198	132	90	150	78	108	114	210	96	186	0	0	0	0	66	72	6	0	102	108
Kids	162	378	24	30	204	192	84	144	66	156	0	12	6	6	228	294	12	30	66	132
Baby strollers	132	120	18	12	84	78	48	60	48	78	0	6	6	6	72	138	6	12	36	48
URM	0	12	0	0	24	12	6	18	0	0	0	0	0	0	12	6	0	0	18	18
Cyclists	3918	3438	606	1044	1452	1446	2124	2208	732	2286	0	0	12	12	1536	1236	18	78	498	768
Pedestrians	3720	3090	696	918	3078	1932	1644	2262	918	1494	42	156	210	216	3216	3978	264	246	1278	1644

	G10a 2019	G10a 2020	G11 2019	G11 2020	G12 2019	G12 2020	G13 2019	G13 2020	G14 2019	G14 2020	G16 2019	G16 2020	G17 2019	G17 2020	G18 2019	G18 2020	G19 2019	G19 2020	G20 2019	G20 2020
E-scooters	156	444	12	12	6	24	138	276	120	72	0	0	72	42	36	198	24	108	156	156
Kids	324	744	18	24	1098	1188	582	1164	1062	966	18	96	234	252	18	84	114	168	210	150
Baby strollers	114	198	6	6	114	264	210	264	264	324	12	0	72	66	0	24	36	72	84	96
URM	54	36	0	0	24	12	24	30	60	42	0	0	6	12	0	0	12	12	0	12
Cyclists	2514	3432	18	6	222	96	2346	3030	708	1062	6	18	2016	756	360	2310	270	372	3630	3888
Pedestrians	4494	6690	792	432	1129	1194	1005	1157	1429	1232	150	90	3408	3618	420	534	2232	2568	2676	2994

Table 34: Peak hour frequency of user groups in 2019 and 2020 on selected gateways in Frankfurt Mainkai (Pandit et al. 2020)



	G1 (Untermainbrücke) 2019	G1 2021	G2 2019	G2 2021	G3 2019	G3 2021	G4 2019	G4 2021	G5 2019	G5 2021	G6 2019	G6 2021	G7 2019	G7 2021
E-scooters	198	294	90	174	78	174	114	246	96	240	0	0	0	0
Kids	162	324	24	84	204	192	84	186	66	168	0	30	6	42
Baby strollers	132	90	18	30	84	42	48	54	48	60	0	0	6	12
URM	0	12	0	0	24	0	6	0	0	6	0	0	0	0
Cyclists	3918	2820	606	708	1452	1284	2124	1914	732	1098	0	6	12	0
Pedestrians	3720	2940	696	822	3078	1584	1644	2304	918	1104	42	60	210	306

	G8 (Riverside) 2019	G8 2021	G9 2019	G9 2021	G10 2019	G10 2021	G10a 2019	G10a 2021	G11 2019	G11 2021	G12 (Eiserner Steg) 2019	G12 2021	G13 2019	G13 2021
E-scooters	66	168	6	0	102	84	156	420	12	42	6	42	138	354
Kids	228	258	12	18	66	114	324	426	18	78	1098	1614	582	1104
Baby strollers	72	108	6	12	36	18	114	168	6	0	114	246	210	240
URM	12	24	0	6	18	6	54	24	0	6	24	12	24	36
Cyclists	1536	1422	18	30	498	636	2514	2490	18	12	222	72	2346	1926
Pedestrians	3216	4062	264	222	1278	1230	4494	7146	792	774	1129	1159	1005	1110

	G14 2019	G14 2021	G16 2019	G16 2021	G17 (Riverside) 2019	G17 2021	G18 2019	G18 2021	G19 2019	G19 2021	G20 (Alte Brücke) 2019	G20 2021
E-scooters	120	108	0	30	72	198	36	168	24	66	156	372
Kids	1062	1092	18	12	234	234	18	48	114	144	210	246
Baby strollers	264	324	12	6	72	72	0	6	36	60	84	48
URM	60	84	0	0	6	36	0	0	12	12	0	6
Cyclists	708	756	6	0	2016	1254	360	846	270	258	3630	3576
Pedestrians	1429	1098	150	84	3408	3474	420	324	2232	2190	2676	2904

Table 35: Peak hour frequency of user groups in 2019 and 2021 on selected gateways in Frankfurt Mainkai

Understanding and inference

With the onset of Coronavirus pandemic in 2020, the on-street space saw more open area being utilized for sitting activities in front of the restaurants, while maintaining social distancing regulations. With less tourists during the pandemic, the immediate space was assumed to be utilized more by local population. In regards to the local integration network of streets, the temporary road-closure experiment results in a more integrated network of streets, especially the Mainkai street itself playing a central role. The streets connecting the Mainkai street and the city centre in the north-south directions (e.g. Am Leonhardstor, Alte Mainzer Gasse, Karmelitergasse etc) also showed better integration values post-road closure. This may result in the effect that the high pedestrian crowding next to Römerberg plaza and the pedestrian bridge i.e. Eiserner Steg, will be diverted and distributed more equally among these north-south connections. This would also depend upon the pedestrians being directly (or indirectly) aware about the scenario through several factors including wayfinding and signalling. Few weeks after the road-closure, people were still observed stopping at the closed traffic lights in order to cross the pedestrianized street. The pedestrianized Mainkai street on the western end adjacent to Untermainbrücke showed favourable conditions for both cyclists and pedestrians walking in the road-closure scenario, making it a priority to sort the inferred attraction of two user groups, i.e. the pedestrians and the cyclists.

The road-closure experiment lasted for a year, and the Mainkai street was reopened to the cars and motorized vehicles in the summer of 2020 (see Fig. 101). The spatial analysis of the immediate and large-scale network of spaces around the Mainkai riverfront assisted in short-term and long-term recommendations, which included provision of a dedicated cycling lane on the Mainkai street, utilization of spaces for leisure activities (which include stationary activities), improved wayfinding signages or installations on streets (showing potential through improved integration values) in close proximity to Mainkai to improve the north-south connectivity between the city centre and the riverfront, and more. In 2021, the city of Frankfurt am Main decided to install dedicated cycling lanes on the Mainkai street (see Fig. 101), reducing one car-lane on the street between the Alte Brücke in the east and Untermainkai Brücke in the west. This move supported the recommended opinion of having a cycling lane on Mainkai street which showed a high potential for direct routes, assisted by high NACH values in the city (within the observed area of 2.5 kilometres from the city centre).

While the immediate road-closure showed an increase in the overall pedestrians and cyclists during the peak hours in 2020, the peak hour frequency of cyclists showed a drop in 2021. The overall pedestrian group around Mainkai showed a slight increase in the frequency, while the cyclists showed a minor decrease during 2021. One of the reasons could be the influence of road-closure experiment being terminated which led to less available street space for different user-groups using the riverfront area. Considering the Mainkai street and the riverside area, the drop in the frequency of cyclists was more apparent in the riverside area, which in a way suggests an acquired behaviour of cyclists preferring the direct route on Mainkai street through the one-year experiment. There were less tourist groups during the early phase of the road-closure experiment due to the coronavirus pandemic in 2020. Participation from locals due to availability of more open space especially during the social-distancing measure was anticipated. These factors influenced the utility of temporary open street space and its immediate surroundings. With new cycling lanes installed in 2021 (see Fig. 101), the impact of the dedicated cycle pathways on the street was not assessed, though it could act as an intermediate space which allows the cyclists to use the direct route through the Mainkai street, as was the scenario during the road-closure experiment. The transition of the Mainkai street from having multiple lanes of vehicular traffic to having a dedicated lane for cycling was supported by added interventions which included installation of navigational signages for cyclists, installation of bollards leading to reduction in on-street car parking adjacent to the cycling lane and adding more safety to slow-moving user-groups, and painted demarcation of lanes. This shows how certain small-scale physical interventions are required while implementing a large-scale allocation of space for different user-groups accessing an urban area.

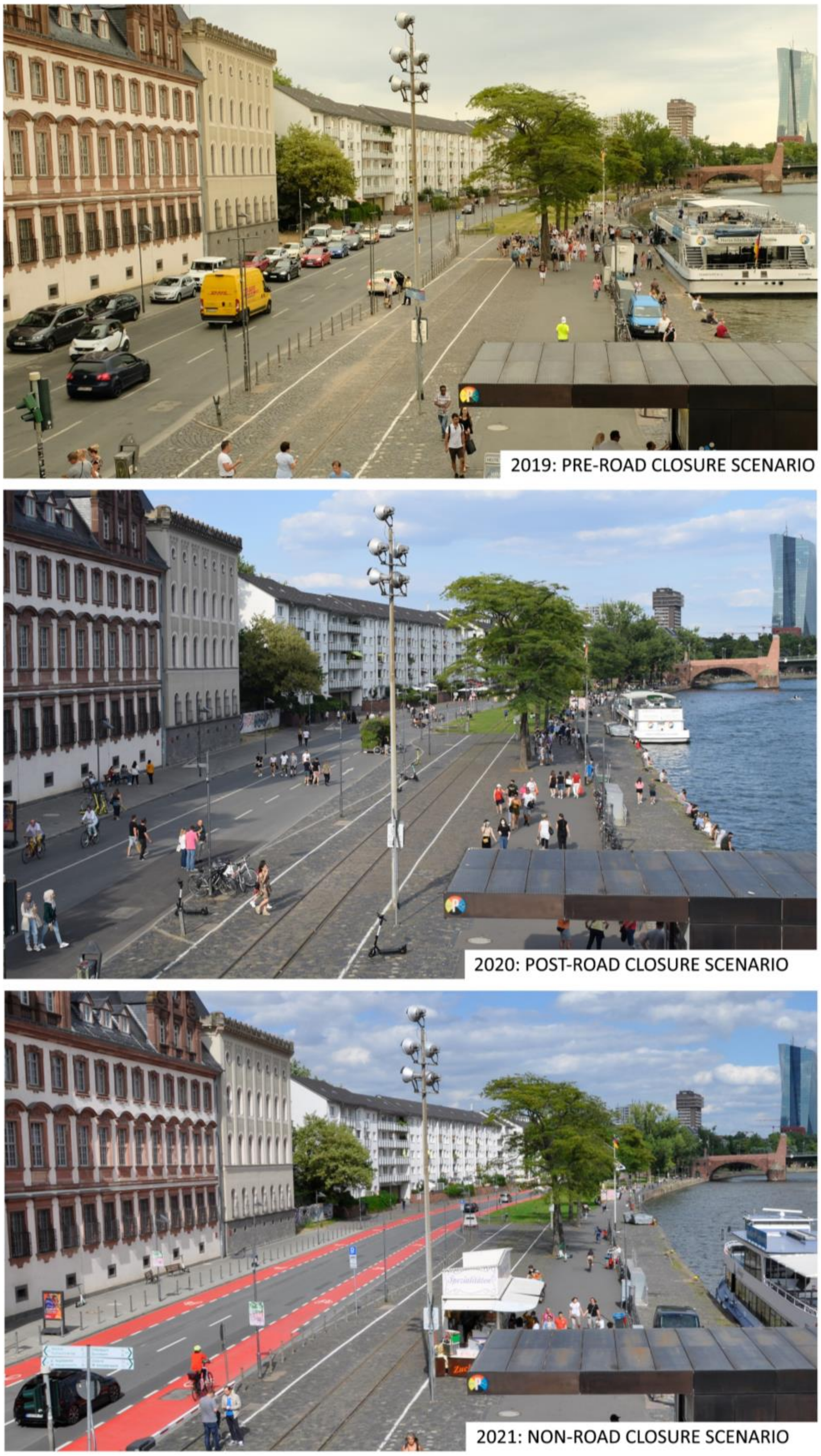


Figure 101: Mainkai street, as viewed from the pedestrian bridge of Eiserner Steg, during the three phases of road-closure experiment i.e. before the road closure in 2019, during the road closure in 2020, and after the end of the road-closure experiment in 2021 (Pandit 2022)
Note: The cycling lane was painted on the Mainkai street in 2021, after the data collection was undertaken.

The road-closure experiment along the Mainkai riverfront in Frankfurt am Main presented as an opportunity to utilize a set of mobility parameters to understand the street configuration; and predict the future mobility patterns based on the intermediate temporary measures. With similar measures being undertaken in different cities and urban areas, the parameters assist in identifying the potential of streets and similar spaces for different user-groups, and also helps in testing certain urban measures in line with the master plans of the city.

5.3 Urban Performance Ranking through Multi-Criteria Decision

Based on the five parameters analysed through different urban areas within the Rhein-Main agglomeration, the selected areas were earlier studied and compared through intra-parametric perspective (including both intra-and intercity perspectives). The inter-parametric comparison of nine urban areas brings forward their relative potential and ranking via multi-criteria decision tool i.e. TOPSIS. The ideal solution (or ideal 'best' or 'least' value), within the domain of TOPSIS, for each parameter is based on the values represented by the individual urban areas and won't be based on the parameter itself separately. Similar to the pilot study, which was conducted for the city of Darmstadt, the TOPSIS analysis in this sub-chapter includes selected urban areas from the cities of Frankfurt and Offenbach. The urban performance ranking reflects the way of ranking urban areas, influenced by the parameters being utilized for the comparison and the weightage each parameter is given. This varies based on priority from public opinion, different urban development plans of the cities, urban areas, and more. The multi-criteria ranking helps in understanding how different urban areas from different city sizes compare to one another based on the generic large-scale (and some small-scale) accessibility parameters within the domains of mobility.

5.3.1 Comparison with equal parametric weightage

The selected five parameters are sorted in an evaluation matrix (in Table 36) with the urban areas surrounding city centres, transit area and the residential area in Darmstadt, Frankfurt am Main and Offenbach am Main as follows:

Evaluation Matrix

Performance measures (x)	Connectivity (c)	Intelligibility (i)	NACH (n)	Crowding (cr)	PTAL (p)
Da Transit	1.46	0.54	0.71	0.83	30.38
Da Residential	1.39	0.57	0.73	0.34	3.25
Da City center	1.62	0.81	0.88	2.16	45.38
Fr Transit	1.88	0.88	0.84	1.64	61.76
Fr Residential	1.62	0.69	0.68	1.04	14.40
Fr City center	1.73	0.82	0.8	4.35	35.41
Of Transit	1.82	0.77	0.7	0.99	14.80
Of Residential	1.62	0.5	0.72	0.91	5.03
Of City center	1.72	0.76	0.75	2.31	22.75
$\sqrt{[(x1)^2 + \ldots (xn)^2]}$	4.97	2.15	2.28	5.94	95.03

Table 36: Evaluation Matrix of the selected parameters (performance measures in the table) and the urban areas in the cities of Darmstadt (Da), Frankfurt am Main (Fr) and Offenbach am Main (Of)

The evaluation matrix includes the conditional formatting through colour scales, where the green values represent the favourable value for a performance measure (or parameter) and red represents the unfavourable value under each parameter. For example, within the NACH (n) column, the selected residential area of Frankfurt, Bornheim, shows the least favourable direct routes while the city centre of Darmstadt, Luisenplatz, shows the most favourable network of direct routes. On the other hand, Bornheim also shows better intelligibility and access to public transport in comparison to other residential areas in the study.

The corresponding colour scale represents the range of values within each vertical column (not row) (in Table 36). The matrix shows how different urban areas perform based on the selected parameters in summary, prior to any normalization. The bottom row in the evaluation matrix, is utilized to normalise the overall matrix in the next step. The evaluation matrix is normalised to have values in between 0 and 1, by dividing the matrix to its corresponding $\sqrt{[(x1)^2 + \ldots (xn)^2]}$ value under the performance measures column. For example, 'PTAL' value of the residential area in Offenbach am Main (i.e. 5.03) in normalised by dividing it by its corresponding normalising factor of 95.03 under PTAL (p), which results in a normalised value of 0.05 (in Table 37). Similarly, the evaluation matrix is normalised for all the urban areas with their corresponding performance measure attributes as follows:

Normalized Evaluation Matrix

Performance measures	Connectivity (c)	Intelligibility (i)	NACH (n)	Crowding (cr)	PTAL (p)
Da Transit	0.29	0.25	0.31	0.14	0.32
Da Residential	0.28	0.27	0.32	0.06	0.03
Da City centre	0.33	0.38	0.39	0.36	0.48
Fr Transit	0.38	0.41	0.37	0.28	0.65
Fr Residential	0.33	0.32	0.30	0.18	0.15
Fr City centre	0.35	0.38	0.35	0.73	0.37
Of Transit	0.37	0.36	0.31	0.17	0.16
Of Residential	0.33	0.23	0.32	0.15	0.05
Of City centre	0.35	0.35	0.33	0.39	0.24

Table 37: Normalized Evaluation Matrix of the selected parameters (performance measures in the table) and the urban areas in the cities of Darmstadt (Da), Frankfurt am Main (Fr) and Offenbach am Main (Of)

The Normalized Evaluation Matrix is further utilized through weighted parameters, in order to rank the selected nine urban areas in the Rhein-Main urban agglomeration. For the initial comparison, equal weightage is given for the five performance measures. For example, connectivity (c) gets 0.2 weightage, similar to Intelligibility (i) and others as there are 5 parameters in the study. The connectivity value for the residential area of Darmstadt, for instance, is 0.056 in the Weighted NEM table with the weightage of 0.2 being considered for the evaluation (i.e. 0.28 x 0.2). Similar weightage of 0.2 is attributed to all performance measures in the Weighted NEM table.

Weighted NEM

Performance measures	(c)	(i)	(n)	(cr)	(p)	E. distance from ideal best (eb)	E. distance from ideal least (el)	eb + el	Performance score (el/el+eb)	Rank
Da Transit	0.059	0.050	0.062	0.028	0.064	0.079	0.131	0.210	0.625	3
Da Residential	0.056	0.053	0.064	0.011	0.007	0.129	0.135	0.264	0.511	6
Da City centre	0.065	0.075	0.077	0.073	0.096	0.072	0.120	0.192	0.626	2
Fr Transit	0.076	0.082	0.074	0.055	0.130	0.044	0.159	0.203	0.782	1
Fr Residential	0.065	0.064	0.060	0.035	0.030	0.106	0.115	0.221	0.520	5
Fr City centre	0.070	0.076	0.070	0.146	0.075	0.147	0.076	0.222	0.340	9
Of Transit	0.073	0.072	0.061	0.033	0.031	0.103	0.119	0.222	0.536	4
Of Residential	0.065	0.047	0.063	0.031	0.011	0.127	0.116	0.243	0.476	7
Of City centre	0.069	0.071	0.066	0.078	0.048	0.107	0.084	0.191	0.440	8
Ideal (best) value	0.076	0.082	0.077	0.011	0.13					
Ideal (least) value	0.056	0.047	0.06	0.146	0.007					

Table 38: Weighted Normalized Evaluation Matrix (NEM) of the selected parameters (performance measures in the table) and the urban areas in the cities of Darmstadt (Da), Frankfurt am Main (Fr) and Offenbach am Main (Of)
Note: The performance measures in this matrix are given equal weightage i.e. 0.2 each, based on 5 parameters in the study.

With respect to the five accessibility parameters through selected urban areas (irrespective of the city size), the transit area in Frankfurt performed the best, followed by the city centre in Darmstadt (in Table 38). This is similar to the pilot study results, where the transit area reflected better performance score than the selected areas. Within the nine urban areas, the less performing areas included residential areas of Offenbach and Darmstadt, with the city centres of Offenbach and Frankfurt performing the least. While the area surrounding Hauptwache had better outcome with other performance measures (i.e. intelligibility, PTAL, NACH, and connectivity), the crowding and movement restriction faced on-site by different user-groups was the highest amongst the selected nine urban areas, which influenced its overall performance score. The Darmstadt city centre showcased a good network for potential direct routes, which was followed by two areas in Frankfurt i.e. the transit area and the city centre. The footway assessment focusing on crowding and movement reflected how urban areas in large cities provide more movement restrictions due to large density of people using the space during peak hours as to comparatively smaller cities. The performance ranking of selected urban areas (with equal parametric weightage) results in two city centres showing less accessibility characteristic. This resists part of the research hypothesis which places city centres to be more accessible than other land uses, but supports it to be concentrated with better access to public transport (via PTAL). With two of the top three ranked urban areas located in Darmstadt, the result also reflects how urban areas in smaller cities have better accessibility characteristic than larger cities. The results also reflect the need to prioritize certain urban areas to improve their potential of providing access to multimodal system. For instance, while the residential area of Bornheim has better access to public transport and intelligibility, its low NACH corresponding to its configuration of open spaces (including streets) makes it difficult to plan for potential cycling routes. On the other hand, the residential area in Darmstadt shows better NACH network reflecting on ease of planning and identifying routes for cycle pathways. But in contrast, the low PTAL of Komponistenviertel also makes it important to improve its access for public transport via close access time. This can be done through better diversity in public transport options (as observed in Bornheim), better integration of public transport station in the inner street network (as observed in Bürgel) or increased frequency of public transport services.

These results show how different urban areas and their accessibility characteristics differ via inter-and intra-city perspective. The overall ranking and the hierarchy of urban areas showcases a data-driven approach where the quantitative outcomes signify certain multimodal accessibility characteristics of selected urban areas. Understanding the priorities of accessibility aspects (discussed in Chapter 6) and then ranking the urban areas adds another layer to the approach, which has a potential to follow a data-informed route of evaluating research outcomes.

5.4 Summary

This chapter initiates the comparative assessment which shows how different urban areas perform through the selected aspects of accessibility via connectivity, intelligibility, closeness, directness and spatial freedom. The utility of multiple parameters for identifying certain mobility characteristics through the outlook of accessibility portrays the possibility of collaborative approach with different authorities and stakeholders from urban planning and design perspective. One of the examples for the collaborative approach includes the case of road-closure experiment in Frankfurt Mainkai with the City of Frankfurt. Crowding and Space syntax attributes were utilized to track and predict the influence of the road-closure experiment on different user-groups using the street (which was closed to car traffic) as a new open space. The research outcomes presented the closed Mainkai street as a favourable segment for cycling (based on city-wide NACH analysis), which did not have any dedicated cycling lane prior to the road-closure experiment. The outcomes also predicted high pedestrian flow, utilizing Space syntax attributes, post road-closure. The combination of crowding attribute and NACH in different cities helped in understanding the utilization of potential direct streets by cyclists (and indirectly car traffic). Similar approaches of relating outcomes from spatial analysis via parameters like PTAL, intelligibility or connectivity to unit street segments via peak hour frequency of user-groups is not possible due to the parameters having an output corresponding to a single value for an area of observation and not a street unit. Though if each street section (where the peak hour frequency of user-groups is collected) is taken as a point of origin, then every street section will have its unique accessibility characteristic pertaining to the identified parameters. This can be utilized for a correlation study but it results in larger gap between required data and available data, corresponding to a long research timeline.

The research findings show how residential areas (e.g. Bornheim in Frankfurt) can have better accessibility characteristics than city centres (with respect to Offenbach and Frankfurt), which on the other hand don't particularly dominate throughout the accessibility parameters overall. Although the residential areas showed low intelligibility characteristic, the ease of navigation could be improved with better connections to highly integrated streets for a long-term improvement (in Fig. 87). This adds towards the short-distance mobility perspective where less cul-de-sacs lead to continuous movement, supporting better walkable network. With urban areas being identified for further densification, bringing in more pedestrians and cyclists, the availability of space and street network characteristics plays a crucial role to provide a network of movement. Along with densification through added residential units and network of green spaces, involving urban planning principles of *Innenentwicklung vor Aussenentwicklung* and *Doppelte Innenentwicklung*, emphasis on street network should be prioritized to provide access to urban areas through different modes. For instance, the residential area of Komponistenviertel is surrounded by green areas with certain cul-de-sacs (in the eastern and western ends) in proximity to it. Extending the street network through initial measures involving addition of pedestrian or cycling routes via green spaces would make the streets more attractive and also connect the main street in peripheral area of the residential area to the internal network of streets creating a continuous flow with less movement restrictions. In regards to the access to public transport, while the PTAL values were within comfortable range for majority of urban areas, the added perspective through users with reduced mobility signifies the need to improve access to public transport with PTAL range below 5.00 index value. While this does not take into consideration the micro-scale architectural perspective of barrier-free standards of accessibility, they should also be prioritized within the umbrella of universal accessibility and design of spaces. The findings in this chapter also contradicts the assumption of larger cities having better accessibility characteristics as compared to smaller cities. For instance, the city centre in Darmstadt while having no access to underground trains had better accessibility to public transport via PTAL, as compared to the city centre in Frankfurt am Main. Although based on the perspective of barrier-free accessibility, it may have its challenges (Knöll et al. 2018). The access to the on-ground bus and tram service stations in the central open plaza of the city centre in Darmstadt contributed to higher levels of access, while the longer travel time to public transport services underground influenced its (i.e. Hauptwache) multimodal accessibility attribute negatively. In cities like Offenbach, the potential of streets with direct routes for cyclists was underutilized, as cars dominated the streets and required lane priority for bicycle as a mode to improve active mobility. This adds to the identification of cycling mobility behaviour in cities which is based on the principle of cyclists favouring direct routes for their movement. The cities of Darmstadt and Frankfurt am Main showed street sections favouring higher NACH values having higher frequency of cyclists positively and significantly.

During the research timeline, as the selected performance measures were studied and completed, the overall ranking of urban areas varied. With the equal weightage of parameters within the multi-criteria decision analytic tool, the transit area in Frankfurt ranked highest in hierarchy of selected urban areas, which was followed by the city centre in Darmstadt. With the next step of including public perception via survey (in Chapter 6), it alters the parametric weightage and reflects the user perspective towards the accessibility measures and their priorities in an urban scenario. While the performance score ranking assists in understanding overall perspective of selected multimodal accessibility attributes, the individual nine urban case studies help in identifying the potential areas which require improvement pertaining to multimodal accessibility. The aspect of utilizing public opinion and individual assessment of urban areas is more inclined towards a data-informed approach as compared to data-driven approach. While the data-informed approach allows human element in the decision-making process, the data-driven approach allows data to control the decision-making (Babich 2020). The former approach assists in understanding the individual accessibility attributes with qualitative input (via public opinion), which assists in improved decision-making process for urban design and planning projects (where public opinion is of importance). This results in identifying relative importance (or priorities) of identified accessibility attributes and urban areas which require improvement in regards to its corresponding multimodal accessibility characteristic.

Knöll, M., Hopp, S., and Miranda, M., H. (2018), Stadtgestaltung für eine inklusive Stadtmitte Darmstadt In: Kulturelle Mitte Darmstadt – Ein kritischer Stadtführer, Jovis, pp. 148-157. Retrieved from https://tuprints.ulb.tu-darmstadt.de/8333/

Babich, N. (2020), Data-Driven vs Data-Informed Decision Making in UX Design, Adobe. Retrieved from https://xd.adobe.com

CHAPTER 6

PUBLIC PERCEPTION AND PRIORITIZATION

Preface

Following the urban performance ranking of selected urban areas based on equal weightage of the parameters, the public perception on the priority of the selected parameters and added attributes are derived from the survey focusing on large-scale scale perspective of accessibility measures on mobility in the Rhein-Main agglomeration. This chapter brings together the quantitative spatial measures and its qualitative outcomes through the perspective of public opinion. It also adds towards better understanding of the mobility culture (Klinger et al. 2013) in the cities through public perception. In addition, addressing the third research question, the chapter reflects upon the subjective priority of urban areas and accessibility parameters in comparison to objective priority (in Chapter 5). This is observed via revised urban performance ranking towards the end of the chapter.

6.1 Survey Design and Objective

The survey is designed with an intention to understand how people perceive accessibility and prioritize different selected attributes catering towards accessibility within their urban surroundings on a large-scale perspective. The accessibility parameters have been identified and studied through different urban areas in the study within the cities of Darmstadt, Frankfurt am Main and Offenbach am Main forming the Rhein-Main urban agglomeration. With the help of the survey outcomes, the added perception of public would lead to a revised performance ranking of different cities and urban areas through the accessibility parameters (or performance measures). The selected parameters for the survey would be prioritized in a sequence through a pair-wise comparison following the Analytic Hierarchy Process (Saaty T. L. 1984). The multi-criteria tool for decision making helps in producing priorities via hierarchy. The process involves using a factor of consistency in order to validate the outcomes, i.e. if they are rational or irrational in nature. By combining the AHP methodology with TOPSIS, the quantitative outcomes from the respective accessibility parameters (or factors) can be re-evaluated through public perception and their desired notion of accessibility through selected mobility modes.

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Saaty T.L. (1984) The Analytic Hierarchy Process: Decision Making in Complex Environments. In: Avenhaus R., Huber R.K. (eds) Quantitative Assessment in Arms Control. Springer, Boston, MA. DOI: https://doi.org/10.1007/978-1-4613-2805-6_12

There are five accessibility parameters in total leading to ten pair-wise comparisons in survey. These parameters include connectivity, public transport accessibility, directness of routes, crowding and intelligibility. The parameters are re-defined for the general public for better understanding of the terms with respect to the objective of the urban mobility research as follows:

Connectivity (referred to as 'Network of Streets' in the survey): This relates to a good walking network with more pedestrian roads and junctions around a place or neighbourhood, offering improved degree of freedom of choice for people to move. A higher connectivity value of a space would indicate a better network of routes for pedestrians to move around with less dead-ends (or cul-de-sacs).

Public Transport Accessibility Level (referred to as 'Access to Public Transport' in the survey): This relates to ease of accessing a public transport service (including trams, buses, trains etc.) based on its frequency of services and its distance from a point of origin. A higher value of public transport accessibility would either indicate that the service stations (bus stops, tram stops etc.) are located closer from a reference point in urban space or have higher number of services (e.g. more frequent buses or trams in an hour on a station) or both.

NACH / Directness of routes (referred to as 'Access to Bicycle routes'): Access to more direct routes for cyclists from the point of origin to destination would make the overall mobility network of urban areas (or cities) more efficient. This parameter emphasizes on prioritizing a network of streets which serve more direct pathways for cyclists, generally leading to less duration for the overall journey where dedicated bicycle lanes ensure safety and comfort.

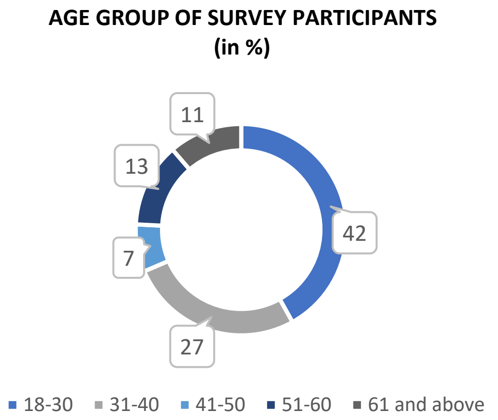
Crowding and movement restriction (referred to as 'Ease of Movement'): While the term 'comfort' is user-specific, a comfortable crowding with less movement restriction specifically relates to movement through the streets with comfortable width of space. Elements like street furniture, parking spaces, or even density of people using a particular street section lead to reduction of space for movement, thereby increasing movement restriction. A street with higher pedestrian comfort would have a good width of space for people (specifically pedestrians and cyclists) to move with less barriers.

Intelligibility (referred to as 'Ease of Navigation'): Intelligibility as a characteristic relates to the ability of a person to understand the surroundings in a broad urban space i.e. the ease of how a person can pinpoint their location in an urban space which helps in navigation and propels movement. An intelligible space would make it easier for a person to move around as compared to unintelligible space.

The overall survey design is discussed in the Appendix, which includes a preface notifying the survey participants about the survey being focused on residents living within the Rhein-Main agglomeration. To have a better reach within the agglomeration, the survey was made available both in English and German language. The five parameters were also represented along with visual aids to have a better grasp of the aspects. With the re-defined parameters for ease of understanding, the online survey was divided in three sections where the first section served as an introduction, the second section focused on the combined aspect of demographics and mobility environment, and the third section focused on the pair-wise prioritization of the selected multimodal accessibility attributes within the study.

6.2 Overall survey outcome within the urban agglomeration

The survey had an overall response of 248 participants within the Rhein-Main agglomeration (of 5.8 million inhabitants), which corresponds to an approximate 6% margin of error within a 95% confidence level (i.e. the probability that the sample size accurately reflects the opinion of the population) for the sample size (Cochran 1977). It comprises of survey participants from the major cities of Darmstadt (44%), Frankfurt am Main (33%) and Offenbach am Main (9%) within the state of Hessen. The rest included participants from the neighbouring cities such as Mainz (within the neighbouring state of Rheinland-Palatinate in the west), Wiesbaden, Hofheim and more within the Rhein-Main agglomeration. 42% of the survey respondents fell within the age group of 18-30, followed by 27% within 31-40 years of age. The remaining 31% were 41 years old or above in age (in Fig. 102). In regards to their preferred mode of mobility, majority preferred cycling (i.e. 35%), followed by use of public transport (i.e. 27%) and cars (i.e. 19%). Walking as a mode shared a similar modal share (i.e. 17%) as that of cars (in Fig. 102).



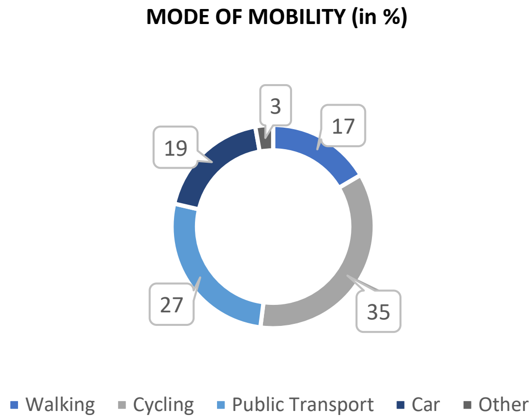


Figure 102: Age group of survey participants and their mode of mobility (in %)

In regards to overall priority within the five selected attributes, the 'access to public transport' was prioritized the most, followed by 'access to bicycle routes' and 'ease of movement' (in Fig. 103). The 'ease of navigation' (reflecting towards the intelligibility of an urban area) was least prioritized. This gives an early overview of subjective weightage via public opinion towards different aspects, which is discussed further in subchapter 6.3.

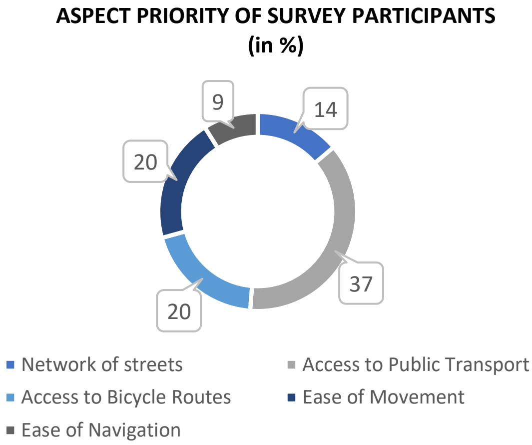


Figure 103: Survey participant's priority towards aspects within Rhein-Main agglomeration (in %)

While the pair-wise prioritization of the five aspects is documented in the subchapter 6.3 leading to an overall weightage of the five parameters, the mean rating of the urban areas the survey participants

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Cochran, W.G. (1977), Sampling techniques (3rd ed.), John Wiley & Sons, New York In: Bartlett, J. E., Kotrlik, J.W. and Higgins, C. C. (2001), Organizational Research: Determining Appropriate Sample Size in Survey Research, Information Technology, Learning, and Performance Journal, Vol. 19, No. 1, pp. 43-50.

resided in was documented. This is analysed through a 5-point rating scale where 1 indicated ‘very poor’, 3 indicated ‘neutral’ and 5 indicated ‘very good’. The ‘access to public transport’ was highest (i.e. 3.86), followed by good ‘network of streets’ (i.e. 3.74), ‘ease of navigation’ (i.e. 3.63), ‘ease of movement’ (i.e. 3.47) and ‘access to bicycle routes’ (i.e. 3.38). This indicates that the urban areas where the survey participants resided in within Rhein-Main agglomeration had a comparatively low access to direct bicycle routes in comparison to other aspects. On the other hand, the access to public transport was better than the other four accessibility aspects.

6.2.1 Perception of priority from participants in major cities

This subsection focuses upon which mode of mobility the survey participants (corresponding to different cities) prefer to travel in general, along with their priority towards the five accessibility aspects (or parameters). With the majority of survey participants residing within the city of Darmstadt (n=109), 57% of the respondents fell within the age group of 18-30, 30% within 31-40, and the rest were above 41 years of age. Approximately 90% of the respondents were either from the residential areas or the city centre, with rest living around major transit area and other land-use. With respect to the mode of mobility, the majority preferred cycling, followed by walking, public transport and cars (in Fig. 104). Other modes of mobility included E-scooters in the city, which in the recent years has become more visible on the streets around the city.

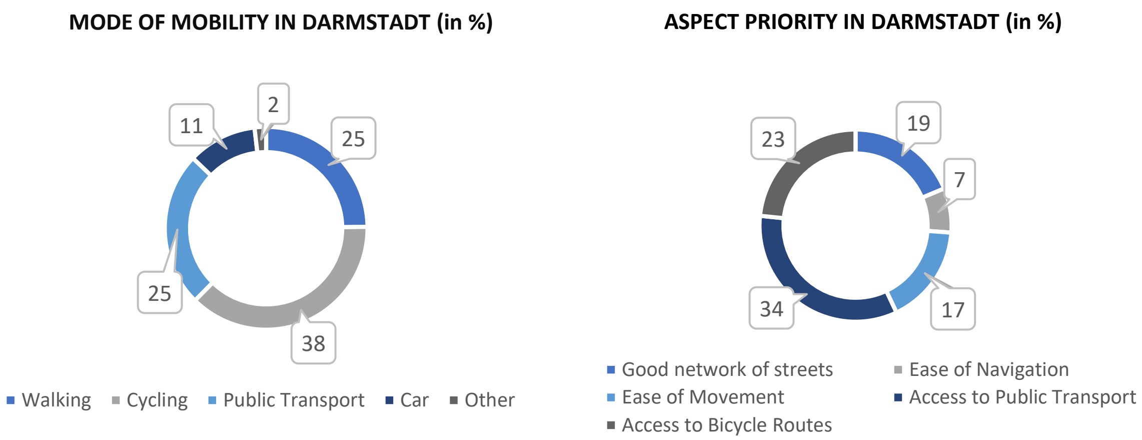
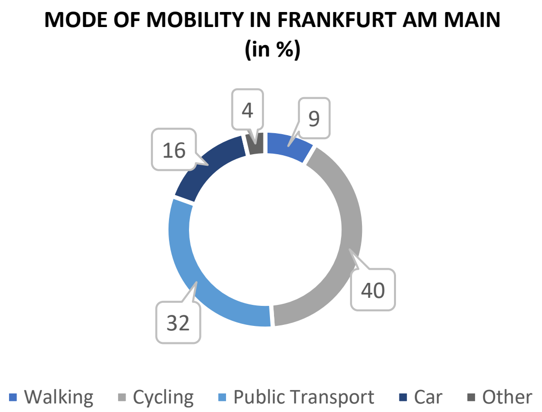


Figure 104: Participant’s mode of mobility in Darmstadt (in %) and their priority towards aspects

With respect to the overall priority within the five selected attributes, the ‘access to public transport’ was the most prioritized aspect within the city of Darmstadt. This was followed by the ‘access to bicycle routes’ and good ‘network of streets’. While the majority of participants preferred cycling as their primary means of movement, the ‘access to public transport’ was dominant over the ‘access to bicycle routes’. This indirectly suggests an intermodal behaviour through different user-groups residing in the city. It also gives the perspective of active mobility (through high share of people walking, cycling or using public transport) and its corresponding accessibility measures to be of a high importance for the residents in Darmstadt. Considering that majority of the participants were either from a residential area or an area surrounding the city centre, the results from the rating of immediate neighbourhood with respect to the five aspects reflects the two urban areas. This is discussed in the comparative rating of the urban areas in the three cities in 6.3.2.

With respect to the survey participants from Frankfurt (n=82), 30% of the respondents fell within the age group of 18-30, 28% within 31-40, and 41% were above 40 years of age. Compared to Darmstadt, there was a larger representation of respondents within the age group of 51 years and above. Approximately, 87% of the respondents were either from the residential areas or the city centre, with rest living around the main transit area, countryside and other areas. With respect to the mode of mobility, the majority preferred cycling and public transport (see Fig. 105). This was followed by car, which had a higher modal share as compared to the city of Darmstadt. Walking and use of other modes of mobility (including E-scooters), combined for a total response of 13% as a preferred mode of mobility amongst the respondents.



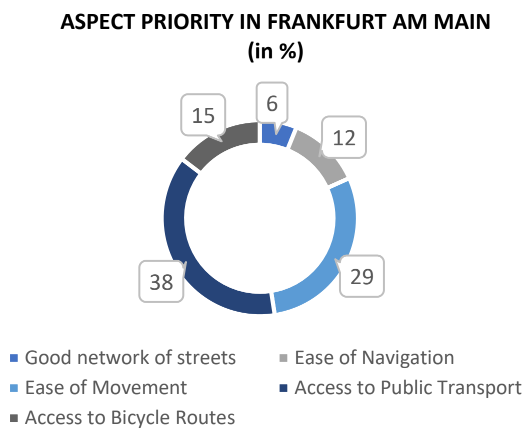


Figure 105: Participant's mode of mobility in Frankfurt am Main (in %) and their priority towards aspects

Similar to Darmstadt, the highest priority amongst the respondents within the five selected performance measures was for 'access to public transport'. This was followed by 'ease of movement', which focused on low movement restriction and crowding as a preferred attribute (in Fig. 105). This result reflects the parametric analysis in chapter 4 and 5, which showed high crowding and movement restriction, especially in the city centre around Hauptwache. The good 'network of streets' was the least prioritized aspect amongst the five parameters in Frankfurt am Main. The aspect of intermodal behaviour can be interpreted by the outcome of the priority towards the attributes, and the mode of mobility people preferred for moving. The modal share of walking amongst the respondents was low, while there was a strong priority towards 'ease of movement'. This shows the importance of width of space in the large city of Frankfurt am Main for an accessible mobile environment. Similarly, while majority of participants preferred cycling as their mode of mobility (in Fig. 105), access to bicycle routes was comparatively less prioritized (which had a comparatively smaller difference in Darmstadt). One of the reasons for the outcome could be high priority towards less movement restriction (via ease of movement) and intermodal behaviour of using public transport in comparatively larger and dense city of Frankfurt am Main. For instance, a person who prefers cycling as a mode also includes part of their journey to be done by public transport in between. Considering that public transport constitutes a larger part of their trip journey, this results in more prioritization towards the aspect of 'access to public transport'.

With respect to the survey participants from Offenbach am Main (n=23), majority were below 41 years of age. With respect to the typology of urban areas, approximately 91% of the respondents lived in either residential neighbourhood or within the city centre area. With respect to the preferred mode of mobility in the city, cycling was the most preferred mode of mobility followed by walking and public transport (in Fig. 106). There was a fair share of respondents using motorized vehicles i.e. cars (17%) as their preferred mode of mobility. Similar to the other cities, E-scooters and other modes of mobility shared a low overall modal share (4%) in the city.

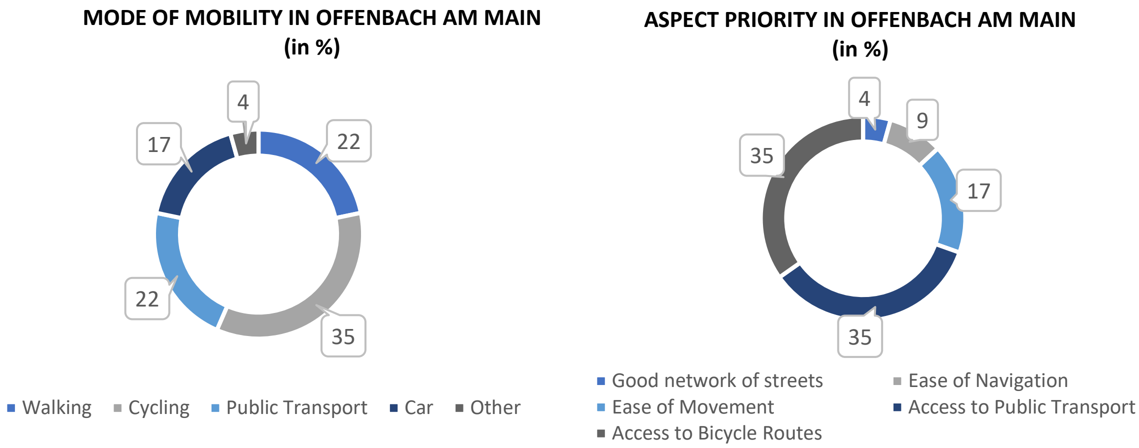


Figure 106: Participant's mode of mobility in Offenbach am Main (in %) and their priority towards aspects

With respect to the overall priority within the five selected performance measures, the 'access to public transport' and 'access to bicycle routes' were the most prioritized aspects within the city of Offenbach am Main. The good 'network of streets' was the least prioritized aspect amongst the five parameters. The preferred mode of mobility and the aspect priority amongst the participants corresponded for the people who cycled or used public transport, which was reflected through high priority towards 'access to bicycle routes' and 'access to public transport'.

Throughout the three cities of Darmstadt, Offenbach am Main and Frankfurt am Main, the attribute of 'access to public transport' shared the highest priority. Walking was more prevalent as a preferred mode of mobility amongst the respondents in comparatively smaller cities of Darmstadt and Offenbach am Main than in the larger city of Frankfurt. Considering the major preferred modes of mobility, cycling and public transport shared a dominant role amongst the survey participants in the three cities. With respect to the survey outcomes, there were certain differences observed between the participant's mode of mobility and the corresponding priority of aspects in the three cities. For instance, while 'cycling' as a mode closely corresponded to the 'access to bicycle routes' as an aspect of priority in Offenbach am Main, there was a certain difference between the two in other cities, especially in Frankfurt am Main. While intermodal behaviour can contribute to this result, the phenomenon of modal captivity (Papaionnou and Martinez 2015), within the modal choice research, can also be one of the reasons for the outcome. This includes captivity by force or captivity by choice (Jacques et al. 2013). For instance, a car captive (by force) is a result when a person cannot use other modes like public transport as the services are too far or less frequent (or less accessible). A public transport captive (by choice) is a result when a person has the ability to choose more than one transport options, and disregards other options but one (i.e. public transport). While a person's reason for modal captivity may vary, it influences their mode of mobility and their prioritized aspect of accessibility.

Other cities within Rhein-Main agglomeration

Apart from the majority of survey respondents residing in Darmstadt, Frankfurt am Main and Offenbach am Main, the remaining participants resided in the neighbouring cities of Mainz,

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Papaioannou, D. and Martinez, L. M. (2015), The role of accessibility and connectivity in mode choice. A structural equation modelling approach, Transportation Research Procedia 10, pp. 831-839. DOI: 10.1016/j.trpro.2015.09.036
Jacques, C., Manaugh, K., and El-Geneidy, A. (2013), Rescuing the captive [mode] user: an alternative approach to transport market segmentation, Transportation, 40, pp. 625-645.

Wiesbaden, Hofheim, Langen and more. While these constituted 14% of the overall respondents (n=34), their perspective reflected towards a more car-dominant modal share. 33% of the respondents from these cities fell within the age range of 61 and above, 30% within 18-30, followed by 27% within the age range of 51-60. With respect to the preferred mode of mobility, car was the most preferred mode (i.e. 52%) (in Fig. 107) followed by public transport (i.e. 21%) and cycling (i.e. 18%).

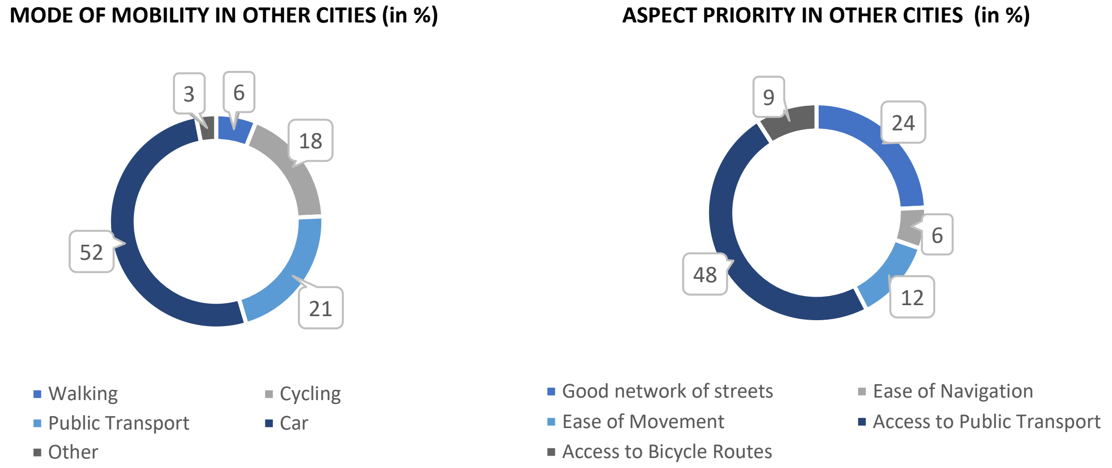


Figure 107: Preferred mode of mobility for survey participants and their aspect priority in other cities (excluding Darmstadt, Frankfurt am Main and Offenbach am Main) within Rhein-Main agglomeration (in %)

While the majority of user-groups preferred using car as a mode, their priority was highest towards the aspect of 'access to public transport', followed by good 'network of streets'. This resonates towards the perspective of priority in the three cities of Darmstadt, Frankfurt am Main and Offenbach am Main within the urban agglomeration. While the mode of mobility may vary in these cities, the 'access to public transport' remained the highest prioritized aspect.

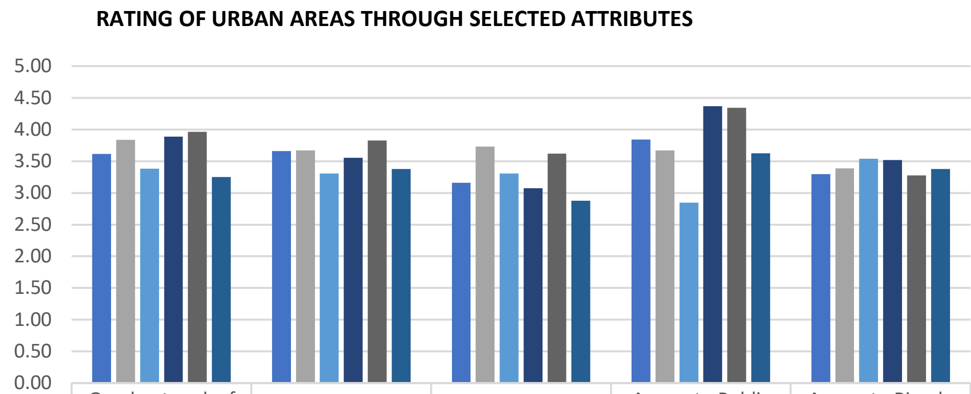
Users with reduced mobility

While the majority of perspectives within the survey included persons, who had no impairment leading to any difficulty for their movement or choice of mode of travel, there is a need to reflect upon the priority towards Persons with Disability (PwD). The group of respondents which had a mobility impairment or had some kind of disability, constituted towards approximately 2% (n=6) of the overall survey participants. Three of these participants fell within the age group of 61 and above. Within the group of respondents who had some kind of impairment or disability, half preferred the use of public transport for their daily commute, followed by cycling and cars. The priority for the 'access to public transport' was high (83% of the respondents prioritized 'access to public transport'). This was followed by the aspect of good 'network of streets' (i.e.17%). Availability of public transport services along with the ease of accessing their service stations through short distances was the most prioritized aspect within the group of users with reduced mobility.

6.2.2 Subjective and objective perspective in selected areas

This subsection reflects upon the initial subjective perception (via selected five aspects) of the survey participants, which is compared with the objective data from chapter 4 and 5. The in-depth subjective priority via public perception is discussed in subchapter 6.3 (addressing the third research question), which shows its influence over the objective ranking of selected urban areas in chapter 5.

Majority of survey respondents within the Rhein-Main agglomeration resided either in a residential area or around the city centre area (i.e. approximately 88% of the participants). The remaining areas included transit areas, countryside areas and more. In order to have a comparative evaluation, the two areas i.e. residential and city centre were selected for three major cities where the respondents lived in (this included Darmstadt, Frankfurt am Main and Offenbach am Main). The rating of the individual urban areas (i.e. the area where the respondent resided) by the participants in accordance to the five selected attributes were utilized and their mean values were calculated for the comparison. A 5-point rating scale was utilized for the evaluation of the urban areas by the participants, where 1 signified 'very poor', 3 signified 'neutral' and 5 signified 'very good'.



	Good network of streets	Ease of Navigation	Ease of Movement	Access to Public Transport	Access to Bicycle Routes
Frankfurt (Residential)	3.61	3.66	3.16	3.84	3.30
Darmstadt (Residential)	3.84	3.67	3.73	3.67	3.39
Offenbach (Residential)	3.38	3.31	3.31	2.85	3.54
Frankfurt (City centre)	3.89	3.56	3.07	4.37	3.52
Darmstadt (City centre)	3.97	3.83	3.62	4.34	3.28
Offenbach (City centre)	3.25	3.38	2.88	3.63	3.38

Table 39: Mean parametric rating by the survey participants in the selected cities of Frankfurt am Main, Darmstadt and Offenbach am Main

With respect to the 'network of streets', the city centre in Darmstadt had a 'good' 3.97 (~4) rating, followed by the city centre area in Frankfurt am Main, and residential area in Darmstadt (see Table 39). The Offenbach city centre was perceived to have a neutral rating for the 'network of streets', which was the least in comparison to the other areas in the three cities. While the link-node ratio under 'connectivity' as a performance measure is utilized for evaluating the actual network of streets for a walkable network, it showed a better network for the city centre in Offenbach am Main as compared to the city centre in Darmstadt. Similar comparison for the residential area cannot be made as there are multiple residential areas (which may vary in comparison to selected residential area in the research study) within the selected cities, though the city centre is a unique area for a city. In regards to the city centre area, the difference in the rating of the 'network of streets' from the 'connectivity' and survey participants can also be influenced by the quality of open spaces available around these areas. For example, the open spaces in and around the city centre of Darmstadt including Marktplatz, Luisenplatz, Staatstheatre, Ludwigsplatz, Friedenplatz and more are accessible within the pedestrian zone of the city centre (which is larger than the pedestrian zone in the city centre of Offenbach am Main), while for Offenbach am Main large open spaces are limited within the pedestrian zone.

With respect to the ‘ease of navigation’, the city centre in Darmstadt had a ‘good’ 3.83 (~4) rating, followed by the residential areas within Darmstadt (see Table 39). The residential areas in Offenbach were perceived as ‘neutral’ in regards to its ‘ease of navigation’ for the people living in the area. This suggests that the orientation for a person to navigate through the network of streets via urban configuration of spaces in city centres were better than the residential areas, with Frankfurt in exception (as the residential areas had a better rating of 3.66 in comparison to the city centre i.e. 3.56). Considering ‘intelligibility’ as the performance measure which relates to the ability of a person to understand the global network of spaces from a local network, the intelligibility of the street networks through the city centres in Frankfurt am Main, Darmstadt, and Offenbach am Main was better than the selected residential areas of the respective cities. This, in a way, corresponds to the survey outcome but the selected residential area in Frankfurt had objectively lower intelligibility than the city centre in comparison to the subjective evaluation by the survey participants.

The residential areas in the city of Darmstadt recorded the highest rating for the ‘ease of movement’, followed by the city centre i.e. Luisenplatz. This was especially low for the city centres in Offenbach am Main (i.e. 2.88) and Frankfurt am Main (i.e. 3.07). With crowding and movement restriction being utilized as a performance measure for the aspect of ‘ease of movement’, the availability of space and frequency of people utilizing the available street space comes into the accessibility perspective. The city centre in Frankfurt am Main had the highest crowding value during the peak hours amongst the selected areas in the agglomeration, which was followed by the city centre in Offenbach am Main. This objective characteristic was reflected through the subjective perception via survey outcome where city centres had low ‘ease of movement’ in comparison to the residential areas in their respective cities. While a moderate density of people utilizing the network of streets (with good width of available space) does not cater to major movement restriction, a high crowding (as observed in the city centre of Frankfurt am Main) would create a barrier for persons with different movement speeds.

The aspect of ‘access to public transport’ had the wide range of rating from the survey respondents (see Table 39), with the two city centres of Frankfurt am Main and Darmstadt having a high rating of 4.37 and 4.34 respectively. On the contrary, the residential areas in Offenbach had a low rating of 2.85 for its access to public transport. The city centre areas had better rating towards ‘access to public transport’ in comparison to the residential areas in all three cities. In regards to the performance measure of Public Transport Accessibility Level (PTAL), which looks into the level of accessibility based on frequency of diverse modes of public transport along with access time, the city centre in Darmstadt had a better PTAL in comparison to Frankfurt am Main and Offenbach am Main. While the city of Frankfurt had added modes of underground rail services around the city centre, the city centre in Darmstadt had better PTAL due to the proximity of service stations for different modes (while it did not have underground rail services). In Offenbach, the lack of on-ground tram services would have a certain impact on access to diverse public transport services, especially in residential areas away from the city centre. This was resonated through the survey outcome from the residents in the city, while with respect to the city centres in Frankfurt and Darmstadt, Darmstadt performed objectively better (via PTAL) but subjectively had similar evaluation rating.

The range of mean rating for ‘access to bicycle routes’ was the smallest amongst the five aspects for the urban area comparison (see Table 39). The residential areas in Offenbach am Main and the city centre in Frankfurt am Main received a high rating for its network of streets having better ‘access to bicycle routes’ in comparison to other urban areas. The residential areas of Darmstadt and Offenbach am Main were rated higher for their street networks providing direct routes for cycling, in contrast to their respective city centres. In regards to the performance measure of NACH, where the potential of street networks is understood for direct bicycle routes (which does not take into consideration the availability of dedicated bicycle pathways), the city centres had better potential for direct bicycle routes with high mean NACH values than the selected residential areas.

Figure 108: A car using dedicated bicycle lane around the city centre in Frankfurt am Main which creates a barrier for cycling

One of the reasons for the difference in the perception of ‘access to bicycle routes’ and NACH could be the aspect of how people found ‘ease of movement’ to be better in residential areas as compared to the city centres, which influences a continuous movement for cyclists from a point of origin to destination. High density of car traffic around the city centre district in cities can also create a sense of less accessibility (see Fig. 108) around the main streets. These factors address how there is a difference between the subjective and the objective perception of the accessibility attributes in certain urban areas within the study. This reflects upon the research hypothesis corresponding towards the difference between the subjective evaluation and the objective characteristics of an urban area (von Wirth et al. 2015; McCrea et al. 2006).

Following the perception of priority towards the modes of mobility, rating of urban areas, and aspect priority, the pair-wise comparison of the five selected attributes is undertaken. This is done to generate

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von Wirth, T., Grêt-Regamey, A., & Stauffacher, M. (2015), Mediating Effects Between Objective and Subjective Indicators of Urban Quality of Life: Testing Specific Models for Safety and Access, Social Indicators Research, 122(1), pp. 189–210.
McCrea, R., Shyy, T.-K., & Stimson, R. (2006). What is the strength of the link between objective and subjective indicators of urban quality of life?, Applied Research in Quality of Life, 1 (1), pp. 79-96. DOI: 10.1007/sl 1482-006-9002-2.

a distinct weightage towards each attribute, which helps in understanding the subjective priority towards the selected performance measures through the public perception within the agglomeration. This is possible, if the survey results are consistent in their outcomes as per the Analytic Hierarchy Process (i.e. AHP) discussed in the following subchapter.

6.3 Revised Urban Performance Ranking

Following the public survey, the pair-wise comparison of five selected parameter (or performance measures) for multimodal accessibility were documented which results in a prioritized subjective weightage for each parameter. This is to be utilized for the revised ranking of selected urban areas based on TOPSIS. The pair-wise prioritization is carried out by a 9-point rating scale with two parameters on the extreme ends, where 9 denotes an extreme priority for either of the two parameters, and 1 denotes neutral or no priority between the pair of parameters (see Fig. 109). AHP, as a multi-criteria decision-making tool utilizes criteria or factors to determine a particular alternative or choice. Considering the five selected parameters as criteria or factors to determine or prioritize between different urban areas, the tool is utilized to combine the public perception towards the five parameters. This assists in prioritizing certain attributes and urban areas for an urban design and planning project timeline, which involves various stakeholders for the immediate decision-making process.

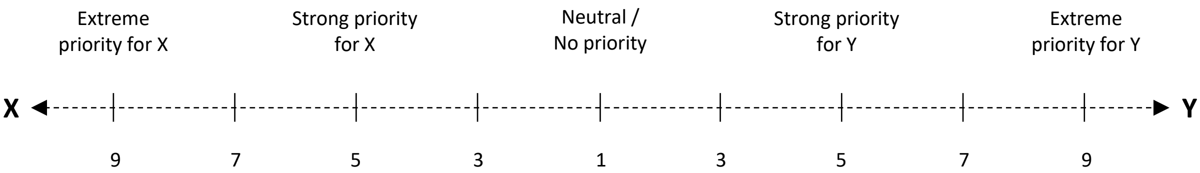

Figure 109: A 9-point rating scale for the pair-wise comparison of two unique factors within the Analytic Hierarchy Process

The Analytic Hierarchy Process takes into consideration certain inconsistencies, as not everyone is always consistent with their priority of choices. This also depends on the number of pair-wise comparisons that are undertaken, which would have a certain impact on the person and their hierarchy of priorities for certain factors. The number of comparisons for prioritization between different criteria or factors (synonymous to the selected five parameters), would depend upon the number of factors being utilized. For example, two factors would require pair-wise comparison to done only once, three factors would require pair-wise comparison to done thrice, five factors would require pair-wise comparison to be done ten times and so on. As the number of factors (z) increase, the number of pair-wise comparisons (i.e. (z(z-1))/2) increase by a bigger margin. Therefore, for large number of factors it would be difficult for humans to maintain the consistency in their prioritization assessment. For example, for 10 to 12 factors a person would have to do a pair-wise comparison between two unique factors 45 to 66 times. This increases the time a person takes to answer a survey and also make it difficult to be consistent.

Within AHP, the measure for evaluating whether a resulting prioritized weightage is consistent is based on a 'consistency ratio'. It is defined as a degree of departure from a pure inconsistency. An acceptable consistency ratio is considered to be less than .10, while a ratio with a value below .20 is considered to be tolerable (Wedley 1993). Pauer et al. (2016), Ho et al. (2005), Dolan (2008) and more have reiterated on using .20 as an upper limit for considering it suitable for consistency ratio. The consistency ratio in the pair-wise comparison study has been relaxed to .20 as the survey participants are not expert group clusters, which allows a certain level of inconsistency that is tolerable for the subjective prioritized weightage.

6.3.1 Pair-wise comparison of aspects

This subchapter section initiates the pair-wise comparison of five selected accessibility attributes (or aspects), which is later utilized for generating subjective weightage to each attribute. Considering the pair-wise comparison between the aspects of 'network of streets' and 'access to public transport', majority of the survey respondents had a 'strong' priority towards 'access to public transport' (i.e. PT5) (in Fig. 110). Only 2% had an 'extreme priority' towards good 'network of streets'. In between 'network of streets' and 'access to bicycle routes', majority had a 'strong' priority towards 'access to bicycle routes' (i.e. B5). While S5 was in close proximity to B5 in hierarchy, the majority of the overall share in priority between the two factors went for 'access to bicycle routes'.

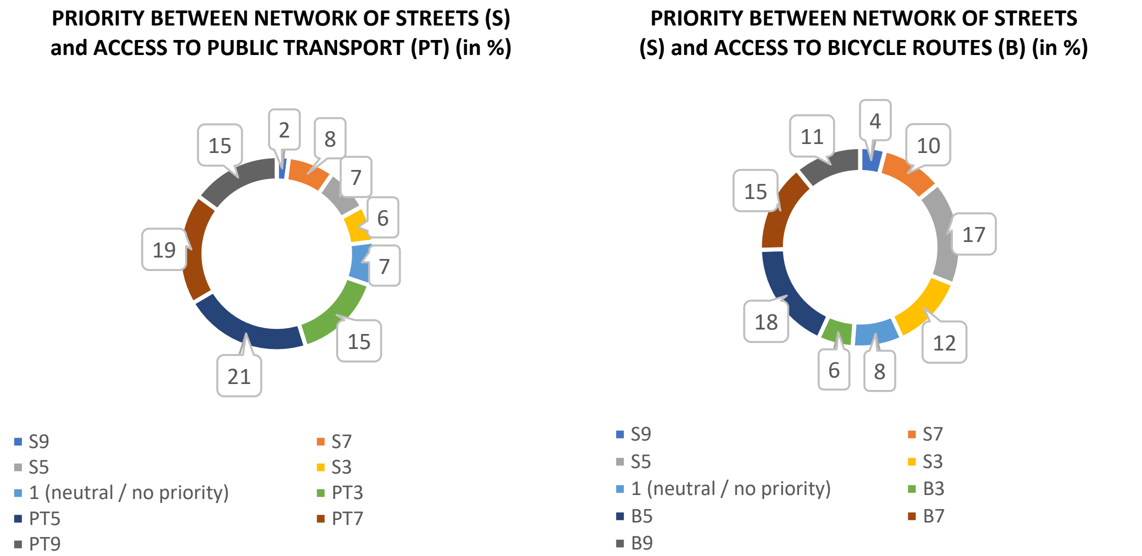

Figure 110: Pair-wise comparison graphics between 'network of streets' and 'access to public transport' (left), and 'network of streets' and 'access to bicycle routes' (right) within AHP

In between the aspect of 'network of streets' and 'ease of movement' (see Appendix IV), majority of the respondents had a 'strong' priority towards 'ease of movement' (i.e. M5). Only 4% had an 'extreme' priority towards 'network of streets'. The 'network of streets' dominated for the first time amongst selected five parameters, with majority favouring it 'strongly' (i.e. S5) over the aspect of 'ease of navigation'. The overall share of respondents favouring 'ease of navigation' slightly, strongly, very strongly, or extremely over 'network of streets' was 32%, while it was 51% vice-versa (excluding the neutral perspective).

Wedley, W.C. (1993), Consistency prediction for incomplete AHP matrices, Mathl. Comput. Modelling, Volume 17, No. 4/5, pp. 151-161.
Pauer, F., Schmidt, K., Babac, A., Damm, K., Frank, M., & von der Schulenburg, J. M. (2016), Comparison of different approaches applied in Analytic Hierarchy Process - an example of information needs of patients with rare diseases, BMC medical informatics and decision making, 16(1), 117. DOI: https://doi.org/10.1186/s12911-016-0346-8
Ho, D., Newell, G. and Walker, A. (2005), The importance of property-specific attributes in assessing CBD office building quality, Journal of Property Investment & Finance, Vol. 23 No. 5, pp. 424-444. DOI: https://doi.org/10.1108/14635780510616025
Dolan, J. G. (2008), Shared decision-making – transferring research into practice: The Analytic Hierarchy Process (AHP), Patient Education and Counselling, Volume 73, Issue 3, pp. 418-425. ISSN 0738-3991, DOI: https://doi.org/10.1016/j.pec.2008.07.032.

The 'access to public transport' was favoured 'strongly' (i.e. PT5) over 'access to bicycle routes' in majority, with only 28% respondents having some form of preference for 'access to bicycle routes' (see Appendix IV). In between 'access to public transport' and 'ease of movement', 61% of the overall respondents had some kind priority towards 'access to public transport' with 21% prioritizing it 'slightly' (i.e. PT3) over the 'ease of movement'. The aspect of 'access to public transport' had a priority over the other four aspects, through pair-wise comparison as well as the overall preference in subchapter 6.2. Especially in comparison with 'ease of navigation', 25% of the overall respondents preferred the aspect (i.e. PT7) very strongly. 74% of the survey participants had some form of priority towards the aspect of accessing a public transport service over the intelligibility characteristic of the urban configuration (see Fig. 111). This reflects how public transport plays an important role within the factors of achieving an accessible multimodal system in an urban environment. In regards to priority between 'access to bicycle routes' and 'ease of movement', there was an equal share of people prioritizing either for the former or the latter aspect (i.e. 41% for both aspects individually). The 'neutral' perspective with 1, was taken into consideration for the pair-wise priority between 'Access to bicycle routes' and 'ease of movement' (see Fig. 111). This was the only pair-wise comparison, where a neutral approach was considered.

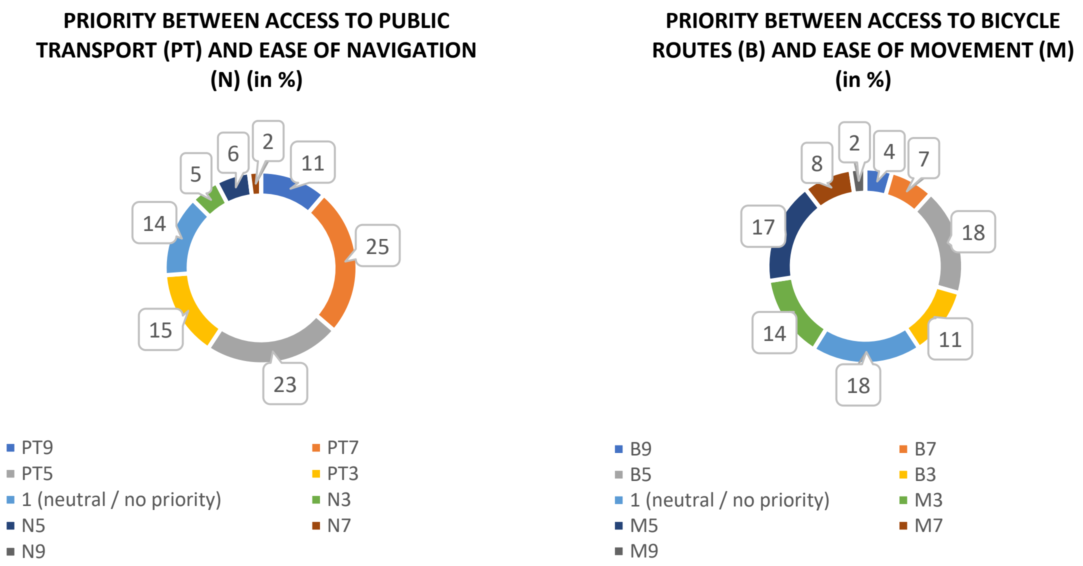

Figure 111: Pair-wise comparison graphics between 'access to public transport' and 'ease of navigation' (left), and 'access to bicycle routes' and 'ease of movement' (right) within AHP

The 'ease of navigation' aspect was dominated by the two factors of 'access to bicycle routes' (i.e. B7) and 'ease of movement' (i.e. M5) in the pair-wise comparison. Large cluster of survey participants (i.e. 26%) 'strongly' prioritized 'ease of movement' over 'ease of navigation'. In both comparisons, the overall share of participants having any form of preference for 'ease of navigation' was less than (or equal to) 30%. Based on the ten unique pair-wise comparisons for the selected five aspects, the priority with respect to the 9-point rating scale was utilized to form a 5 x 5 matrix, in order to proceed with the AHP priority weight calculation.

6.3.2 Matrix formation and revised urban performance ranking

The pair-wise comparison in the previous section helped to initiate the formation of a 5 x 5 comparison matrix (for the five aspects). The hierarchy of priority by the survey participants based on the 9-point rating scale was utilized to form the comparison matrix. The diagonal of the comparison matrix signifies neutral perspective due to the comparison with same factor, and is represented by 1 (see Table 40). Comparing connectivity and PTAL, as majority of the survey participants 'strongly' favoured 'access to public transport' over good 'network of streets', 1/5 represents the relationship between the two aspects on row 1 and column 2 of the reciprocal matrix (and comparison matrix). Similar relationship was observed between connectivity and PTAL, NACH and crowding which was represented by 1/5 on the first row. Comparing connectivity and intelligibility, majority of the survey participants 'strongly' prioritized good 'network of streets' over 'ease of navigation' and 5 on row 1 column 5 of the comparison matrix reflects the 'strong' prioritization. Following the methodology, the first reciprocal matrix was generated for the immediate relationship between the five factors based on the survey.

Reciprocal Matrix	Connectivity	PTAL	NACH	Crowding	Intelligibility
Connectivity	1	1/5	1/5	1/5	5
PTAL		1	5	3	7
NACH			1	1	7
Crowding				1	5
Intelligibility					1

Comparison Matrix	Connectivity	PTAL	NACH	Crowding	Intelligibility
Connectivity	1	1/5	1/5	1/5	5
PTAL	5	1	5	3	7
NACH	5	1/5	1	1	7
Crowding	5	1/3	1	1	5
Intelligibility	1/5	1/7	1/7	1/5	1

Table 40: Reciprocal and complete comparison matrix (5x5) for the five parameters based on the paired comparison through survey

The reciprocal values of the preference between five factors in the upper triangular matrix (from the diagonal) in the reciprocal matrix was utilized to fill the lower triangular matrix, leading to a completed comparison matrix. The generated comparison matrix is later utilized to compute the normalized Eigen vector (in Table 41c), which is also known as priority vector, and the Eigen value. Following the mean of normalized values (Ishizaka and Lusti 2006), the normalized principal eigen vector is obtained.

Comparison Matrix	Connectivity	PTAL	NACH	Crowding	Intelligibility
Connectivity	1	1/5	1/5	1/5	5
PTAL	5	1	5	3	7
NACH	5	1/5	1	1	7
Crowding	5	1/3	1	1	5
Intelligibility	1/5	1/7	1/7	1/5	1
Sum	16 (1/5)	1 (7/8)	7 (12/35)	5 (2/5)	25

(a)

Normalized Matrix

	Connectivity	PTAL	NACH	Crowding	Intelligibility
Connectivity	0.06	0.11	0.03	0.04	0.20
PTAL	0.31	0.53	0.68	0.56	0.28
NACH	0.31	0.11	0.14	0.19	0.28
Crowding	0.31	0.18	0.14	0.19	0.20
Intelligibility	0.01	0.08	0.02	0.04	0.04
Sum	1	1	1	1	1

(b)

Normalized Eigen Vector

Connectivity	0.0865
PTAL	0.4716
NACH	0.2033
Crowding	0.2015
Intelligibility	0.0370

Principal Eigen Value (PEV)	5.7927
Consistency Index (CI)	0.1982
Consistency Ratio (CR)	0.1769

(c)

Table 41: Normalized Matrix and Normalized Eigen Vector for the priority weights of selected five parameters

The normalized matrix (in Table 41b) is generated from dividing the sum of each column of the comparison matrix. This leads to the overall sum of the column in normalized matrix to be 1. The normalized eigen vector is then calculated as the mean of the row values in the normalized matrix. The normalized eigen vector showcases the relative weights of one factor to the other. PTAL is the factor that is prioritized the most, followed by NACH, crowding, connectivity and intelligibility (in Table 41c). The factors also have a relative priority in comparison to each other. For example, PTAL is prioritized 2.32 (=0.4716/0.2033) times more than NACH or 5.45 times (=0.4716/0.0865) more than connectivity by the survey participants.

While there is a certain priority between the five parameters, there is a need to check the consistency within the survey outcome. This is done by calculating principal eigen value, which is obtained from the overall summation of the products between each value of normalized eigen vector and sum of column in the comparison matrix (i.e. (0.0865 x 16 (1/5)) + (0.4716 x 1 (7/8)) + …. (0.0370 x 25)). The consistency index (CI) is calculated as (PEV – n / n-1), where n is the number of factors within the matrix i.e. 5. In order to obtain the consistency ratio, where 0.20 is considered as a maximum limit (discussed in section 6.3), the consistency index is divided by the random consistency index for 5 factors, which is 1.12 (Saaty 1980). This results in the consistency ratio of 0.1769 for the comparison matrix. As it is

Ishizaka, A., & Lusti, M. (2006), How to derive priorities in AHP: a comparative study, Central European Journal of Operations Research, 14(4), 387-400. DOI: 10.1007/s10100-006-0012-9
Saaty, T.L. (1980), The Analytic Hierarchy Process, McGraw-Hill, New York In: Wedley, W.C. (1993), Consistency prediction for incomplete AHP matrices, Mathl. Comput. Modelling, Volume 17, No. 4/5, pp. 151-161.

within the limits for consistency, the weightage can be utilized for further ranking of urban areas based on the public perception.

Furthermore, the comparison matrix was also utilized to see the difference in principal eigen vector through AHP-OS tool (Goepel 2018), where the tool yielded the principal eigen value which was within 5% error with similar hierarchy and priority weights for the five parameters. These priority weights, generated through the outcome of the survey in Rhein-Main agglomeration, are utilized to see the urban area ranking revised based on the public perception towards the five parameters. Based on the Analytic Hierarchy Process, the priority weights put PTAL on top of the hierarchy while Intelligibility was the least prioritized aspect for the survey participants in the Rhein-Main agglomeration. With the new subjective priority weights for the five accessibility parameters, the ranking of the selected urban areas in the agglomeration for the study is revised to understand the impact of the difference between the subjective priority and the objective priority (addressing the third research question).

Weighted NEM

Performance measures	(c)	(i)	(n)	(cr)	(p)	E. distance from ideal best (eb)	E. distance from ideal least (el)	eb + el	Performance score (el/el+eb)	Rank
Da Transit	0.026	0.009	0.063	0.028	0.151	0.158	0.180	0.338	0.533	3
Da Residential	0.024	0.010	0.065	0.012	0.016	0.291	0.136	0.427	0.318	8
Da City center	0.028	0.014	0.078	0.073	0.225	0.102	0.223	0.325	0.686	2
Fr Transit	0.033	0.015	0.075	0.055	0.307	0.044	0.305	0.349	0.875	1
Fr Residential	0.028	0.012	0.061	0.035	0.072	0.237	0.125	0.362	0.345	7
Fr City center	0.030	0.014	0.071	0.147	0.176	0.188	0.160	0.349	0.460	4
Of Transit	0.032	0.013	0.062	0.033	0.074	0.235	0.128	0.363	0.352	6
Of Residential	0.028	0.009	0.064	0.031	0.025	0.283	0.117	0.400	0.292	9
Of City center	0.030	0.013	0.067	0.078	0.113	0.205	0.119	0.325	0.368	5
Ideal (best) value	0.033	0.015	0.078	0.012	0.307					
Ideal (least) value	0.024	0.009	0.061	0.147	0.016					

Table 42: Weighted Normalized Evaluation Matrix (NEM) of the selected parameters (performance measures in the table) and the urban areas in the cities of Darmstadt (Da), Frankfurt am Main (Fr) and Offenbach am Main (Of)
Note: The performance measures in this matrix are given prioritized weightage based on AHP from the survey

The weighted Normalized Evaluation Matrix (in Table 42) is revised from the subchapter 5.3 (see Table 38), where the five parameters were given equal weightage of 0.20 (i.e. PTAL had a priority weight of 0.20, which is less than half of the priority weight derived from the subjective evaluation of the public opinion). This results in a revised performance score of the 9 selected urban areas in the cities of Darmstadt, Frankfurt am Main and Offenbach am Main. The change in the overall weightage of the five parameters led to a revised ranking of the urban area which differs from the former performance ranking with equal weightage of the five parameters.

The area surrounding Frankfurt Hauptbahnhof remained on top of the hierarchy of urban areas, based on their performance score through the five parameters with subjective prioritized weightage. Within

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Goepel, K.D. (2018), Implementation of an Online Software Tool for the Analytic Hierarchy Process (AHP-OS), International Journal of the Analytic Hierarchy Process, Vol. 10 Issue 3, pp 469-487. DOI: https://doi.org/10.13033/ijahp.v10i3.590

the top three urban areas of the hierarchy, the city centre in Darmstadt and the area surrounding Darmstadt Hauptbahnhof reclaimed the second and third position. This reflects how the major landmarks of the comparatively smaller cities can outperform the larger cities through the multimodal accessibility parameters in cluster. The ranking of urban areas (after the prioritized weightage) from the bottom had a major change, where the selected residential areas of the three cities had an overall low score based on the five parameters. The residential area of Bürgel in Offenbach am Main ranked the lowest amongst the nine urban areas in the study, followed by the residential area of Komponistenviertel in Darmstadt. The residential area around Bornheim in Frankfurt am Main (a comparatively larger city) performed better than the other selected residential areas.

The city centre in Frankfurt am Main showed a major jump in the overall performance ranking after the subjective prioritized weightage of the five parameters. Prior to the priority weightage, the city centre (with equal parametric weightage) ranked lowest in the hierarchy of urban areas. After the priority weightage, the city centre in Frankfurt am Main came fourth in the overall ranking (see Table 42), which surpassed five urban areas in the study. With 'access to public transport' being the highly prioritized aspect amongst the five parameters, and the city centre in Frankfurt performing the third best comparatively within the PTAL study, the revised weightage had a certain impact on the favoured aspect and the urban area. The city centre in Frankfurt had the worst aspect of 'ease of movement' through crowding parameter (in 5.1.5), which had a mean crowding value of more than twice than that of the urban area following it in the hierarchy. This contributes to a much smaller Euclidean distance from the ideal least value, for the city centre in Frankfurt am Main, which results in low performance score. With weighted priorities and city centre in Frankfurt having a PTAL value which is closer to the ideal best value, the impact on the overall performance results in the city centre of Frankfurt am Main performing better than the other five selected urban areas.

6.4 Summary

This chapter initiates the dialogue of bringing public perception quantitatively through a qualitative way, which assists in understanding the subjective priority towards certain aspects. With the five parameters being re-defined and introduced within the survey for the better understanding of the participants within the Rhein-Main agglomeration, the perception of user-groups towards the combined mobility and accessibility characteristic assists in meeting the objective. The perception of public towards the subject of mobility and accessibility, especially within the cities forming Rhein-Main agglomeration, adds to the better understanding of the mobility culture (Klinger et al. 2013) and brings forward different prioritized aspects. This is done by addressing subjective dimension through public perception (which was recommended for the future work (Klinger et al. 2013) for understanding mobility culture). The preferred mode of mobility, aspect of priority, immediate neighbourhood rating, and pair-wise comparison of identified aspects with certain consistency by the survey participants adds a broader perspective to the mobility environment within the urban configuration of spaces. The priority towards certain dominant aspects (like 'access to public transport' in the overall survey outcome) was influential which resulted in the revised ranking of urban areas. The city centre in Frankfurt am Main had a major impact in its performance score through the five parameters, which resulted in it surpassing five urban areas in the hierarchy. While the survey outcome for the pair-wise comparison of aspects stays consistent with respect to the Analytic Hierarchy Process, a wider reach of survey participants would enhance and reflect a more accurate public perspective.

The introduction of multi-criteria decision-making tool for prioritizing certain urban areas brings together different stakeholders, which is beneficial for diverse urban development projects. The inclusion of subjective and objective dimensions in the research study, contributes to the importance of improving an urban area (which is deprived of certain aspects or does not meet its spatial potential) through policy implications (Cummins 2000; Liao 2009). Improving the overall accessibility characteristic of an area (through brownfield and greenfield projects) can be done with prioritization of certain aspects by urban planners, designers and experts within the field of study (both via inter- and intra-city parametric perspective) during the design of a masterplan timeline for a city or a group of cities forming the agglomeration.

SECTION 3

CONCLUSION

CHAPTER 7

SUMMARY AND CONCLUSION

Preface

The chapter summarizes the key takeaways through the literature and on-site study, and reflects upon the identification of potential utility of the attributes and its link with the current urban development practices through the three cities in the Rhein-Main urban agglomeration. Certain key outtakes from the on-site and on-desk research findings are discussed along with future outlook of urban areas and limitations which may influence the overall outcome.

7.1 Summary and discussion

7.1.1 Perspectives through identified parameters

Being one of the major urban agglomerations within the country and Europe, the Rhein-Main agglomeration as a region presents an opportunity to study and compare cities and urban areas with a common goal of improving their present state of mobility through multiple measures. Based on the overall commuter flow (in-flow and out-flow) and population growth within the region, the cities of Darmstadt, Frankfurt am Main and Offenbach am Main were selected to identify potential areas of improvement for their multimodal accessibility. The urban areas in the study had their own development plans in accordance to the master plans of their respective cities. These urban areas were studied and analysed through the identified accessibility aspects of connectivity, access to public transport, access to direct routes, ease of movement and ease of navigation. The corresponding methodologies involved utility of certain index measures and spatial algorithms (based on distance and time) from the literature study, which included state-of-the-art measures being utilized to understand the influence of spatial configuration directly or indirectly on the urban mobility environment.

There has been an observed impact of the identified aspects, such as connectivity, on travel behaviour, which includes pedestrian activity and travel mode choice (Hajrasouliha and Yin 2015; Marshall and Garrick 2010). The travel behaviour can also be influenced by the ease of understanding a space and navigating through the network of open spaces, which is characterized by its intelligibility. The measure of intelligibility for a space has shown to be predictive of wayfinding and environmental cognition (Hag and Girotto 2003), which adds to its accessibility characteristic. The accessibility of modes where the angle of movement plays an important role, including cyclists, the access to direct routes (analysed via NACH) reflects the potential of routes for their movement (Nordström and Manum 2015). Between the two selected attributes of Space Syntax i.e. intelligibility and NACH, while the measure of intelligibility utilizes the factor of integration which directs towards a 'to' movement potential, the parameter of NACH directs towards a 'through' movement potential. This reflects towards the potential destinations and routes within a network of open spaces. With respect to the diverse public transport services, the PTAL index integrates the two aspects of urban transport and land-use planning, assists in improving and identifying potential residential locations, helps in understanding mobility requirements and more (Adhvaryu et al. 2019). The walk access time within the PTAL index brings the factor of distance and time, which is influenced by the shortest route between the origin and destination (it being the public transport service station). The shortest route, determined by how the network of open spaces (or streets) are arranged, varies for different spatial configurations. The quality of these open spaces is further determined by its movement restriction and crowding characteristic, which characterizes its ease of movement. The buffer spaces from different street elements, associated barriers, and peak hour frequency of different user-groups utilizing diverse open spaces determines the comfort with which these spaces are being used for one's movement.

Walkable network: The parametric approach of analysing selected urban areas through varying observational radii presents an opportunity to compare similar urban spaces in different cities within the Rhein-Main urban agglomeration. The network of streets within the identified areas showcased a walkable network with connectivity index (i.e. link node ratio) being in close proximity to 1.40 value, which denotes a bare minimum. Comparatively, the residential areas had low connectivity index with respect to city centres and main transit stations, due to higher frequency of cul-de-sacs from the non-distributed street network. This was more prevalent within the residential area of Komponistenviertel (in Fig. 45 and Table 29), with its detached housing and cul-de-sacs, which showed the least connectivity through its street network amongst the nine urban areas. The large commercial and industrial space in proximity to the area surrounding the main railway station (i.e. Hauptbahnhof) in Darmstadt reduced the density of streets and junctions which are accessible to the public, in turn resulting in comparatively lower connectivity than similar urban areas in other cities. On the contrary, the orthogonal street network with linear pattern of blocks and streets towards the east of Frankfurt Hauptbahnhof contributed to its high street connectivity, which was further supported by it being a terminal station (in contrast to the non-terminal stations in Darmstadt and Offenbach, giving more space for streets and junctions in Frankfurt am Main). This shows how different land use and spatial configuration can influence the accessibility characteristic through connectivity.

Ease of navigation: The network of streets in selected urban areas showed varying range of intelligibility with high and moderate values. Similar to the observed outcome through the connectivity index, the residential areas showed low intelligibility characteristic excluding Komponistenviertel in Darmstadt (Fig. 86 and Table 30), which had better intelligibility than the area surrounding the main transit station in Darmstadt (i.e. Hauptbahnhof). The high density of cul-de-sacs in the residential areas resulted in corresponding low integration values, which led to segregation of local streets from highly integrated streets. This, in turn, supports the nature of privacy for the people residing in the residential area, while it creates a negative impact on the navigable environment. Overall, the city of Frankfurt am Main dominated the characteristic of intelligibility through its selected urban areas as compared to the smaller cities of Darmstadt and Offenbach am Main. The uniform closeness of a street's connectivity (i.e. the Space Syntax attribute) and its global integration attribute, along with the location of highly integrated streets influenced the navigable street network for the intelligible areas. Connecting more streets to the highly integrated street, or extending the highly integrated street to other areas with low integrated streets assists in increasing the overall intelligibility on a long-term perspective. While this is more directed towards greenfield projects, the influence of new streets (for projects such as densification) on the overall intelligibility (see Fig. 87) assists in looking at various design alternatives prior to implementation. The utilization of signages or landmarks around the areas with low and high integrated streets influences the overall navigation experience for a person. For instance, locating distinct landmarks (e.g. street elements like benches, sculptures, urban landscape etc.) on streets with moderate or weak integration values, brings a unique sense of belonging and addresses towards navigating the immediate surrounding area with better ease.

Access to public transport: Through peak hour frequency of diverse modes and proximity of the service station, PTAL was analysed during similar timeline in the selected urban areas forming the agglomeration. The city centres dominated the PTAL values in the cities of Darmstadt and Offenbach am Main, while the area surrounding the main transit station in the larger city of Frankfurt am Main recorded the highest PTAL value from all the modes. Based on the diversity of modes, the city of Offenbach am Main lacked the service of trams, while they were available in Darmstadt and Frankfurt am Main. With respect to the city centres, Frankfurt am Main being a larger city had more diversity in its public transport services which included bus, tram and train services in the area surrounding the city centre. Although Luisenplatz in Darmstadt had only bus and tram services, its overall PTAL value was higher than that of Hauptwache (see Table 31), as it was supported by on-ground level access to the services. On the contrary, Offenbach am Main had the lowest PTAL value amongst the city centres with bus and train services. This showcases how the diversity of public transport modes and its proximity as a destination contributes to the overall access to public transport, and how comparatively smaller cities can have areas with more access to public transport than larger cities. The on-ground provision of public transport in comparison to the underground services usually leads to short access time and favours an area's potential of accessibility to public transport services (unless the frequency and diversity of underground rail routes compensate for the long access times and add to better PTAL index) catering to the people-centred planning. On the contrary, the long-term effects of underground transit investments have shown to change the modal split in favour of public transport (Girnau and Blennemann 1989), and led to more space for pedestrians (ITA Working Group 13 2004). The opening of new underground U-Bahn service in Karlsruhe (Ruf-Morlock 2021) adjacent to the main pedestrian street in the city centre adds to the discussion on the priority of type of public transport services required (i.e. surface vs underground services). While the socio-economic factors including benefit-cost ratio of new urban development projects (within the domain of improving public transport services) has an influence on decision-making process, the impact on the area's accessibility to public transport also needs to be taken into consideration. This makes it even more important to prioritize factors influencing the decisions on greenfield surface and underground public transport development projects.

Furthermore, regarding the PTAL values in selected residential areas within Rhein-Main region, while the diverse services contributed towards the higher PTAL in Frankfurt am Main, the positioning of the service stations in Offenbach am Main and Darmstadt had an impact on the area's access to public transport. For instance, the public transport service stations were positioned within the inner parts of the residential area of Bürgel, in contrast to Komponistenviertel where they were positioned on the

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Girnau, G. and Blennemann, F. (1989), Cost-Benefits in Underground Urban Public Transportation, Planning and Development, Tunnelling and Underground Space Technology, Vol. 4, 1, pp. 23-30.

Ruf-Morlock, I. (2021), Kombilösung Karlsruhe: Tunnel ist eröffnet – alle Infos zum Milliarden-Projekt, Badische Neueste Nachrichten, Karlsruhe. Retrieved from https://bnn.de/karlsruhe/karlsruhe-stadt (22-08-22)

ITA Working Group 13 (2004), Underground or aboveground? Making the choice for urban mass transit systems A report by the International Tunnelling Association (ITA). Prepared by Working Group Number 13 (WG13). 'Direct and indirect advantages of underground structures', Tunnelling and Underground Space Technology, 19, pp. 24-28.

peripheral streets. This led to long access time in Komponistenviertel, in turn decreasing its potential PTAL value. Improving access to public transport, especially in areas with low PTAL values (including the added perspective of URM e.g. wheelchair users) by increasing peak hour frequency, better positioning of service stations with respect to the urban configuration or by diversifying public transport modes contributes towards higher multimodal accessibility through short-distance mobility.

Route directness: The two perspectives (i.e. small scale and large scale) of direct routes and their potential with on-site frequency of users presents an opportunity to improve the on-site condition of streets supporting better access. On a small-scale perspective in Darmstadt and Offenbach am Main, the city centres showed network of direct routes with highest mean NACH values, while in Frankfurt am Main, the area surrounding Hauptbahnhof showed maximum mean NACH value. On a large-scale perspective, the city of Frankfurt am Main had the highest mean NACH value followed by Darmstadt and Offenbach am Main. Based on the network of open spaces and configuration of buildings and blocks, the street segments with high NACH value passed through the central core of the city in Offenbach am Main and Frankfurt am Main, while in Darmstadt the location of segments with high NACH value was located in the east from the city centre (see Fig. 53). The industrial and commercial land use on the western end of Darmstadt influences this outcome, where the network of streets is inaccessible to general public. The correlation of on-site cycling frequency and corresponding NACH values of the street segments show how cities are able to utilize the potential of the direct routes, while certain factors (like lower safety, quality or absence of dedicated routes for user-groups) deter utilizing its full potential. In addition to the cyclists, the direct routes can also be utilized by other fast-moving user-groups including car users which commute a longer distance. The overall identification of potential direct streets is essential and beneficial, especially for undertaking urban experiments like street closure, implementing bicycle streets, or tactical urbanism which would be inclined towards the masterplan of the city directly or indirectly. In addition, the representation of direct routes through NACH also assists in bringing a more visual and universal perspective to diverse stakeholders.

Spatial freedom: The movement restriction and crowding caused by the on-site street elements (including on-street parking, informative signages, public service stations etc.), space for an individual's movement and density of people during peak hour period determined the ease of movement for an urban space. In regards to the hierarchy of crowding values, the city centres played a dominant role with high density of people using the space during the peak hour period. Amongst the selected cities, the city centre in Frankfurt am Main recorded the highest on-street crowding value which was approximately 12ppm, corresponding to 41% movement restriction (in Fig. 93). The mean crowding value of the streets surrounding the city centre in Frankfurt am Main was almost double the value of the streets surrounding the city centres in smaller cities of Darmstadt and Offenbach am Main (see Table 33). Through all the selected urban areas within the cities, the larger city of Frankfurt am Main dominated the crowding aspect on streets surrounding its city centre, main transit station, and selected residential area. With respect to the available pathway widths, the residential areas of Bürgel in Offenbach am Main had the least mean width as compared to Bornheim and Komponistenviertel. The location of the spaces in high density areas also influenced the overall crowding. For instance, while the area surrounding Offenbach Hauptbahnhof recorded low access to public transport services through PTAL as compared to similar area in Darmstadt, the streets around Offenbach Hauptbahnhof recorded more crowding within comfortable range, which could be contributed by its close proximity to the city centre and dense urban settlement which is in contrast to the area surrounding Darmstadt Hauptbahnhof within the observation limits.

In regards to the overall parametric characteristic of selected urban areas within the Rhein-Main agglomeration, the prioritized subjective weightage of parameters from the public survey led to the area surrounding the city centre and main railway station in Darmstadt and Frankfurt am Main performing better than the similar areas in Offenbach am Main. The area surrounding the city centre in Frankfurt showed a major jump in the overall performance ranking through prioritized weightage under TOPSIS, where prior to the public survey equal weightage was given to each parameter. The aspect of data-informed approach towards prioritizing certain areas from the data-driven approach assists in having an overview of different accessibility parameters with a public outlook, which is crucial during different progress timelines for a masterplan of a city or a group of cities with common objectives. It is also influential for policy implications catering to improve accessibility deprived urban areas, which should consider both the objective characteristics and subjective evaluations of the space.

7.1.2 Application of identified parameters for urban planning and design projects

In addition to previous discussion, this subsection reflects further inferences and recommendations for accessibility planning. The utilization of spatial analysis through identified accessibility parameters for the urban design and planning projects brings in added perspectives of accessibility as a factor to accelerate the process of decision-making in several greenfield and brownfield projects. Analysing direct routes via Space Syntax attribute of NACH assists in understanding the potential of streets for supporting certain user-groups for their travel. This aspect when utilized for certain outcomes can support identified measures within the master plans of the cities. For example, the 'Innenstadtkonzept' in Frankfurt am Main focuses on revitalization of area surrounding the city centre and is limited to the area within the green belt of Wallanlagen (which is also prioritized to reduce conflict points between pedestrians and cyclists). One of the objectives within the concept includes improvement of pedestrian and cycling network to link the city centre with the Mainkai riverfront in the south and the surrounding areas of the green belt of Wallanlagen. The identified direct routes through NACH analysis (small and large perspective) can be utilized to further strengthen the streets for improving its accessibility. The two routes moving towards the south, via the old city i.e. Altstadt, from the central intersection of segments with high NACH value showed the potential for directness linking the central pedestrian plaza to the Main river in south (see Fig. 98). With the Mainkai road-closure experiment, the large-scale analysed map of Frankfurt am Main (via NACH) visualizes the high potential of Mainkai street which was underutilized with no dedicated pathways for cyclists. Following this, the attribute of local integration within Space Syntax also assisted in predicting the future scenarios of pedestrian movement in the area. The analysed maps through different Space Syntax attributes showcased higher potential of Mainkai street as a direct way for cycling and attracted more pedestrians (which was earlier dominated by car users) as compared to riverside area (which was earlier used a shared space between user groups with different speed of movement i.e. cyclists and pedestrians). Through the research cooperation between the City of Frankfurt and the Urban Design and Planning Unit (formerly Urban Health Games, TU Darmstadt), the research analysis via outcomes and recommendations were presented to the city in 2020. One of the recommendations included on-site intervention through the implementation of dedicated bicycle pathway (see Fig. 112), which reflected Mainkai street's potential for cycling (via NACH). The on-site frequency of user-groups supported the spatial analysis and the installation of new cycle lanes along with the reduction of car-lanes in 2021 provided a pathway to meet the street's potential for supporting both cyclists and car users.

In the city of Offenbach am Main, the area surrounding the city centre i.e. Marktplatz had a similar scenario where the street of Berlinerstrasse played an important role as a direct route (through NACH) in east-west direction. The street of Schloßstrasse through the HfG (Hochschule für Gestaltung Offenbach am Main) connecting the southern Main riverside with the city centre showed a high potential for direct routes as well. The street segment would play a major role especially considering the future plans of the city, which focuses on a potential bridge north of the city connecting the northern and the southern riverside, for pedestrians and cyclists. The network of street segments around the street of Schloßstrasse and their corresponding attribute values could be utilized to create a new network of direct routes for different user-groups enhancing the mobility network and also consider the present values of crowding and movement restriction on-site to plan an accessible network of streets with available pathway widths.


Figure 112: Recommended intervention render (left) of dedicated cycle pathway based on the NACH analysis in 2020 and the on-site implementation of dedicated bicycle pathway in 2021. Note: The NACH analysis and recommendations were presented to the City of Frankfurt in 2020 via research cooperation between Urban Design and Planning Unit (previously Urban Health Games), TU Darmstadt and Stadt Frankfurt am Main.

With the growing population in many cities within the Rhein-Main urban agglomeration, the densification projects in different residential areas is one of the several measures being implemented through a city's corresponding master plan. Within the cities of Darmstadt and Offenbach am Main, the identified residential areas for densification included Komponistenviertel and Bürgel respectively. Following the research outcomes from the crowding aspect, these areas had the least available pathways for active modes. The narrow streets with their corresponding low mean pathway widths for movement, had crowding values within comfortable range. With more housing units being planned in these areas, the potential dense housing neighbourhood would lead to higher crowding values, which would imply higher movement restriction considering the pathway measurements remain the same. The narrow pedestrian pathways, absence of cycling lanes, on-street parking and low level of access to public transport (calculated via PTAL) would create a barrier with respect to the short-distance mobility in these residential areas. As observed in the PTAL evaluation, the different positioning of public transport service stations in the residential areas of Bürgel and Komponistenviertel had an impact on the overall access time which in turn influenced the overall PTAL value. In Komponistenviertel, the revival of old public transport service station around the central intersection (i.e. along the street of Flotowstrasse) (see Fig. 33) would decrease the overall access time and add further access to the public transport. Similarly, in the area surrounding Bürgel, the proposed diversion of traffic from the street of Langstrasse (which was evaluated with high potential for direct route) to the alternative street of Mainzer Weg would further strengthen the utilization of the street (i.e. Langstrasse) for other user-groups, as the narrow street width acts as a barrier towards its potential for providing access to multiple modes of mobility. In addition, the extension of street network in Komponistenviertel (i.e. extension of cul-de-sacs in the eastern and western ends to highly main streets in proximity linking green spaces) following the objectives of *Doppelte Innenentwicklung* would address the urban planning principle and also make the streets more attractive for continuous movement, especially when further densification of residential area takes place.

The utilization of available open spaces and their potential for being reused for other purposes has been discussed in many urban development strategies. In Offenbach, the selected transit area had low access to public transport (via PTAL), mainly contributed by the bus services. This led to its PTAL value almost comparable to that of the residential area in Frankfurt am Main (i.e. Bornheim). While the close proximity of bus service stations already contributes towards public transport accessibility, the increased frequency of services especially via train would contribute towards better PTAL. This would allow utilization of existing open space around the railway station for other purposes, as relocation of transit service stations wouldn't be necessary for added value towards PTAL (in contrary to the observed outcomes in selected residential areas). This justifies the identification of the open space (close to the bus service station) around the main railway station under the Masterplan 2030 of Offenbach am Main to utilize the area through business, residential and other purposes. Considering its low PTAL value, while added frequency of services would add towards better access to public transport, certain space allocation can be made for better access to alternative means of mobility (like car or bike sharing and e-scooter rental spaces) to compensate for the low accessibility. The network of streets surrounding the main railway station in Offenbach am Main with high integration values, less cul-de-sacs, high NACH values (not the overall mean but the individual segment values) and comfortable crowding range provides an opportunity for potential urban development projects.

Urban clusters

The prioritization of urban areas for added infrastructure requirements based on their multimodal accessibility attributes and public perception can be utilized to identify the hierarchy of potential areas for improvement. Urban areas can be grouped into clusters based on their similar objective accessibility characteristics, which helps in identifying similar set of urban development measures. Following the Agglomerative Hierarchical Clustering method (Zepeda-Mendoza and Resendis-Antonio 2013) resulting in a dendrogram (see Fig. 113), two such major clusters were identified.

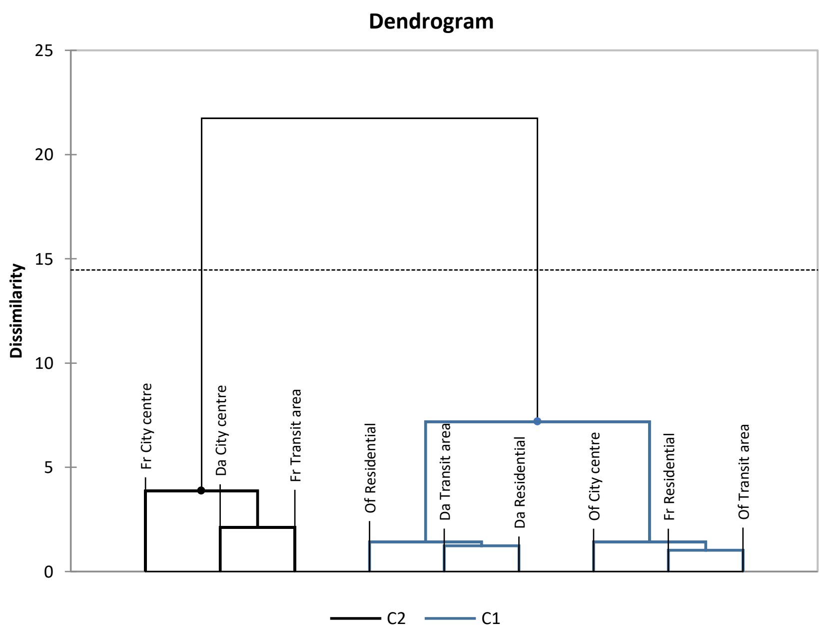

Figure 113: Dendrogram (via Agglomerative Hierarchical Clustering) representing two clusters of urban areas with similar objective accessibility characteristics

The Dendrogram (in Fig. 113) shows two major clusters of C1 and C2 (see Appendix V) with their subclusters showing similar multimodal accessibility characteristics.

C2 cluster: The C2 cluster (including the city centres of Frankfurt am Main and Darmstadt, and the area surrounding Frankfurt Hauptbahnhof) shows a more homogenous nature than the C1 cluster (with C2 being flatter on the dendrogram with less dissimilarity). Based on the identified C2 cluster, the urban areas showed a high walkable network of streets (via connectivity), high intelligibility, high mean NACH value of street network, high public transport accessibility levels and comparatively low ease of movement through high crowding and movement restriction. This addresses the need to prioritize (objectively) less movement restriction in the C2 urban cluster. At the same time, it is also crucial to address the narrow streets in residential areas for less movement restriction once the future new residential projects (via densification planning concept) are identified.

C1 cluster: C1 urban subclusters with low accessibility characteristics assist in focusing on improving their identified aspects. For instance, the sub cluster of Offenbach am Main's transit area and residential area of Bornheim in Frankfurt show (similar) low mean NACH value and moderate PTAL value. This makes the urban planning authorities focus more on the area's ability to provide better cycling and public transport infrastructure. The C1 subcluster of transit and residential area in Darmstadt showed similarly low values of walkable network of streets (via connectivity), low intelligibility, moderate mean NACH value, favourable (low) movement restriction in their network of streets yet contrasting PTAL values. This addresses the need to incorporate urban development strategies to improve the subcluster's intelligibility and connectivity (discussed in subchapter 5.1), and utilize the street network with high individual NACH values for cycling. For instance, the street on the western entrance of Darmstadt Hauptbahnhof had high NACH value yet did not have a dedicated bicycle pathway.

For a city planning authority, more urban areas of a city can be analysed individually and later clustered to implement similar set of urban development measures focusing on improving its multimodal accessibility. Different parameters can be utilized in combination to understand certain mobility and accessibility characteristics of an urban area, to implement particular on-site measures for a short-term (including tactical urbanism) and a long-term period.

7.1.3 Improvement potential and combined parametric perspective

The identified parameters for analysing different spatial configurations of the urban areas were utilized to quantify the attributes within the domain of multimodal accessibility. While these parameters focus upon a specific subject or have a particular boundary of observation, certain upgrades are made to increase its potential of analysis. For instance, the added perspective of users with reduced mobility through the existing index of PTAL can be utilized to prioritize areas which fall towards a lower range of PTAL values. As the existing PTAL index utilizes normal human movement speed for its access time calculation to the public service stations, including user-groups with slow speed of movement caters to higher degree of accessibility with diverse perspectives within its domain. These user-groups include person on wheelchair, person with a baby stroller, person using a walking support (e.g. a cane, walking stick etc.), and more. Through the added perspective of users with reduced mobility, the revised PTAL index showcases how the same urban areas with similar radius of observation for public transport

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Zepeda-Mendoza, M.L. and Resendis-Antonio, O. (2013), Hierarchical Agglomerative Clustering. In: Dubitzky, W., Wolkenhauer, O., Cho, KH., Yokota, H. (eds) Encyclopedia of Systems Biology. Springer, New York, NY. DOI: 10.1007/978-1-4419-9863-7_1371 services cater to different people and highlight if any inequity (within the domain of PTAL) of the services exists towards the user-group.

The revised PTAL index through the added perspective of persons with reduced mobility was introduced post literature study and calculated for each selected urban area in the three cities. The revised PTAL index was not used for the ranking of urban areas under TOPSIS, but was done to have an individual perspective for each area parallel to the existing PTAL index. The revised PTAL led to a decrease in the original PTAL value for all the nine areas, while it maintained the previous category of range value for majority of them. The two residential areas of Bornheim and Bürgel, in Frankfurt am Main and Offenbach am Main respectively, fell below their original PTAL range category. For Komponistenviertel in Darmstadt, while the PTAL range category remained the same it was in proximity to the worst PTAL range based on revised PTAL value. The outcome brings more clarity towards the different levels of accessibility to public transport services for different user-groups, and brings forward a perspective towards a universal approach which can be utilized to further prioritize urban areas requiring better access to public transport services.

Similar to some changes within the PTAL, other factors are also introduced to the identified parameters including crowding. For the understanding of how different user-groups utilize a particular space or a network of streets in an urban area, the peak hour crowding of different street widths included different user groups being identified prior to the on-site data collection. The identification of different user-groups is done within the study ranging from pedestrians, cyclists, to persons using motorized vehicles such as cars. The diversification of user-groups helps in utilizing certain parts of the on-site data which is already contributing towards the overall crowding and movement restriction. This is used for identifying potential streets for particular user groups like cyclists (via NACH), to observe change in the mobility behaviour of different user-groups based on urban experiments (e.g. road-closure, traffic calming, tactical urbanism etc.), and more. In case of Frankfurt Mainkai road closure, the shift of fast-moving user-groups towards the main street of Mainkai from the shared space of riverside area (which included cyclists, e-scooter users and pedestrians using the same width of space for their movement) helps in understanding the priority of certain user-groups relying on direct routes for their movement. This in turn resulted in the installation of dedicated cycle lanes on the main Mainkai street post road-closure experiment, supporting the fast-moving user groups of car users and cyclists.

Combining the data outcomes from two identified parameters (or more) analysing the spatial configuration contributes towards a better understanding of space utilization by different user-groups. This can be done on a city-wide level or on a small-scale, depending upon the objective of the study and the hypothesis. Referring to the city-wide perspective, the aspect of ‘access to direct routes’ and ‘ease of movement’ have been utilized to understand the usage of different street segments by a user-group (i.e. cyclists). As cyclists prefer direct routes for their movement, the street segments analysed through NACH obtain an individual attribute value. With the on-street peak hour frequency data of the user-group collected, its correlation with a street’s NACH value determines if the user-group is utilizing the direct route to its full potential. Being statistically significant, the correlation between NACH and on-site peak hour frequency of the cyclists was positive within the three cities of Darmstadt, Frankfurt am Main and Offenbach am Main. The comparatively lower correlation within the city of Offenbach suggests the low utilization of direct routes by the cyclists. This in turn assists in understanding how the mobility behaviour and accessibility towards a mode of travel exists for a user-group, and is different in cities due to other factors. This adds to the existing literature of Space Syntax analysis, where NACH is relatively a new concept as compared to other Space Syntax attributes. For Offenbach am Main, one of the reasons for the underutilization of the direct routes in the city could be the dominant role of other user-group on streets i.e. car users, combined with absence of dedicated lanes on potential direct routes for the user-group.

The understanding of 'ease of navigation' aspect through added perspective of cul-de-sac density under the connectivity index, helps in identifying different factors responsible for a lower intelligibility characteristic for an urban area. In regards to the intelligibility characteristic, the moderate intelligibility of the selected residential areas in the study was contributed by high frequency of cul-de-sacs, which in turn led to high number of streets with low integration values. This results in lower reach of highly integrated streets within the residential areas. While the distant local streets from highly integrated streets (with more car traffic) support the privacy in residential areas, it has a negative impact on the navigable environment of the area for pedestrians. This also shows how the street networks favouring walkable and navigable environments are more distributed in nature generating different movement possibilities, while the limited non-distributed streets (which include cul-de-sacs as their terminating points from further distribution) contribute to less diverse movement patterns i.e. less multimodal access.

The revised and improved parameters focusing on different user-groups with priority, along with utilization of multiple parameters in coherence focuses towards a learning approach. This approach finds it utility in different ways to improve the diverse factors of multimodal accessibility in continuum and helps in narrowing down the influential factors shaping the urban mobility environment within the urban planning discipline. In addition, while certain iterations can be made to some identified parameters, certain limitations need to be addressed to factor in added possibilities for improvement.

7.1.4 Impact of Coronavirus pandemic on data

The onset of Coronavirus (COVID-19) pandemic during 2020-21 resulted in several disruptions on normal public lifestyle. The social distancing norms and controlled occupancy of indoor and outdoor spaces based on the density of people using the area, influenced how people utilized and accessed different public spaces. This also resulted in change in the modal share of people using different modes of mobility. The amount of people using bus or rail services in Germany decreased by 11% in the first quarter of 2020, which in turn led to the change in reduction of frequency of public transport services (Statistisches Bundesamt 2020). Anke et al. (2021) in their study found an impact of the pandemic period on the mobility behaviour of the people in Germany where people shifted away from the use of public transport services, and moved towards alternative means of transport (including walking, cycling and car usage). This also led to certain changes in the data collection timeline for the on-site and on-desk study for the selected urban areas in the Rhein-Main agglomeration.

Prior to the pandemic, the pilot study was carried within the city of Darmstadt where the data for calculating PTAL was collected. This resulted in an overall PTAL value for the three selected urban areas within the city of Darmstadt, which later on were influenced during pandemic. In order to have a similar environment for the obtained data within the aspect of access to public transport services, where similar time period is utilized for the data collection for all three cities post pandemic, the pre-pandemic data from the pilot study was revised. Similar to the data collection for the PTAL parameter, the on-site data collection for the peak hour frequency of user-groups and measurement of the on-street widths of available pathways for movement were postponed during the initial lockdown stages of the pandemic in 2020. While the reconnaissance visit to the selected urban areas were done prior

Statistisches Bundesamt (2020), Transport by bus and rail: number of passengers expected to be down 11% in the first quarter of 2020, Press release, DESTATIS. Retrieved from https://www.destatis.de/EN/Press/2020/05/PE20_N025_461.html
Anke, J., Francke, A., Schaefer, LM. et al. (2021), Impact of SARS-CoV-2 on the mobility behaviour in Germany, European Transport Research Review 13, 10. DOI: https://doi.org/10.1186/s12544-021-00469-3

to the pandemic, the on-desk approach of mapping and analysing Space Syntax attributes was carried forward.

The initial outcomes through the PTAL index values prior to the pandemic in Darmstadt resulted in a similar hierarchy of urban areas after the pandemic, though there were differences in the individual PTAL values. For instance, the PTAL for the area surrounding main transit station i.e. Hauptbahnhof and the city centre had higher value prior to the pandemic (Pandit & Knöll 2019) as compared to the revised data post pandemic. The slight increase for the PTAL value in the selected residential area can be attributed towards the change in the frequency of new bus services around Komponistenviertel, with no changes to the location of the public transport service station. The overall performance ranking for the selected urban areas based on their parametric characteristics before and after the public survey excludes the pre-pandemic data for PTAL in Darmstadt in order to have a comparison with similar mobility environment.

7.1.5 Limitations and future studies

The spatial analysis of different selected urban areas within the Rhein-Main agglomeration prioritizes on different aspects through the accessibility parameters. These prioritizations are based on the individual parametric perspectives along with the people's perspective residing within the cities forming the agglomeration. Considering the overall timeline of the on-site and on-desk approach of the research, there were some limitations which should be taken into consideration for future studies of urban areas. Regarding the survey, as the data collection was planned post the spatial analysis of the identified urban areas and cities, the coronavirus pandemic delayed the on-site procedure. Based on the online survey data collection and the overall population of the Rhein-Main agglomeration (i.e. 5.8 million inhabitants), the response of 248 participants corresponds towards an approximate 6% margin of error within a 95% confidence level (i.e. the probability that the sample size accurately reflects the opinion of the population). This is derived from the sample size calculation (Cochran 1977) used for the survey in the study. While the sample size has a low margin of error, it could be further reduced with a larger sample size. This can be utilized to gain a perspective that is closer to the population than the gained perspective from the sample size in the study. Regarding the proportion of respondents within the sample size representing inhabitants within the Rhein-Main agglomeration, the diversity of residents from other cities in comparison to Darmstadt, Frankfurt am Main and Offenbach am Main was low. This can be improved with a larger sample size focusing on cities individually representing the Rhein-Main urban agglomeration.

Based on the pilot study and the research timeline, the manual axial and segment mapping of the street networks on a small-scale and a large-scale perspective (following the principles within Space Syntax theory) leads towards a long data collection timeline. Based on the literature study, while the minimum observation limits were set for each attribute being utilized for the multimodal accessibility analysis, a larger observation radius covering a wide area beyond the city limits represents an intra-city and inter-city perspective with a comprehensive approach. The uniform axial mapping of the streets for the whole agglomeration, including the road network between the cities, would provide an overview of different areas having an influence on a city's mobility network. This would require an added amount of manual mapping hours which would surpass the existing data preparation time and impact the data collection for other parameters in the study. Regarding other urban areas, while the two urban areas of city centre and main transit station are unique urban landmarks, multiple residential areas exist within a city. The residential areas for the study were selected as one of the areas which were prioritized for their respective city's master plan under some measures, and also were not in proximity to the city centre or main transit area. Including more areas for intra-city perspective assists in focusing on different spatial configuration typologies for the multimodal accessibility assessment.

In regards to the timeline for the data collection, the study acknowledges different peak hour periods for certain attributes (or parameters) corresponding to the area surround the selected space. It also focuses on accessibility as a measure to reach an urban space where distance of access is understood as a certain distance in space (topological or metric) or as an amount of time. The impact of micro-climate conditions or the environment on the accessibility of a space is not directly focused upon in the study. This has an impact on different range of distance and time measures for active mobility user-groups in an urban environment. For instance, Gruen (1964) suggests that in a good designed environment, which is protected from any discomfort caused by the adverse weather conditions, people can walk 1500m and spend 20 minutes walking. This range reduces with increasing discomfort caused by rain or scorching sun, and can be as low as 400m and 5 minutes of walking for no protection from the weather conditions (given the designed urban environment is still attractive). With unattractive urban surroundings and no protection against rain or sun, the walking distance can further reduce to 200m of walking, with 2 minutes of travel time. The observation limits for the identified parameters in the research study within Rhein-Main agglomeration correspond to mostly radial distances between 400m to 1500m for walking, and is different for other user groups (for e.g. 2500m for minimum cycling distances for the consideration under NACH). These distances are derived from the state-of-the-art practices and urban studies conducted to assess the accessibility of a city or a neighbourhood. The perspective of micro-climate conditions on the overall outcome of accessibility measures provides an added perspective of accessibility, having an influence over distance and time.

Following the micro-climate conditions and its impact on different aspects of accessibility, the considerations made for certain parameters should be addressed for further prioritization and on-site development. This includes the aspect of access to direct routes identified through the application of NACH within the Space Syntax theory. The segment analysis of NACH caters to the direct routes, while the gradient (or the slope) of the street section the segment corresponds to is not utilized for the spatial analysis. As the potential direct routes are identified in the spatial analysis, further prioritization is required for street segments which favour accessible slopes (usually between 6-10%) to establish cycling infrastructure (unless it already exists on-site). The combination of the two factors i.e. on-street slope and its corresponding NACH value can be utilized for a better approach, where street segments with high NACH value and low gradient are prioritized for cycling routes. In situations where streets having high slope fall within the direct route network under NACH, that is beyond the maximum permissible range (i.e. 10%), the parallel (or adjacent) streets in proximity to the original street can be analysed and considered for direct route network (given it falls within the permissible slope range and has a good NACH value as an attribute). These streets can be identified based on the peak hour frequency of different user-groups attained from the 'crowding and movement restriction' methodology focusing on the ease of movement.

In addition, while the identified aspects of direct routes and global integration (within the intelligibility parameter) indirectly address mobility by car, further parameters can be explored which support accessibility by cars as mobility mode. The future mobility perspective of Rhein-Main agglomeration focuses on an objective of improving its modal share towards walking, cycling and public transport. This would result in the decrease of the overall modal share for cars. While the approach cannot ignore car as a mode, it can implement alternative measures to obtain its objective. For instance, compensating low accessibility for certain modes (e.g. public transport) in an area by allocation of space for alternative modes (like car or bike sharing) improves an area's ability to provide better access and choice for movement (as discussed for the area surrounding Offenbach Hauptbahnhof with low PTAL). New residential development projects, like that of Lincoln-Siedlung in Darmstadt (BVD New

Living GmbH n.d.), focus on less space for private cars (with space priority for persons with disability) but more alternative opportunities like car-sharing, car-pooling, bike sharing (including e-cargo bikes) and public transport.

7.2 Conclusion

The urban assessment in the study combines selective aspects of modal accessibilities through different urban areas within an agglomeration, which focus on a common objective of achieving a better mobile and accessible environment. It identifies the potential area of improvement and relative priority of aspects. The priority of aspects through data-driven and data-informed approach brings together different perceptions, including public perspective, which is important for the discipline of urban planning and also influences the implementation of different urban development projects. The aspects identified cater to the six principles of inclusive urban design for streets (Burton and Mitchell 2006) and five variables which influence travel demand and trip generation (Ewing and Cervero 2010). With the identified parameters for the study being concise, the limited number of aspects also assist in addressing the public perspective of priority which is consistent via combination with multi-criteria decision-making tools.

As mentioned in the literature study, the public survey in Germany showcases the opinion prioritizing urban development for their community or city which focuses on an *alternative* approach that is not car-centric in nature. The focus towards achieving an accessible short-distance mobility environment would influence the overall modal share of different urban areas and cities, given the measures supporting the *alternative* approach are implemented with different user-groups taken into consideration in equity. The multimodal accessibility study in Rhein-Main agglomeration focuses towards the added perspective of spatial configurations and its influence on the overall mobility environment (in accordance to the different aspects of accessibility) inducing certain characteristics. The diversity of different urban areas in the study, through different cities, assists in understanding how the configuration of open and built spaces in areas of varying sizes and functionality, dictated its overall utility on different users. It also helps in identifying different potential areas which require improvement within the accessibility paradigm as compared to its present functionality and usage.

In order to obtain an overview of the multimodal accessibility with Rhein-Main agglomeration through major urban areas, the selection of cities was done which represents the area through its growing population and showcases high commuter flow within the region. Based on the in-flow and out-flow of the commuters within the Rhein-Main agglomeration, the cities of Darmstadt, Frankfurt am Main and Offenbach am Main were selected which have a poly-central characteristic in the region. This addresses the subject of travel demand and trip generation on a large-scale within the agglomeration, where the active cities with moving population are focused upon. The study can be expanded to other cities based on the hierarchy of commuter flows in order to impact a cluster of user-groups in majority. In cities where space allocation for different modes of travel can be a barrier for an efficient mobility environment, the identified shift towards active modes of travel including public transport would have a positive influence on the overall space consumption with each mode. The efficient utilization of the identified urban areas to their potential of providing multimodal accessibility on a long-term basis should be a main priority than a short-term benefit. For instance, the potential of direct routes in the cities can be met through the application of measures similar to the 'green wave' in Copenhagen, which

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BVD New Living GmbH n.d., Die Lincoln-Siedlung in Darmstadts Süden verändert sich, accessed on 15-11-2022. Retrieved from https://www.lincoln-siedlung.de/

influences the speed of movement with least restrictions for an identified travel route and can be utilized for the new cycle highways where the inter-city travel extends from an intra-city network of direct routes. At the same time, the implementation of pathways for a user-group would not function properly unless they are also executed with a certain standard of comfort and safety (as seen through shared lanes for cycling and motorized vehicles on the streets of San Francisco). In Frankfurt am Main, the execution of dedicated coloured cycling lanes (after the tactical urbanism approach) on the potential street of Mainkai was supported with the reduction in on-street parking of motorized vehicles on the street edge along with the installation of directional signage for cyclists on major intersections. The allocation of the Mainkai street space for cars on the two-lane also directs the measure of equity where other fast-moving user-groups are also able to utilize the potential of direct routes. These interventions cater towards long-term utilization of urban space, which influences the mobility characteristic of an area and its surrounding.

The approach of studying and analysing different urban areas within the same urban agglomeration in an identified timeframe (for certain identified parameters) relates to a mobility environment which would be different from time to time. For instance, the density of people using a space would be different during a peak hour as opposed to any other time. By focusing on the extreme potential limits of the utility of urban areas by its ability to provide multimodal access, concrete recommendations can be made which influences the overall functionality of the urban space. Based on the on-site and on-desk data collection, analysis, comparison and interpretation, the main conclusions which address the overall research design are encapsulated as follows:

- The large domain of accessibility can be distributed into different aspects, where certain attributes supporting multimodal travel behaviour represent or cater to the inclusive urban design for streets and influence travel demand (along with trip generation). The network of urban streets, which is influenced by the layout of diverse built infrastructure and the natural ecosystem (and vice versa), has an impact on the physical distances and routes an individual takes for their travel to different destinations. The multimodal accessibility relates to the ease of accessing a space through movement by different modes individually, which involve streets as a primary medium. Analysing the street network through different identified aspects (including connectivity, access to public transport, access to direct routes, ease of movement and ease of navigation) of multimodal accessibility narrows down the potential area of improvement for the urban neighbourhoods and cities. The identified parameters correspond mostly towards the topological-based accessibility measures which are utilized to understand and analyse the impact of built environment (via street networks) on the movement and overall accessibility. While these do not evaluate existing opportunities (as seen in gravity or cumulative opportunities-based measures), they have the potential to be utilized as planning tools, identifying intervention priorities or impacts of the urban development proposals.

- In regards to different spatial configurations, the identified aspects for analysing multimodal accessibility showed varied outcomes based on inter-city and intra-city perspective. The comparative assessment shows how different urban areas performed based on the selected aspects of accessibility via connectivity, intelligibility, closeness, directness and spatial freedom. The influence of orthogonal, distributed or non-distributed street network, cul-de-sacs, location of transit station services, block sizes, land-use typology and other related aspects on different attributes of multimodal accessibility reiterate the need of addressing different characteristics of a space to understand the impact of spatial configuration on a street network's accessibility. Within the research study, the main transit station in Frankfurt am Main, followed by the city centre and main transit station in Darmstadt showed a better combined potential for its overall multimodal accessibility. This shows how different urban areas other than the city centres can have a better access to multimodal services. It also reflects how certain urban areas in comparatively smaller cities can outperform the ones in larger cities for different aspects of accessibility.

- The derived characteristics of different urban areas based on their spatial analysis can be utilized to improve the corresponding gap between its on-site and potential accessibility. This can be utilized for different urban experiments like the measure of road-closure on Frankfurt Mainkai riverfront during 2019-2020, or for understanding existing urban mobility characteristics of a city through combination of different parameters like the correlation of potential for direct routes and the on-site peak hour frequency of user-groups (including cyclists). Focusing on certain user-groups, like users with reduced mobility, identified parameters can be improved and revised to reflect and prioritize their level of access (e.g. the revised PTAL index). Apart from the individual and combined parametric perspective, the prioritization of aspects through public perception utilizing multi-criteria decision-making tools with a low margin of error adds to the existing narrative of data-driven approach, leading towards a data-informed approach which contributes to subjective understanding of a mobility culture. The research outcomes confirm the difference between the objective characteristics of urban areas and their corresponding subjective perceptions relating to the multimodal accessibility. This is more prevalent in urban areas showing objectively lower accessibility characteristics, i.e. they varied in their subjective ranking in contrast to urban areas performing better objectively.

Different parametric perspectives in the research study have assisted to understand the influence of spatial configuration in urban areas, both individually and through its combination with other identified aspects of multimodal accessibility. The diverse understanding and interpretation of accessibility as a quality of space through different disciplines creates a challenge to combine certain aspects in a cluster to address a common narrative of ease of accessing an urban space. Frameworks that incorporate different aspects to measure accessibility vary globally, which makes it difficult to grasp the overall concept of accessibility, eventually leading to certain obstacles for it to be incorporated into urban development policies. This research study narrows down certain parameters which connect and integrate different aspects of accessibility, through different modes, and focuses on a topological approach which brings urban research and practice closer to each other. These parameters can be utilized by urban planning authorities where data collection takes less time, excluding crowding (requiring on-site measurements including street widths and peak hour frequency of user-groups) and Space Syntax attributes (requiring manual mapping following the Space Syntax theory). While the selected parameters can guide urban planning and design professionals on reaching a particular objective incorporating accessibility as a quality of the urban space, acknowledgment of a mobility environment as one of the leading concepts would influence the undertaking of spatial developments. Understanding of the urban spaces as both static and mobile environments would enable bringing a broad perspective where accessibility is considered through different attributes, addressing different disciplines of work to conceive a space that is accessible economically, socially, and environmentally. Involving broad spectrum of multiple disciplines addressing accessibility, including factors and perspectives which are not considered within the research study, would help in having a holistic approach where the understanding and implementation of an accessible mobile environment is complete. In addition, it is important to understand the gaps between the potential accessibility quality of an urban area and its existing utility. The identification of these gaps in the research study lead to further prioritization of spaces which require improvement, in turn influencing the urban planning and design strategies for a city.

Cities and urban areas have different geographical layouts, as well as different population with varying priorities where certain inhabitants prioritize one aspect of accessibility over the other subjectively. In this scenario, the two dimensions of subjective evaluation and objective characteristics of an urban area (or city) plays a crucial role, which is important for policy implications focusing on improving an area. In addition, there is a need to identify how different urban policies impact accessibility, where certain corresponding investments improve accessibility for one mode but can also act as a disadvantage over the other. The spatial study through an intermodal perspective, where different modes interact together as a mobility system, can further contribute towards urban development timeline for a city within the urban mobility and accessibility domain. Expanding the scope of spatial research to a larger area, say agglomeration, can have a possibility of identifying further factors which play a decisive role in its mobility and accessibility planning. These are different frameworks for future studies which, similar to this study, contribute towards better understanding of spatial configurations and its corresponding quality to facilitate mobility.

APPENDIX I

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A1.2 Abbreviations

ADAC - Allgemeiner Deutscher Automobil-Club

AHP - Analytic Hierarchy Process

BiWET - Bikeability and Walkability Evaluation Table

BMUB - Bundesministerium für Umwelt, Naturschutz, Bau und Reaktorsicherheit

CBM - Christoffel Blindenmission

CIVITAS - Cities Vitality Sustainability

CNR - Connected Node Ratio

COVID-19 - Coronavirus Disease 2019

DADINA - Darmstadt-Dieburger Nahverkehrsorganisation

DIAUD - Disability Inclusive and Accessible Urban Development Network

EDF - Equivalent Doorstep Frequency

eKFV - Elektrokleinstfahrzeuge Verordnung

FFCS - Free Floating Car Sharing

HfG - Hochschule für Gestaltung

IC - Intercity

ICE - Intercity Express

ITDP - Institute for Transportation and Development Policy

LTA - Land Transport Authority

MiD - Mobilität in Deutschland

NACH - Normalisation of Angular Choice

NALP - Neighbourhood Active Living Potential

NiO - Nahverkehr in Offenbach

PTAL - Public Transport Accessibility Level

PwDs - Persons with Disabilities

RB - Regionalbahn

RE - RegionalExpress

RMV - Rhein Main Verkehrsverbund

SCI - Spinal cord injury

SNAMUTS - Spatial Network Analysis for Multimodal Urban Transport Systems

SUMP - Sustainable Urban Mobility Plan

TFL - Transport for London

TOPSIS - Technique for Order of Preference by Similarity to Ideal Solution

TSK - Technická správa komunikací

TU - Technische Universität

UBA - Umweltbundesamt

UC Davis - University of California Davis

UOL - Universo Online

URM - Users with reduced mobility

US - United States

WCU - Wheelchair Users

WHO - World Health Organization

APPENDIX II

LIST OF FIGURES AND TABLES

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APPENDIX III

STREET WIDTHS IN SELECTED URBAN AREAS

A3.1 Preface

This appendix includes the street widths measured for the spatial analysis within the selected 'Crowding and movement restriction' parameter. These street widths were measured with the assistance of the Laser meter on-site through different spaces and surroundings in Darmstadt, Frankfurt am Main and Offenbach am Main.

A3.1.1 Selected streets and their widths in Darmstadt

The following street widths were measured in the selected urban areas surrounding city centre, main transit station and residential area of Komponistenviertel in Darmstadt. The buffer spaces on the street ends through its width are usually from the building or the street edges, unless stated otherwise. The annotations are measured in millimetres (mm), and represent the street widths during the on-site conditions of the urban area. The street widths and buffer spaces (in red) for the residential area of Komponistenviertel are as follows:

Figure 114: Street width and buffer spaces (in mm) for FS gateway in residential area of Komponistenviertel in Darmstadt

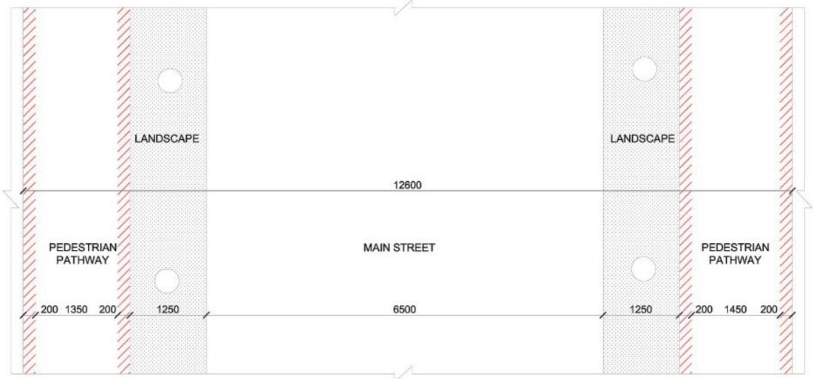

Figure 115: Street width and buffer spaces (in mm) for FN gateway in residential area of Komponistenviertel in Darmstadt

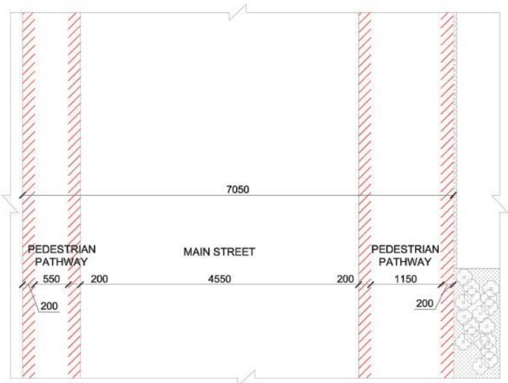

Figure 116: Street width and buffer spaces (in mm) for N1 gateway in residential area of Komponistenviertel in Darmstadt

Figure 117: Street width and buffer spaces (in mm) for S2 gateway in residential area of Komponistenviertel in Darmstadt

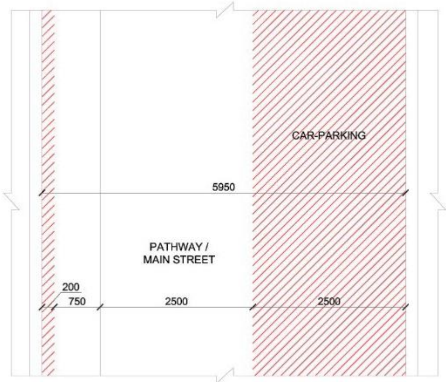

Figure 118: Street width and buffer spaces (in mm) for S1 and S3 gateway in residential area of Komponistenviertel in Darmstadt

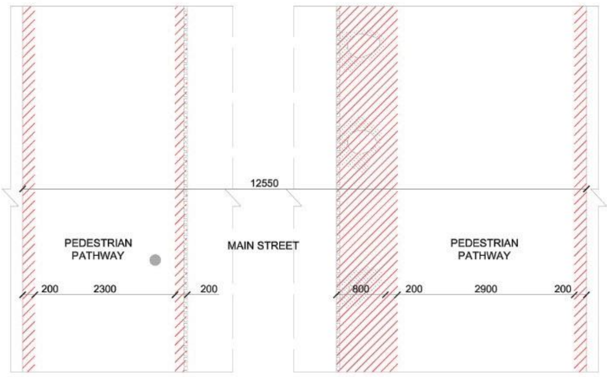

Figure 119: Street width and buffer spaces (in mm) for S4 gateway in residential area of Komponistenviertel in Darmstadt

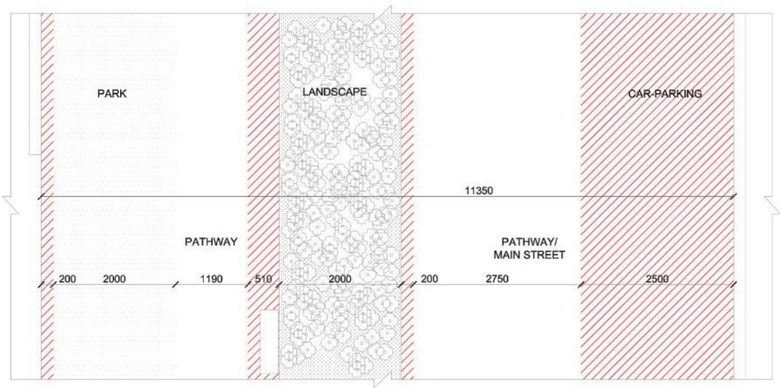

Figure 120: Street width and buffer spaces (in mm) for N2 gateway in residential area of Komponistenviertel in Darmstadt

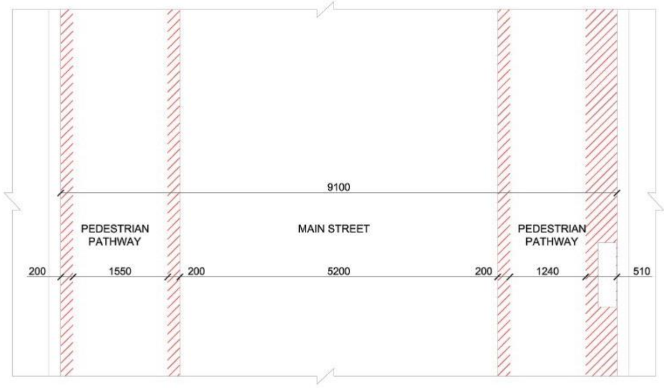

Figure 121: Street width and buffer spaces (in mm) for N3 gateway in residential area of Komponistenviertel in Darmstadt

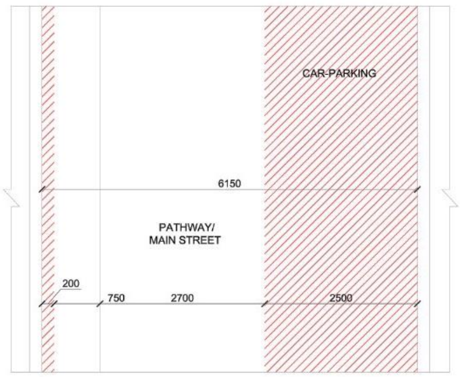

Figure 122: Street width and buffer spaces (in mm) for N4 gateway in residential area of Komponistenviertel in Darmstadt

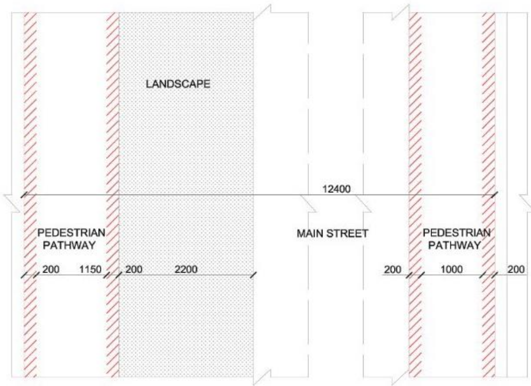

Figure 123: Street width and buffer spaces (in mm) for N5 gateway in residential area of Komponistenviertel in Darmstadt

The street widths and buffer spaces (in red) for the area surrounding the main transit station in Darmstadt are as follows:

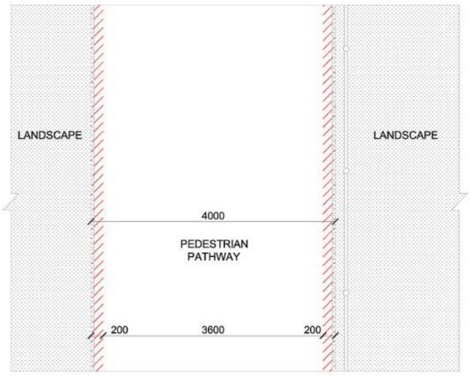

Figure 124: Street width and buffer spaces (in mm) for Gateway 1 in the area surrounding Darmstadt Hauptbahnhof

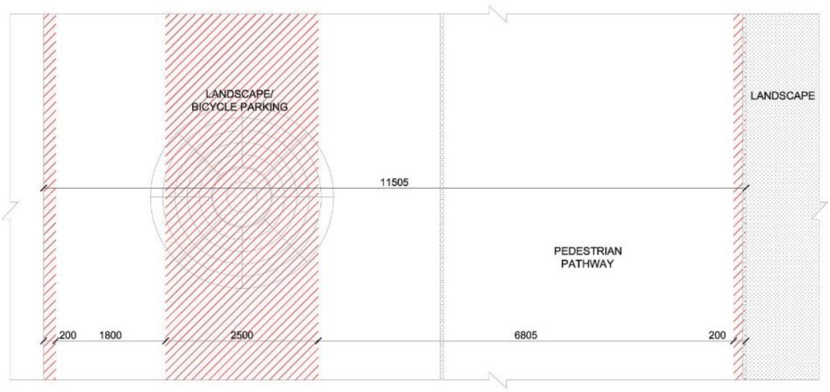

Figure 125: Street width and buffer spaces (in mm) for Gateway 2 in the area surrounding Darmstadt Hauptbahnhof

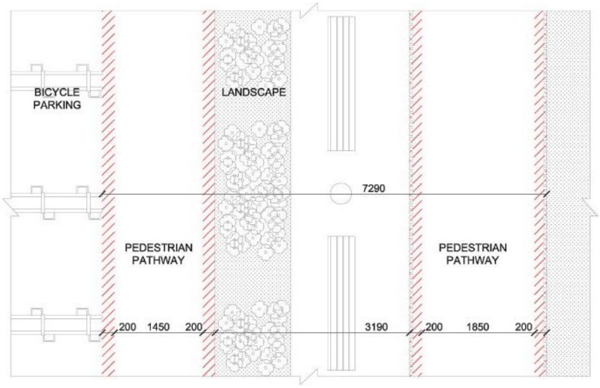

Figure 126: Street width and buffer spaces (in mm) for Gateway 3 in the area surrounding Darmstadt Hauptbahnhof

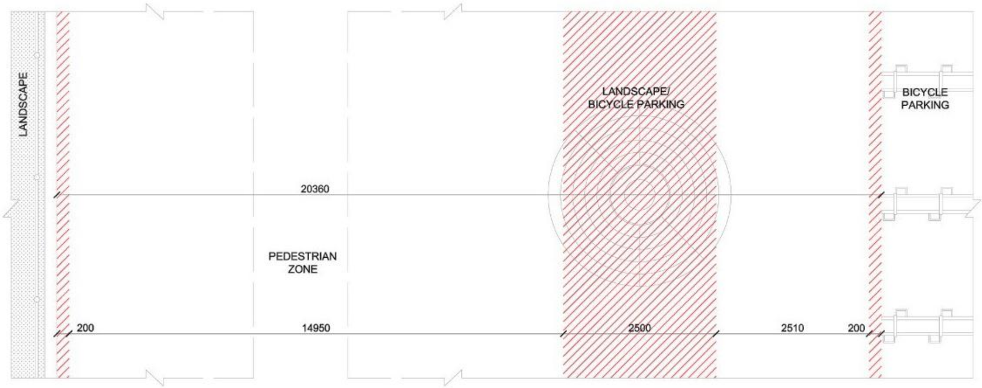

Figure 127: Street width and buffer spaces (in mm) for Gateway 4 in the area surrounding Darmstadt Hauptbahnhof

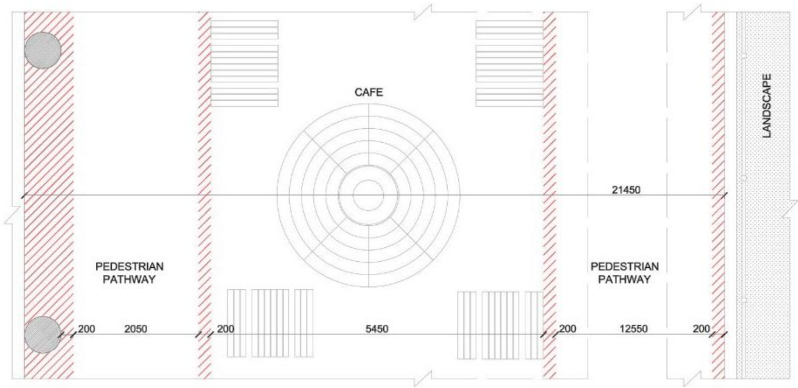

Figure 128: Street width and buffer spaces (in mm) for Gateway 5 in the area surrounding Darmstadt Hauptbahnhof

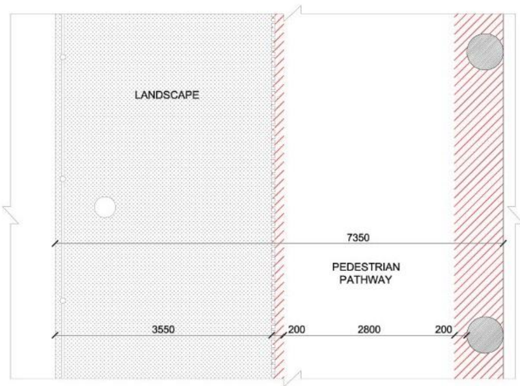

Figure 129: Street width and buffer spaces (in mm) for Gateway 6 in the area surrounding Darmstadt Hauptbahnhof

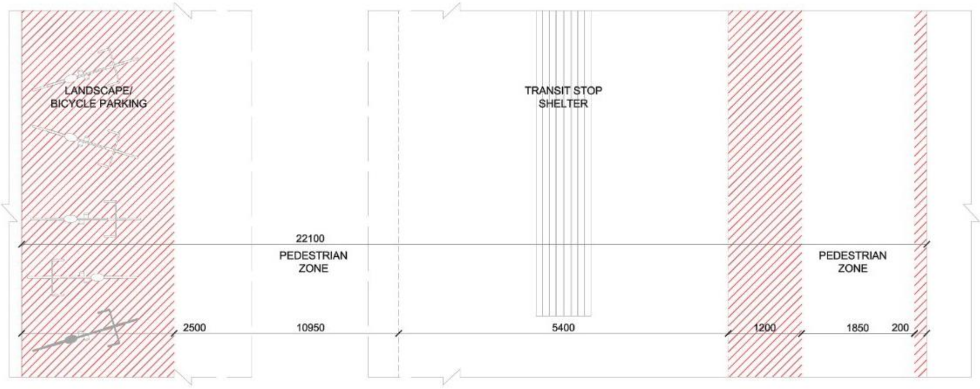

Figure 130: Street width and buffer spaces (in mm) for Gateway 7 in the area surrounding Darmstadt Hauptbahnhof

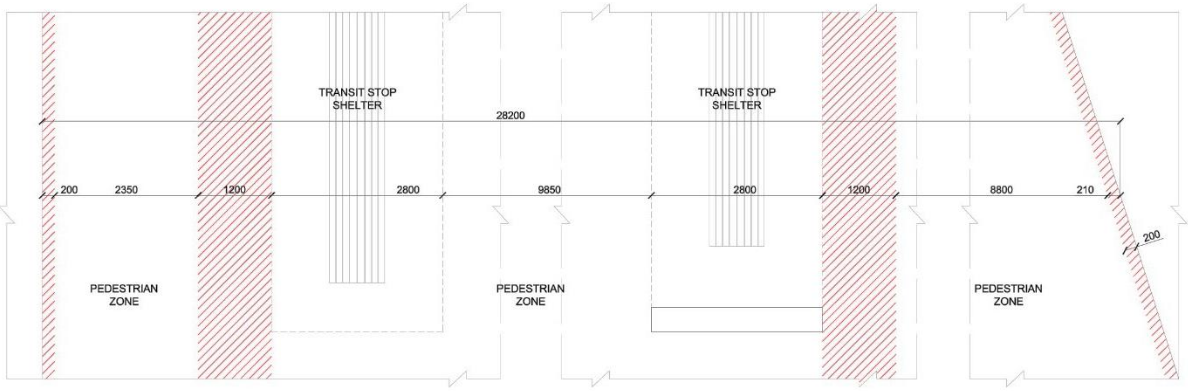

Figure 131: Street width and buffer spaces (in mm) for Gateway 8 in the area surrounding Darmstadt Hauptbahnhof

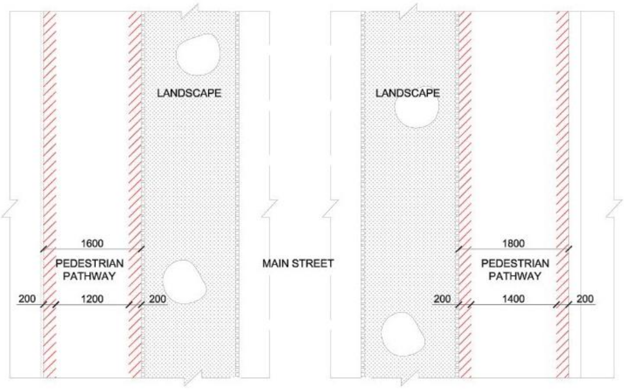

Figure 132: Street width and buffer spaces (in mm) for Gateway 9 in the area surrounding Darmstadt Hauptbahnhof
Note: The main street includes a bicycle pathway which is taken into consideration for the crowding calculation

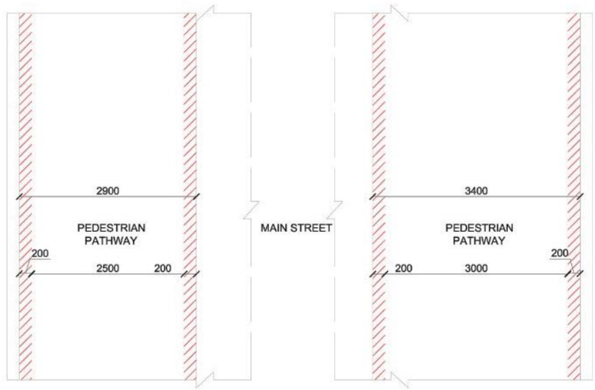

Figure 133: Street width and buffer spaces (in mm) for Gateway 10 in the area surrounding Darmstadt Hauptbahnhof

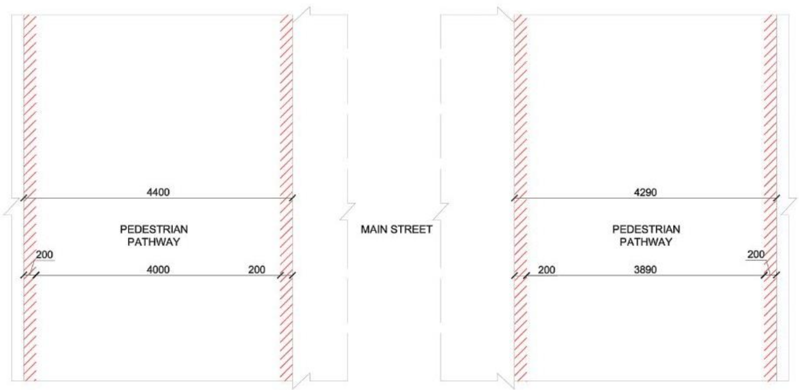

Figure 134: Street width and buffer spaces (in mm) for Gateway 11 in the area surrounding Darmstadt Hauptbahnhof

The street widths and buffer spaces (in red) for the area surrounding the city centre in Darmstadt are as follows:

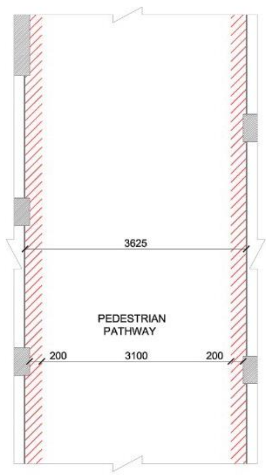

Figure 135: Street width and buffer spaces (in mm) for Gateway 1 in the area surrounding Luisenplatz in Darmstadt

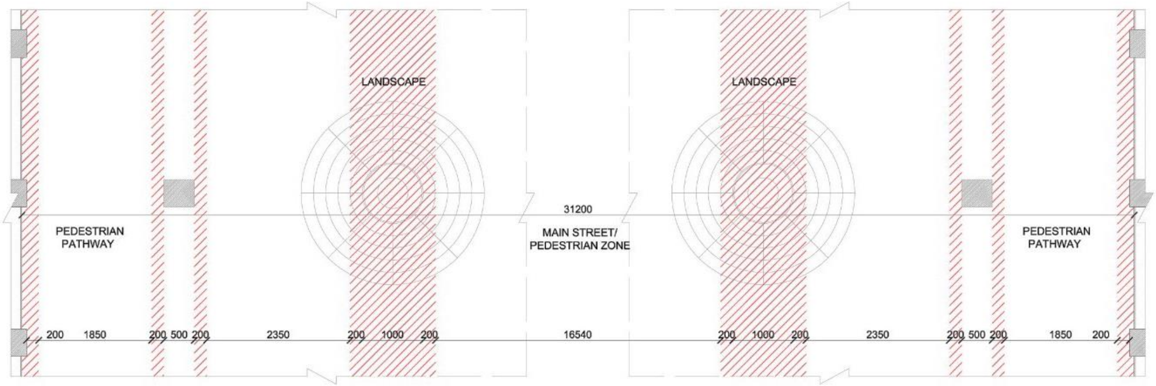

Figure 136: Street width and buffer spaces (in mm) for Gateway 2 in the area surrounding Luisenplatz in Darmstadt
Note: Excludes the central rail line for trams running through the central axis of the main street and bicycle parking (taken into consideration for crowding)

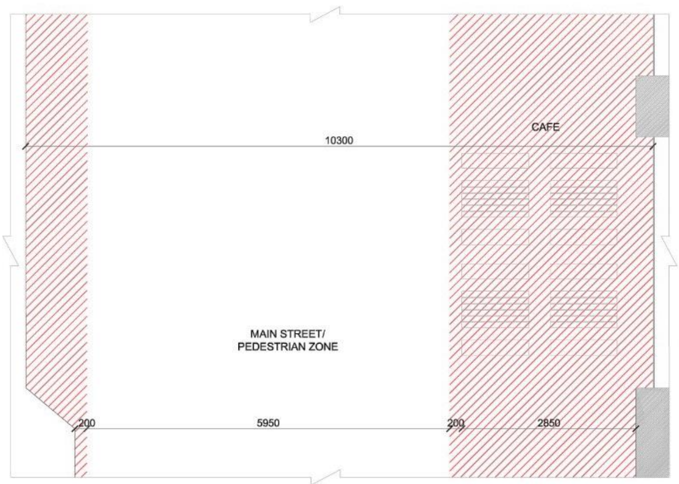

Figure 137: Street width and buffer spaces (in mm) for Gateway 3 in the area surrounding Luisenplatz in Darmstadt

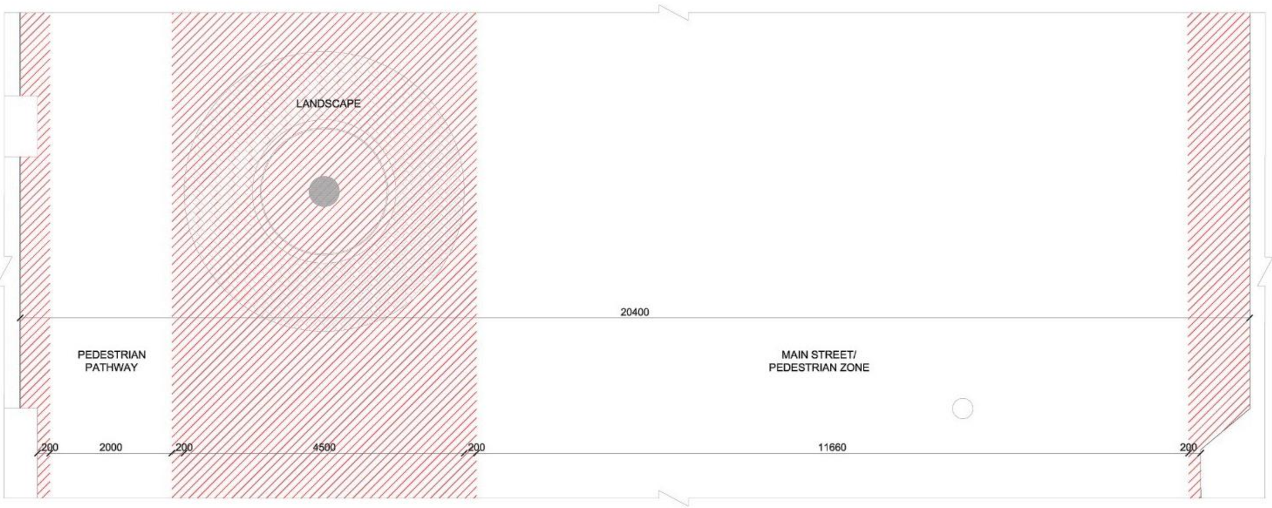

Figure 138: Street width and buffer spaces (in mm) for Gateway 4 in the area surrounding Luisenplatz in Darmstadt

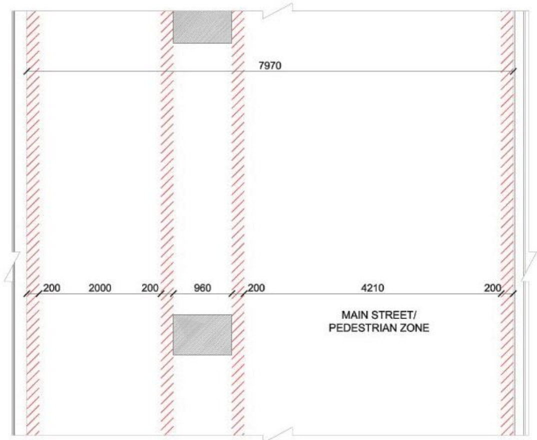

Figure 139: Street width and buffer spaces (in mm) for Gateway 5 in the area surrounding Luisenplatz in Darmstadt
Note: Added buffer width of 125m (due to added edge space) is included for the calculation of crowding

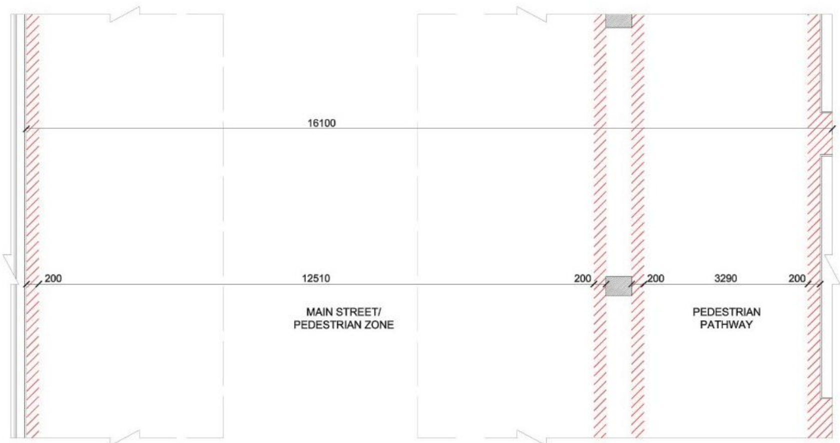

Figure 140: Street width and buffer spaces (in mm) for Gateway 6 in the area surrounding Luisenplatz in Darmstadt
Note: Added buffer width of 1020m (due to edge space adjacent to tram rail) is included for the calculation of crowding

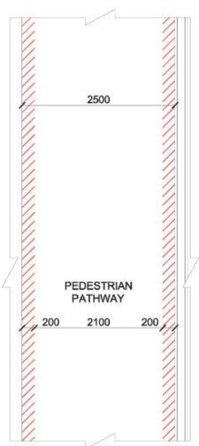

Figure 141: Street width and buffer spaces (in mm) for Gateway 7 in the area surrounding Luisenplatz in Darmstadt

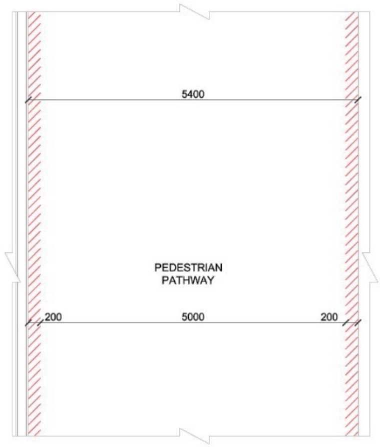

Figure 142: Street width and buffer spaces (in mm) for Gateway 8 in the area surrounding Luisenplatz in Darmstadt

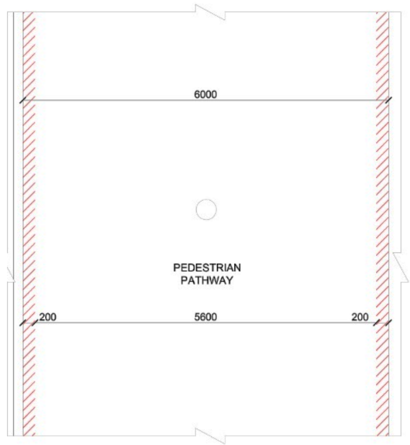

Figure 143: Street width and buffer spaces (in mm) for Gateway 9 in the area surrounding Luisenplatz in Darmstadt Note: Street element (i.e. electric pole with width of 150mm) is included for the calculation of crowding

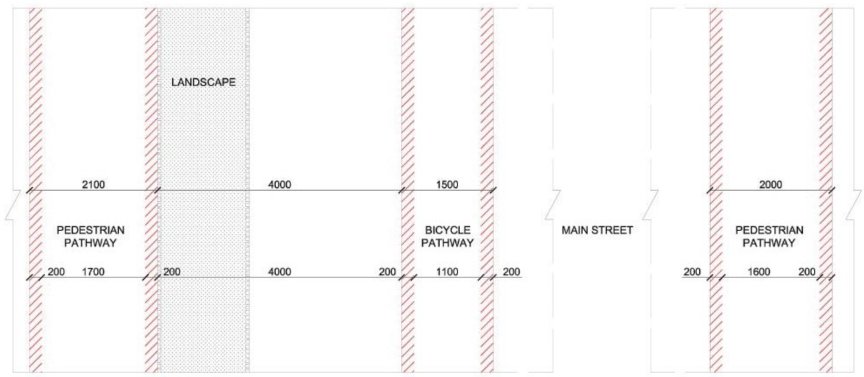

Figure 144: Street width and buffer spaces (in mm) for Gateway 10 in the area surrounding Luisenplatz in Darmstadt

Figure 145: Street width and buffer spaces (in mm) for Gateway 11 in the area surrounding Luisenplatz in Darmstadt

A3.1.2 Selected streets and their widths in Frankfurt am Main

The following street widths were measured in the selected urban areas surrounding city centre, main transit station and the residential area of Bornheim in Frankfurt am Main. The buffer spaces on the street ends through its width are usually from the building or the street edges, unless stated otherwise. The annotations are measured in millimetres (mm), and represent the street widths during the on-site conditions of the urban area. The street widths and buffer spaces (in red) for the area of Bornheim are as follows:

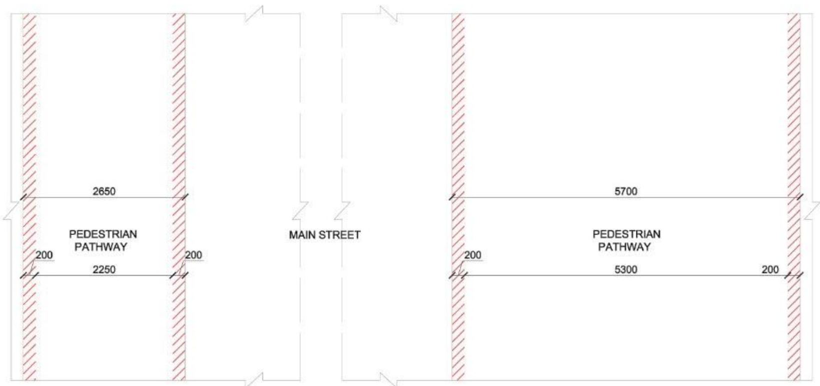

Figure 146: Street width and buffer spaces (in mm) for Gateway 1 in the residential area of Bornheim in Frankfurt am Main

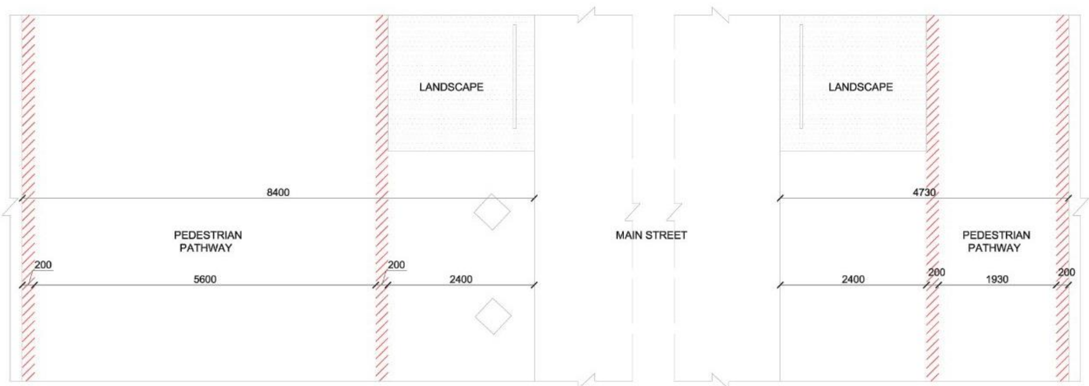

Figure 147: Street width and buffer spaces (in mm) for Gateway 2 in the residential area of Bornheim in Frankfurt am Main

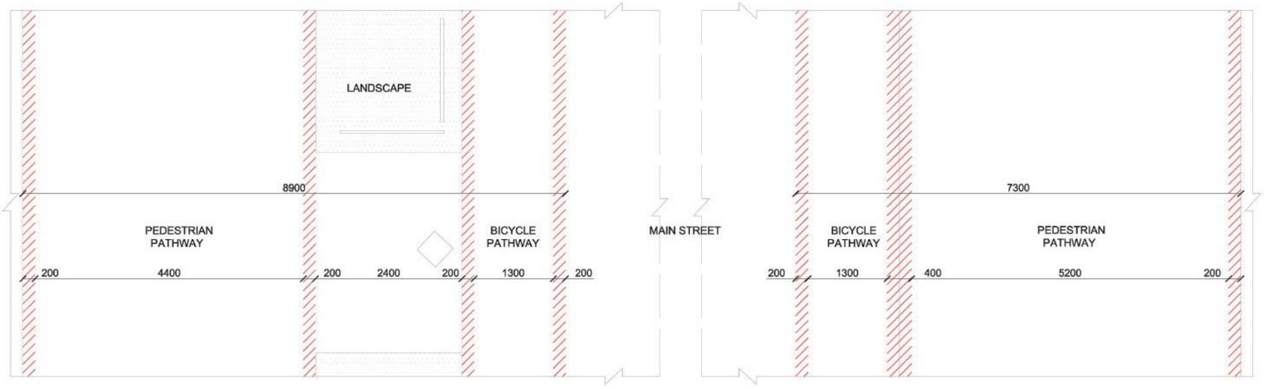

Figure 148: Street width and buffer spaces (in mm) for Gateway 3 in the residential area of Bornheim in Frankfurt am Main

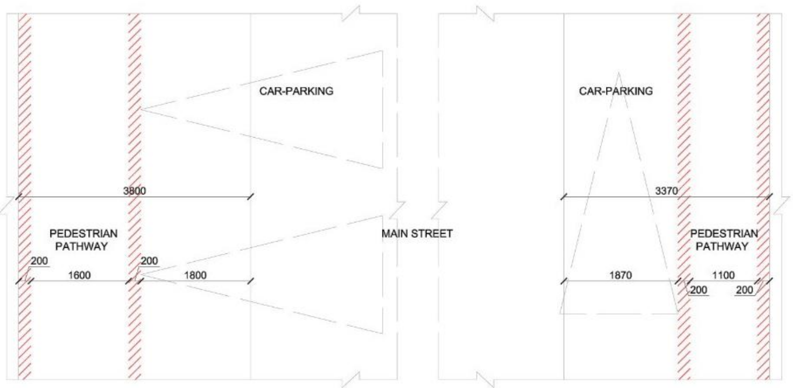

Figure 149: Street width and buffer spaces (in mm) for Gateway 4 in the residential area of Bornheim in Frankfurt am Main

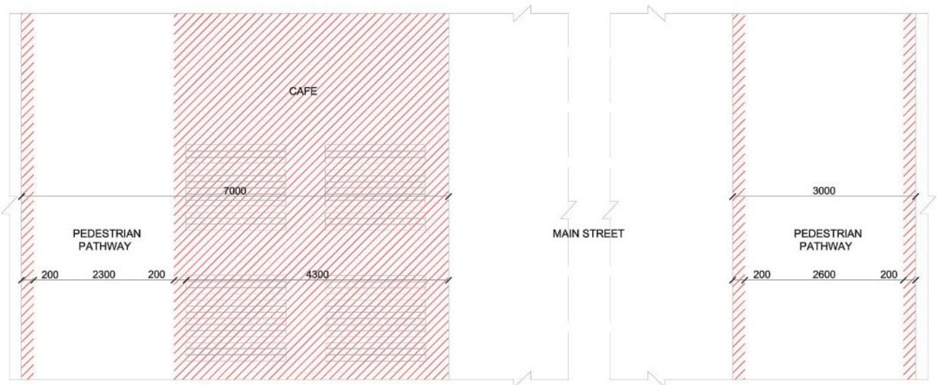

Figure 150: Street width and buffer spaces (in mm) for Gateway 5 in the residential area of Bornheim in Frankfurt am Main

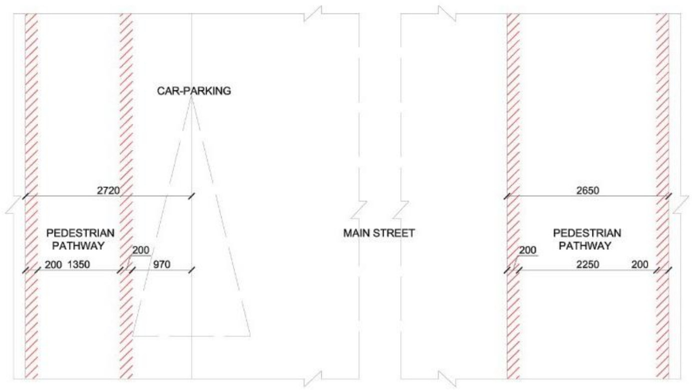

Figure 151: Street width and buffer spaces (in mm) for Gateway 6 in the residential area of Bornheim in Frankfurt am Main

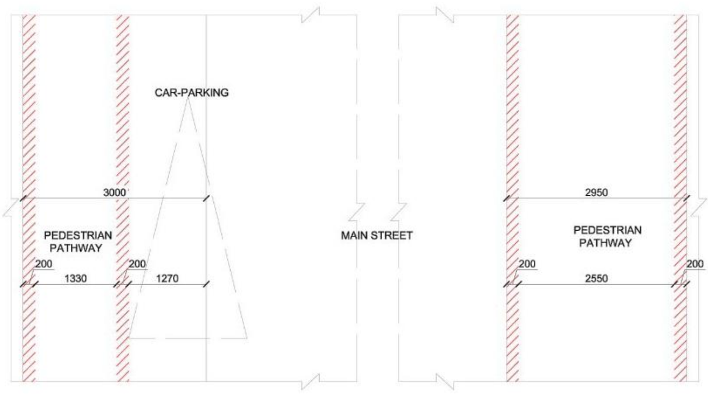

Figure 152: Street width and buffer spaces (in mm) for Gateway 7 in the residential area of Bornheim in Frankfurt am Main

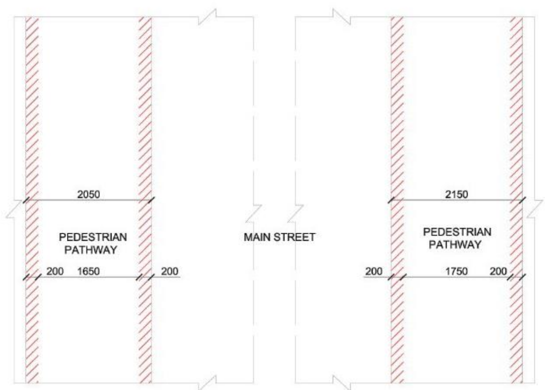

Figure 153: Street width and buffer spaces (in mm) for Gateway 8 in the residential area of Bornheim in Frankfurt am Main

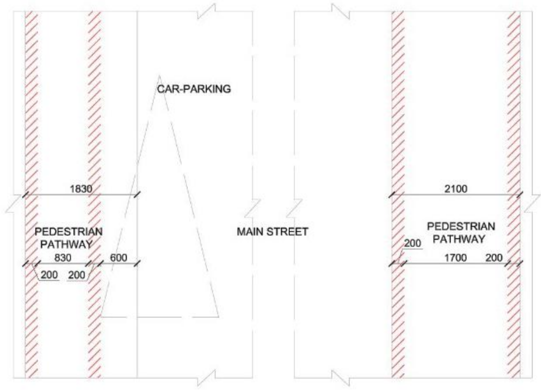

Figure 154: Street width and buffer spaces (in mm) for Gateway 9 in the residential area of Bornheim in Frankfurt am Main

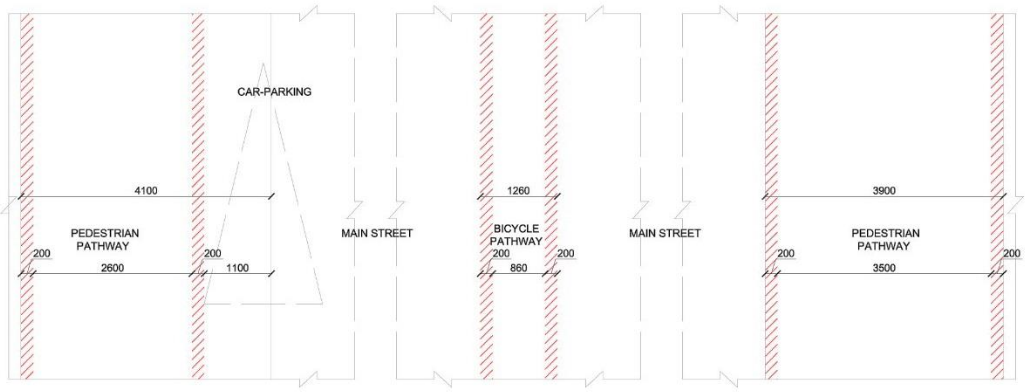

Figure 155: Street width and buffer spaces (in mm) for Gateway 10 in the residential area of Bornheim in Frankfurt am Main

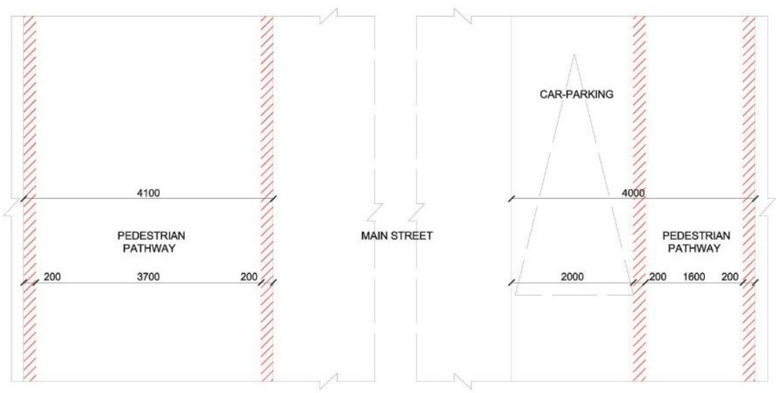

Figure 156: Street width and buffer spaces (in mm) for Gateway 11 in the residential area of Bornheim in Frankfurt am Main

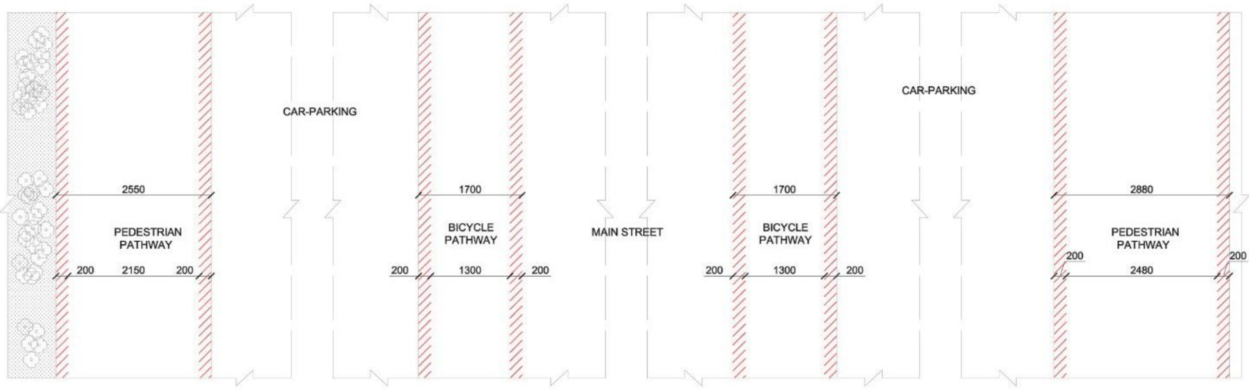

Figure 157: Street width and buffer spaces (in mm) for Gateway 12 in the residential area of Bornheim in Frankfurt am Main

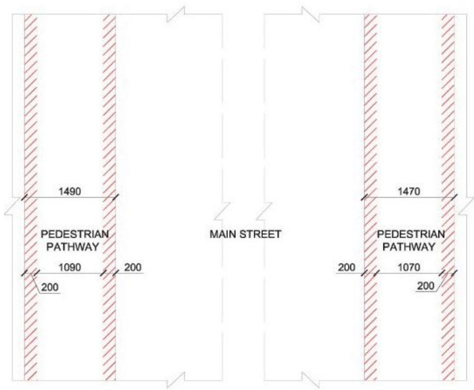

Figure 158: Street width and buffer spaces (in mm) for Gateway 13 in the residential area of Bornheim in Frankfurt am Main

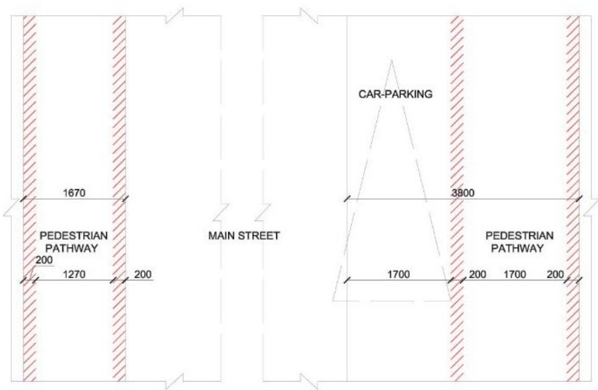

Figure 159: Street width and buffer spaces (in mm) for Gateway 14 in the residential area of Bornheim in Frankfurt am Main

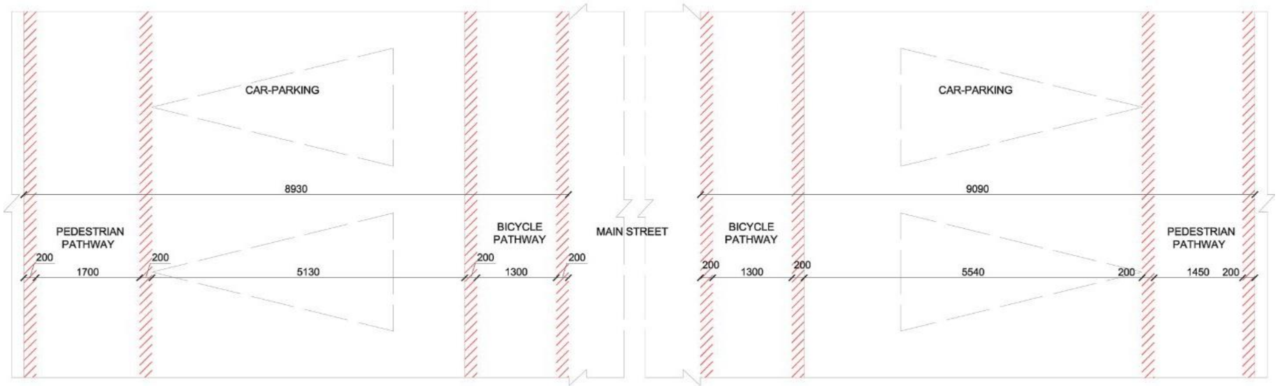

Figure 160: Street width and buffer spaces (in mm) for Gateway 15 in the residential area of Bornheim in Frankfurt am Main

The street widths and buffer spaces (in red) for the area surrounding the main transit station in Frankfurt am Main are as follows:

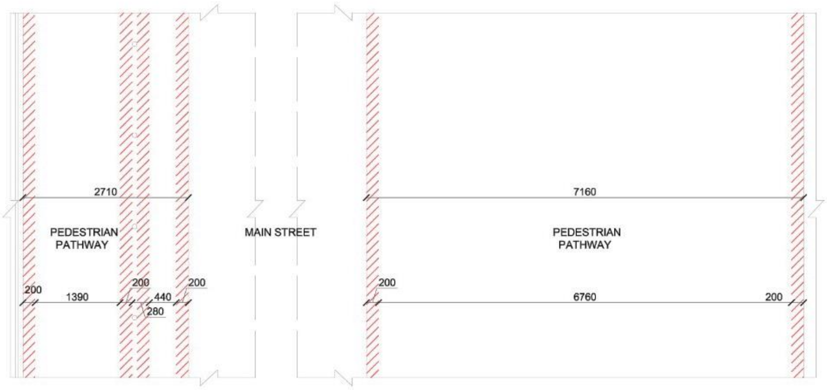

Figure 161: Street width and buffer spaces (in mm) for Gateway 1 in the area surrounding Frankfurt am Main Hauptbahnhof

Figure 162: Street width and buffer spaces (in mm) for Gateway 2 in the area surrounding Frankfurt am Main Hauptbahnhof

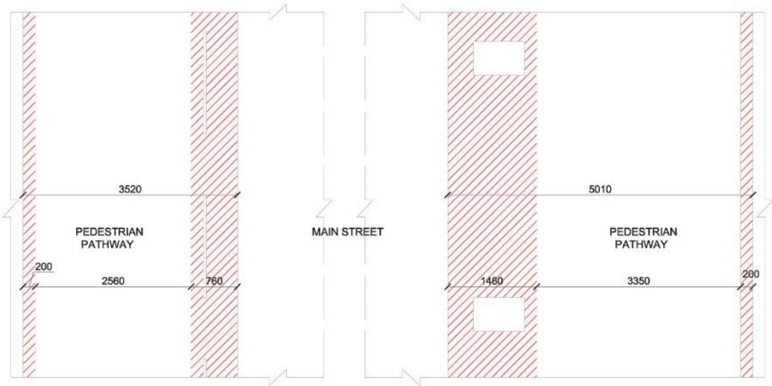

Figure 163: Street width and buffer spaces (in mm) for Gateway 3 in the area surrounding Frankfurt am Main Hauptbahnhof

Figure 164: Street width and buffer spaces (in mm) for Gateway 4 in the area surrounding Frankfurt am Main Hauptbahnhof

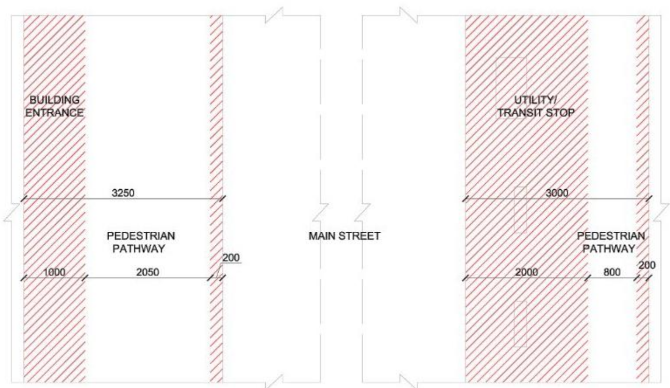

Figure 165: Street width and buffer spaces (in mm) for Gateway 5 in the area surrounding Frankfurt am Main Hauptbahnhof

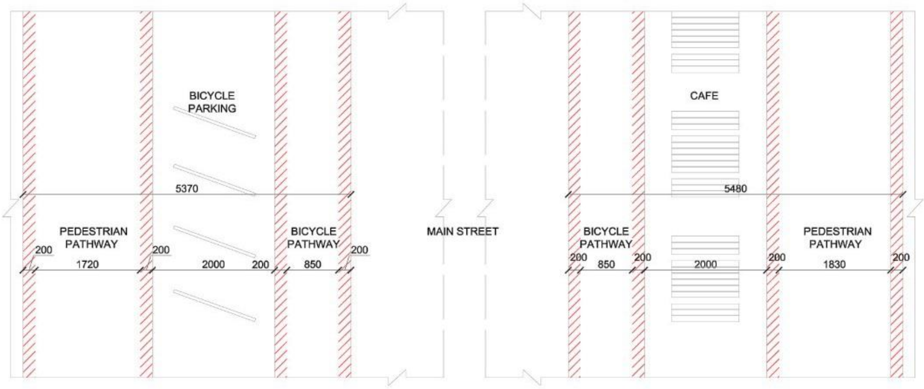

Figure 166: Street width and buffer spaces (in mm) for Gateway 6 in the area surrounding Frankfurt am Main Hauptbahnhof

Figure 167: Street width and buffer spaces (in mm) for Gateway 7 in the area surrounding Frankfurt am Main Hauptbahnhof

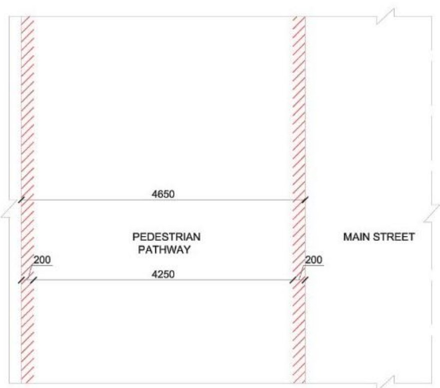

Figure 168: Street width and buffer spaces (in mm) for Gateway 8 in the area surrounding Frankfurt am Main Hauptbahnhof
Note: The street includes measurements which excludes the pathway during a construction phase on the adjacent end

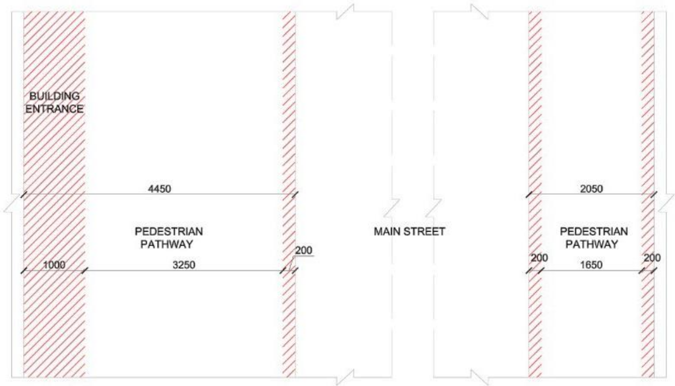

Figure 169: Street width and buffer spaces (in mm) for Gateway 9 in the area surrounding Frankfurt am Main Hauptbahnhof

Figure 170: Street width and buffer spaces (in mm) for Gateway 10 in the area surrounding Frankfurt am Main Hauptbahnhof
Note: The street includes measurements which excludes the extended pathway (on the right) due to a construction work

Figure 171: Street width and buffer spaces (in mm) for Gateway 11 in the area surrounding Frankfurt am Main Hauptbahnhof

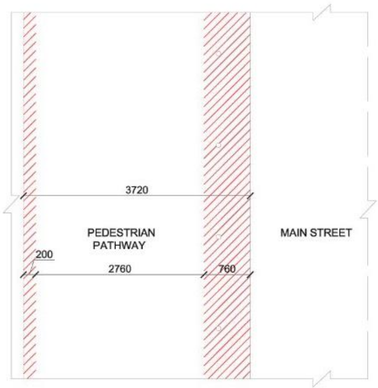

Figure 172: Street width and buffer spaces (in mm) for Gateway 12 in the area surrounding Frankfurt am Main Hauptbahnhof

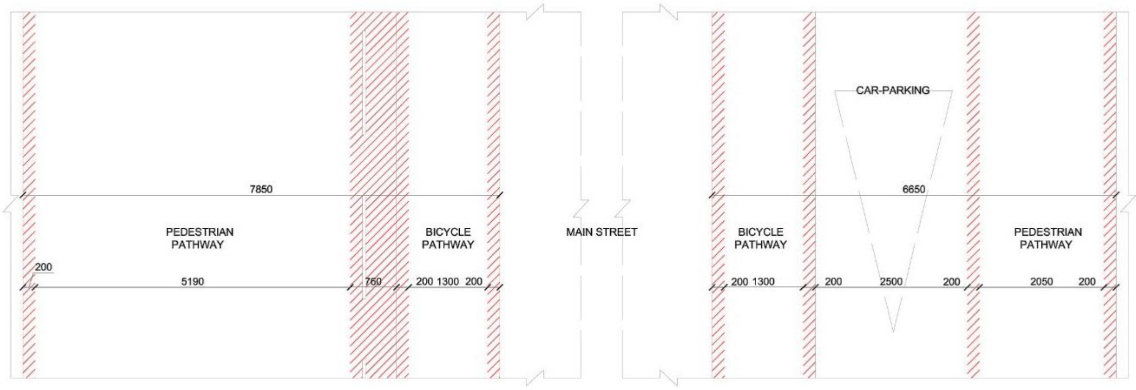

Figure 173: Street width and buffer spaces (in mm) for Gateway 13 in the area surrounding Frankfurt am Main Hauptbahnhof

The street widths and buffer spaces (in red) for the area surrounding the city centre in Frankfurt am Main are as follows:

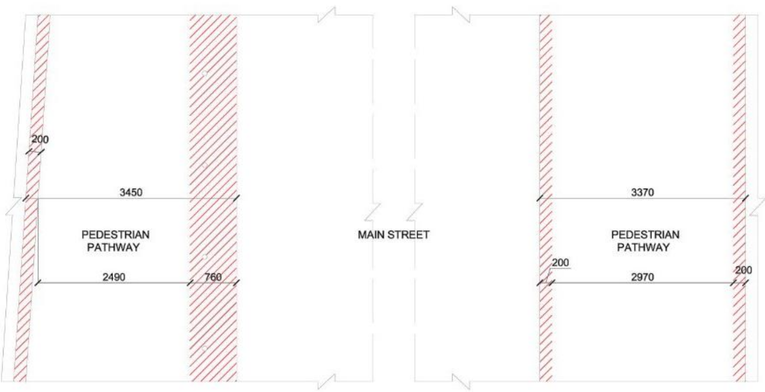

Figure 174: Street width and buffer spaces (in mm) for Gateway 1 in the area surrounding Hauptwache in Frankfurt am Main

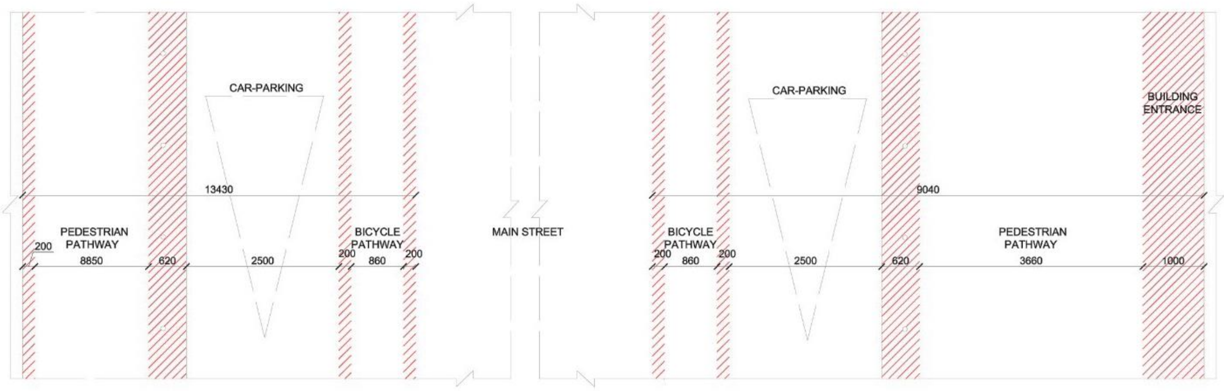

Figure 175: Street width and buffer spaces (in mm) for Gateway 2 in the area surrounding Hauptwache in Frankfurt am Main

Figure 176: Street width and buffer spaces (in mm) for Gateway 3 in the area surrounding Hauptwache in Frankfurt am Main

Figure 177: Street width and buffer spaces (in mm) for Gateway 4 in the area surrounding Hauptwache in Frankfurt am Main

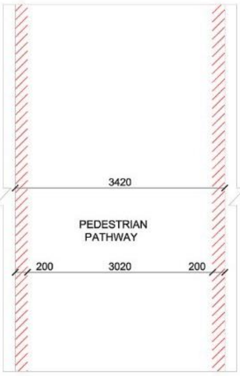

Figure 178: Street width and buffer spaces (in mm) for Gateway 5 in the area surrounding Hauptwache in Frankfurt am Main

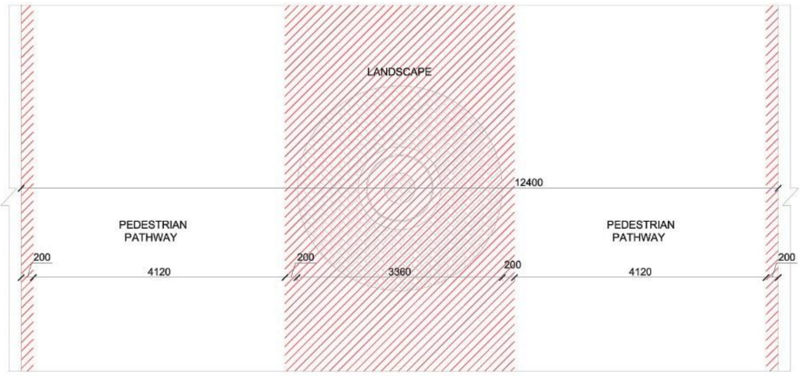

Figure 179: Street width and buffer spaces (in mm) for Gateway 6 in the area surrounding Hauptwache in Frankfurt am Main

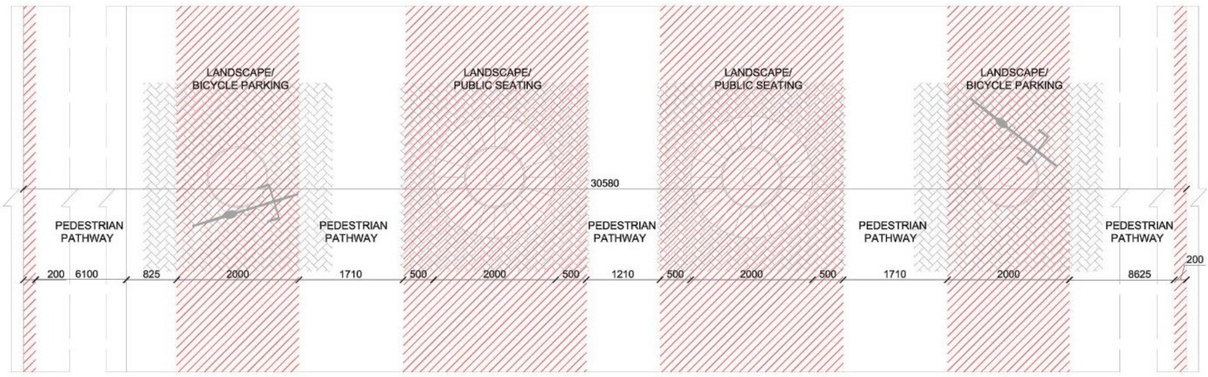

Figure 180: Street width and buffer spaces (in mm) for Gateway 7 in the area surrounding Hauptwache in Frankfurt am Main

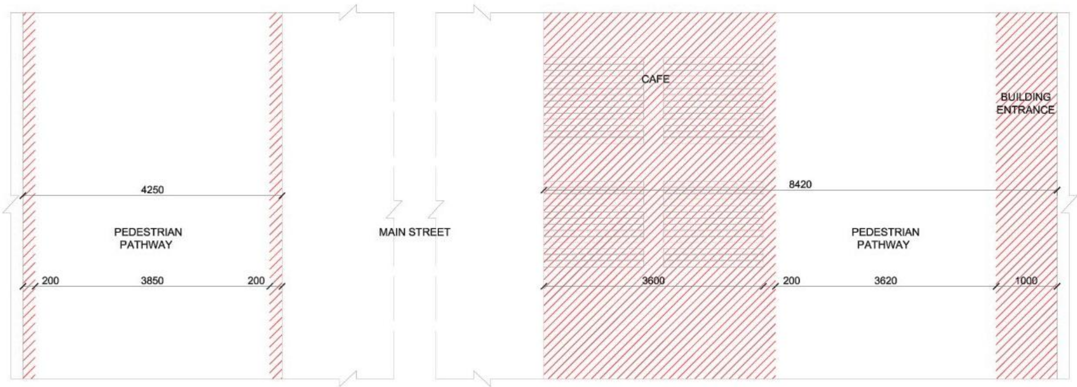

Figure 181: Street width and buffer spaces (in mm) for Gateway 8 in the area surrounding Hauptwache in Frankfurt am Main

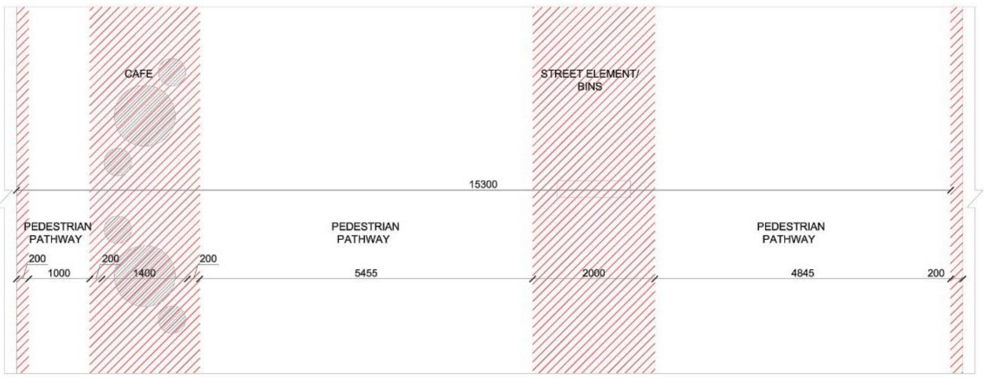

Figure 182: Street width and buffer spaces (in mm) for Gateway 9 in the area surrounding Hauptwache in Frankfurt am Main

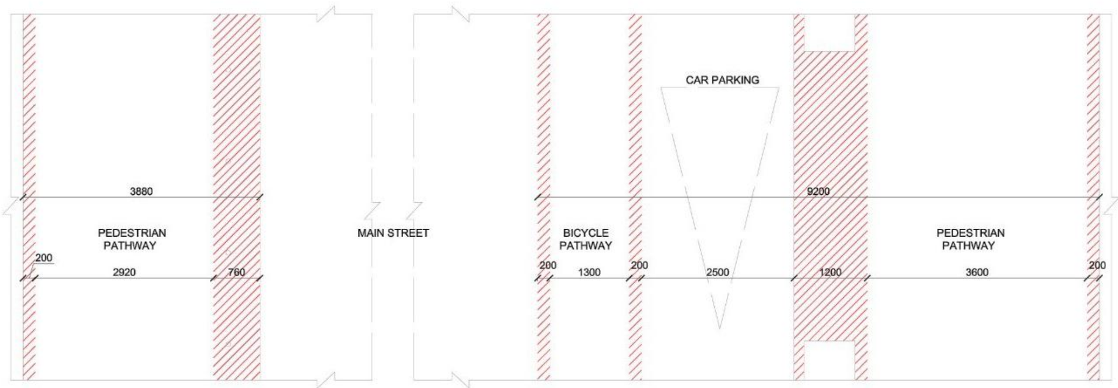

Figure 183: Street width and buffer spaces (in mm) for Gateway 10 in the area surrounding Hauptwache in Frankfurt am Main

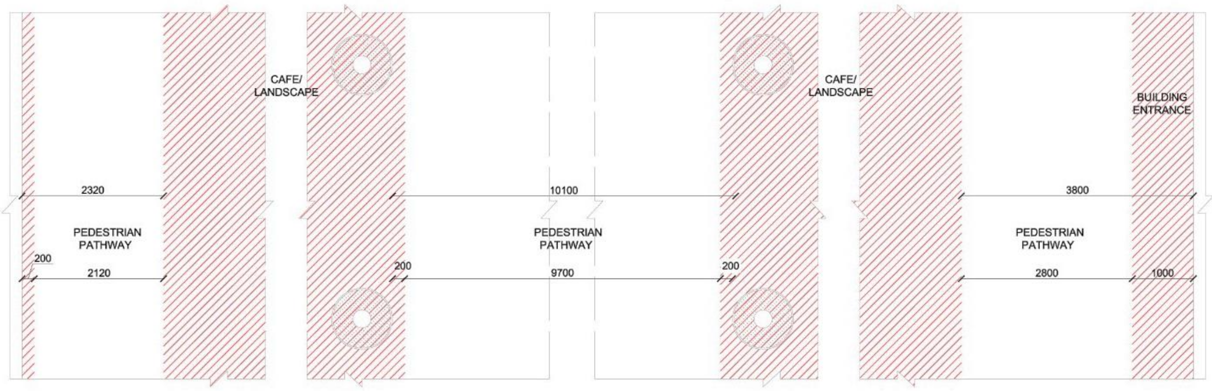

Figure 184: Street width and buffer spaces (in mm) for Gateway 11 in the area surrounding Hauptwache in Frankfurt am Main

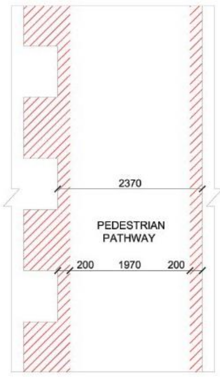

Figure 185: Street width and buffer spaces (in mm) for Gateway 12 in the area surrounding Hauptwache in Frankfurt am Main

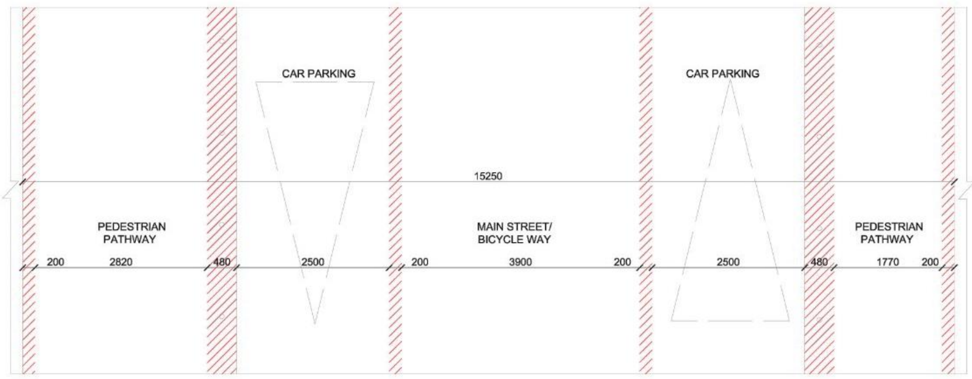

Figure 186: Street width and buffer spaces (in mm) for Gateway 13 in the area surrounding Hauptwache in Frankfurt am Main

Figure 187: Street width and buffer spaces (in mm) for Gateway 14 in the area surrounding Hauptwache in Frankfurt am Main

A3.1.3 Selected streets and their widths in Offenbach am Main

The following street widths were measured in the selected urban areas surrounding city centre, main transit station and the residential area of Bürgel in Offenbach am Main. The buffer spaces on the street ends through its width are usually from the building or the street edges, unless stated otherwise. The annotations are measured in millimetres (mm), and represent the street widths during the on-site conditions of the urban area. The street widths and buffer spaces (in red) for the residential area of Bürgel are as follows:

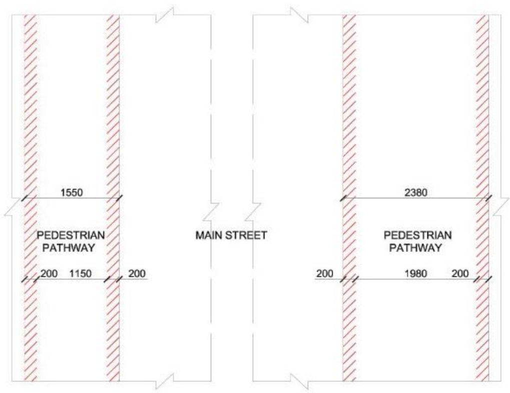

Figure 188: Street width and buffer spaces (in mm) for Gateway 1 in the residential area of Bürgel in Offenbach am Main

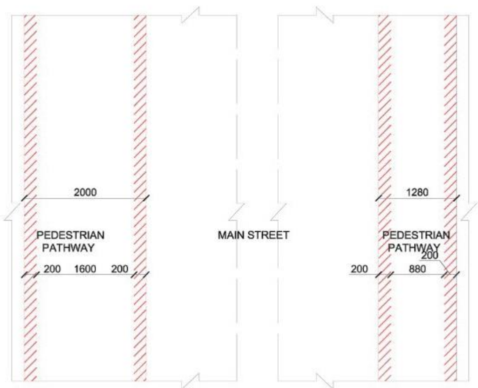

Figure 189: Street width and buffer spaces (in mm) for Gateway 2 in the residential area of Bürgel in Offenbach am Main

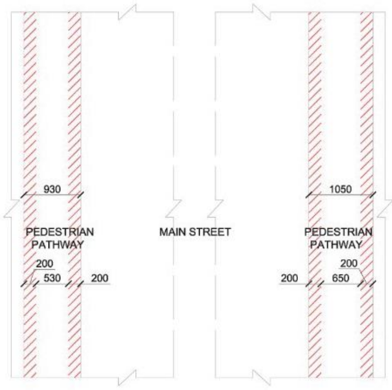

Figure 190: Street width and buffer spaces (in mm) for Gateway 3 in the residential area of Bürgel in Offenbach am Main

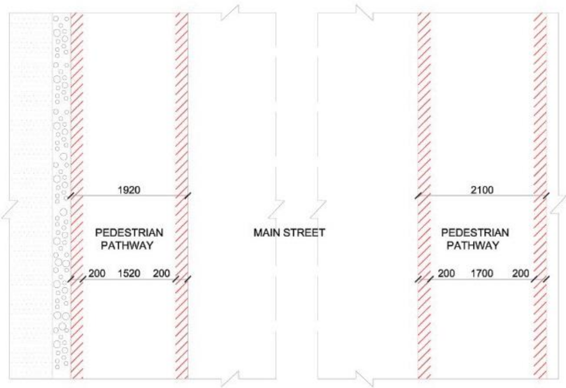

Figure 191: Street width and buffer spaces (in mm) for Gateway 4 in the residential area of Bürgel in Offenbach am Main

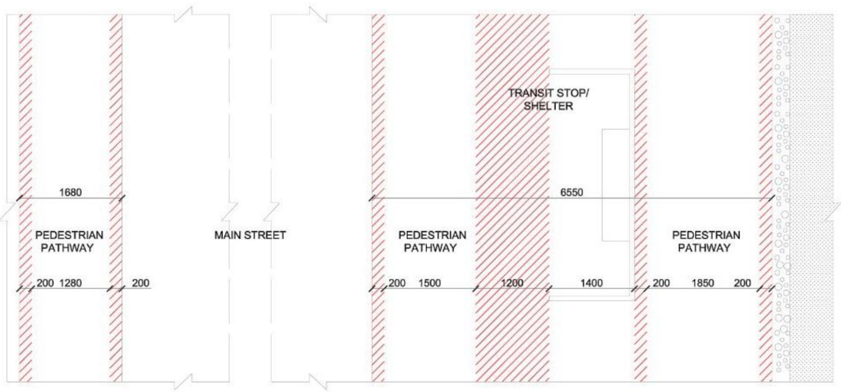

Figure 192: Street width and buffer spaces (in mm) for Gateway 5 in the residential area of Bürgel in Offenbach am Main

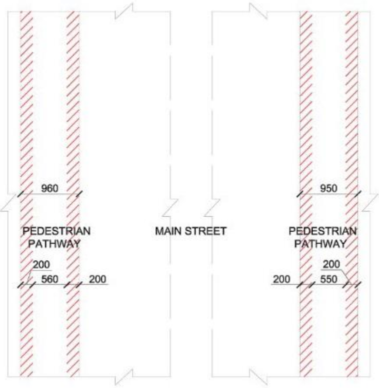

Figure 193: Street width and buffer spaces (in mm) for Gateway 6 in the residential area of Bürgel in Offenbach am Main

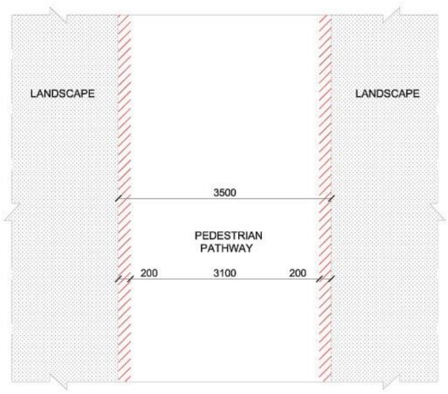

Figure 194: Street width and buffer spaces (in mm) for Gateway 7 in the residential area of Bürgel in Offenbach am Main

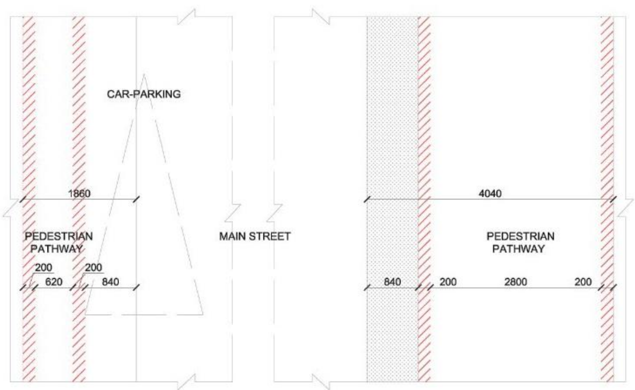

Figure 195: Street width and buffer spaces (in mm) for Gateway 8 in the residential area of Bürgel in Offenbach am Main

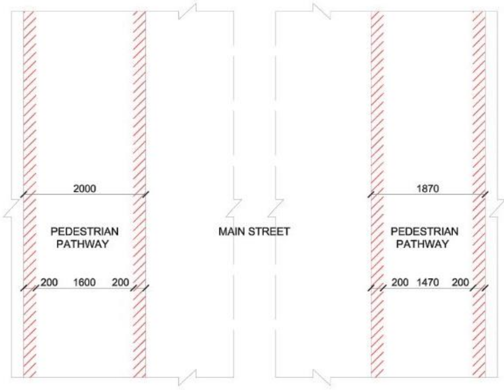

Figure 196: Street width and buffer spaces (in mm) for Gateway 9 in the residential area of Bürgel in Offenbach am Main

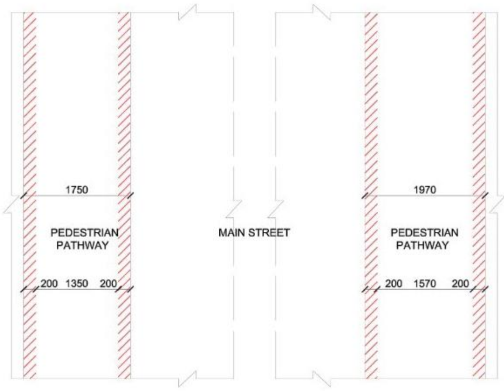

Figure 197: Street width and buffer spaces (in mm) for Gateway 10 in the residential area of Bürgel in Offenbach am Main

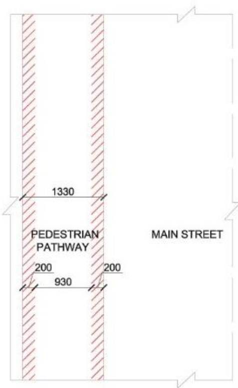

Figure 198: Street width and buffer spaces (in mm) for Gateway 11 in the residential area of Bürgel in Offenbach am Main

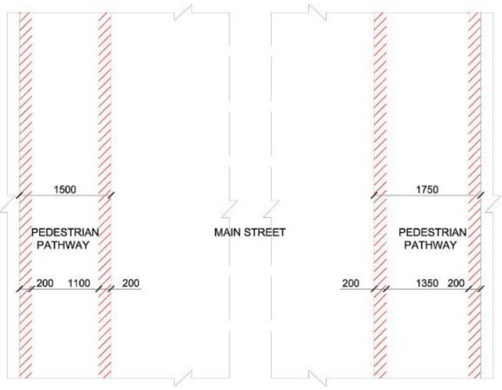

Figure 199: Street width and buffer spaces (in mm) for Gateway 12 in the residential area of Bürgel in Offenbach am Main

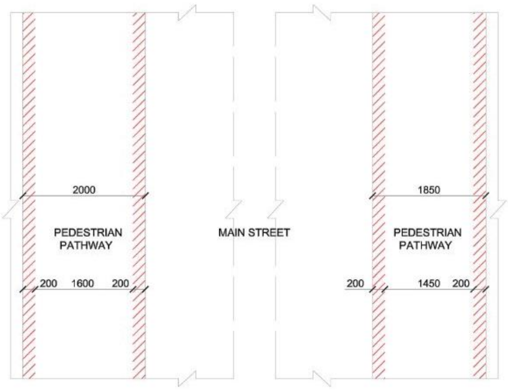

Figure 200: Street width and buffer spaces (in mm) for Gateway 13 in the residential area of Bürgel in Offenbach am Main

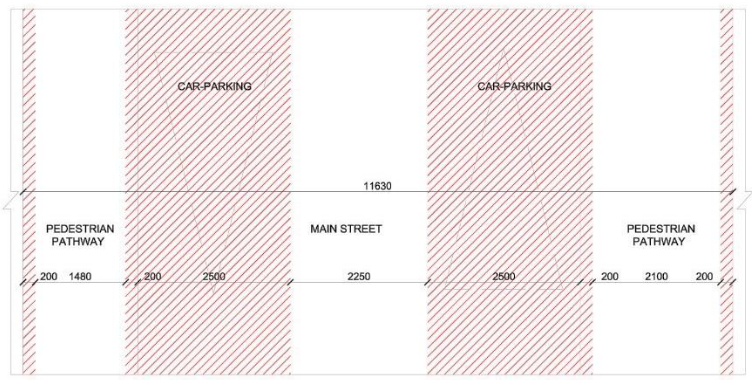

Figure 201: Street width and buffer spaces (in mm) for Gateway 14 in the residential area of Bürgel in Offenbach am Main

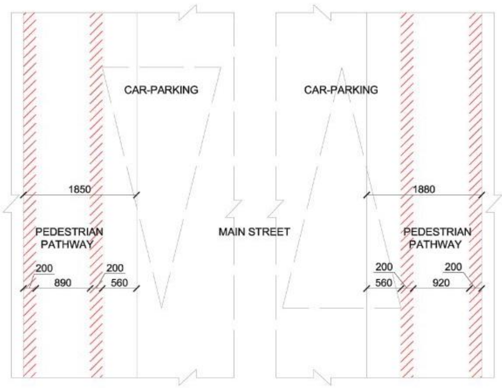

Figure 202: Street width and buffer spaces (in mm) for Gateway 15 in the residential area of Bürgel in Offenbach am Main

The street widths and buffer spaces (in red) for the area surrounding Offenbach Hauptbahnhof are as follows:

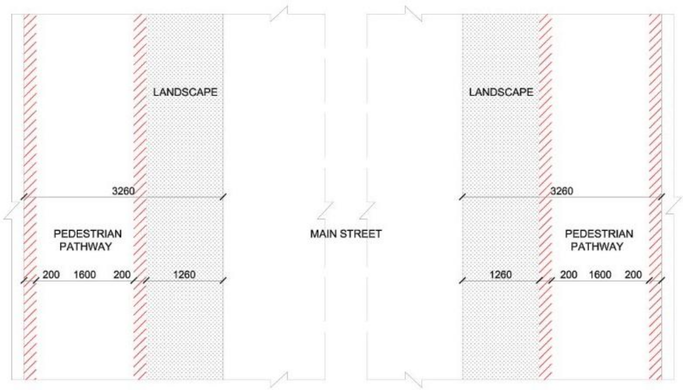

Figure 203: Street width and buffer spaces (in mm) for Gateway 1 in the area surrounding Offenbach am Main Hauptbahnhof

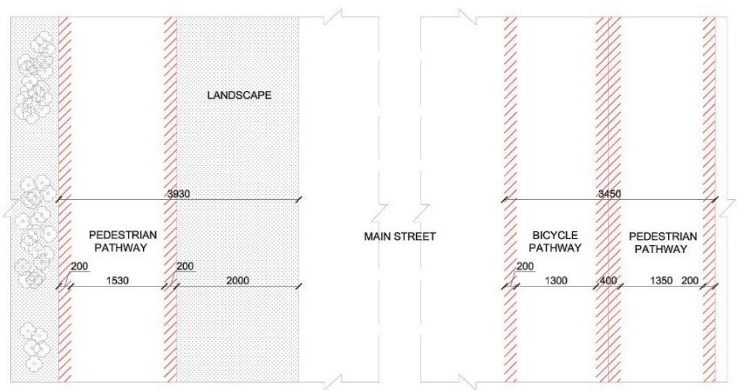

Figure 204: Street width and buffer spaces (in mm) for Gateway 2 in the area surrounding Offenbach am Main Hauptbahnhof

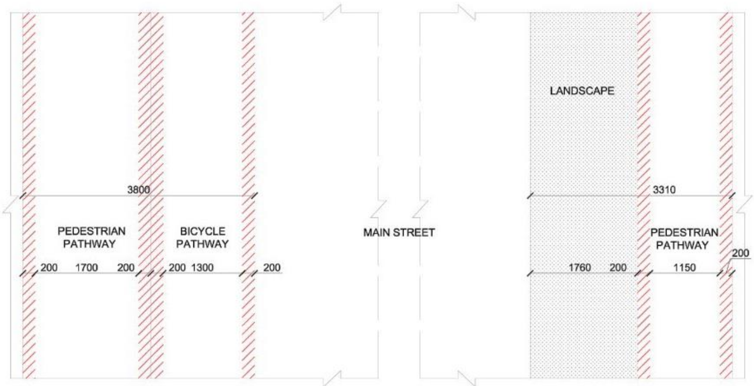

Figure 205: Street width and buffer spaces (in mm) for Gateway 3 in the area surrounding Offenbach am Main Hauptbahnhof

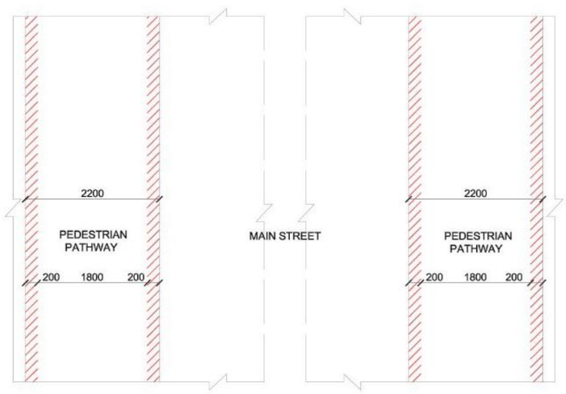

Figure 206: Street width and buffer spaces (in mm) for Gateway 4 in the area surrounding Offenbach am Main Hauptbahnhof

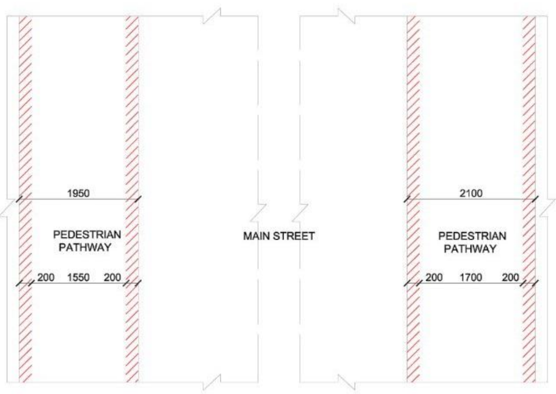

Figure 207: Street width and buffer spaces (in mm) for Gateway 5 in the area surrounding Offenbach am Main Hauptbahnhof

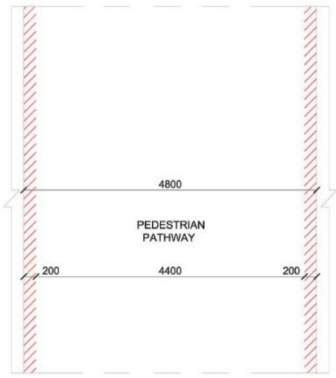

Figure 208: Street width and buffer spaces (in mm) for Gateway 6 in the area surrounding Offenbach am Main Hauptbahnhof

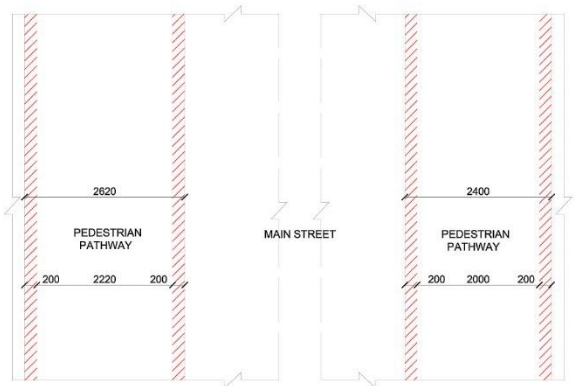

Figure 209: Street width and buffer spaces (in mm) for Gateway 7 in the area surrounding Offenbach am Main Hauptbahnhof

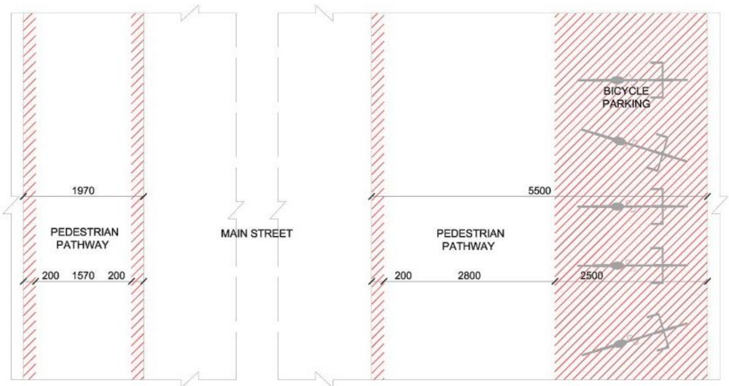

Figure 210: Street width and buffer spaces (in mm) for Gateway 8 in the area surrounding Offenbach am Main Hauptbahnhof

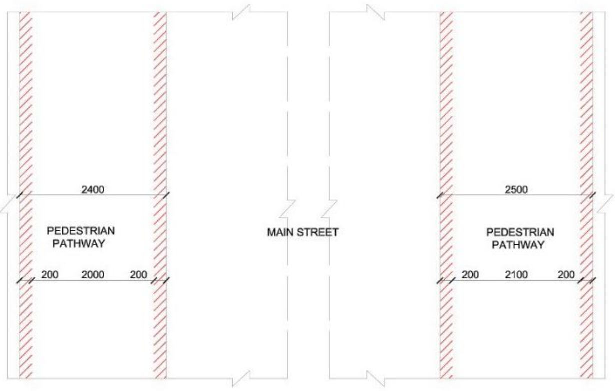

Figure 211: Street width and buffer spaces (in mm) for Gateway 9 in the area surrounding Offenbach am Main Hauptbahnhof

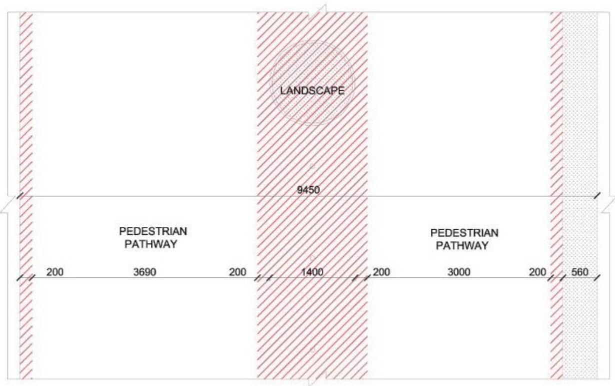

Figure 212: Street width and buffer spaces (in mm) for Gateway 10 in the area surrounding Offenbach am Main Hauptbahnhof

Figure 213: Street width and buffer spaces (in mm) for Gateway 11 in the area surrounding Offenbach am Main Hauptbahnhof

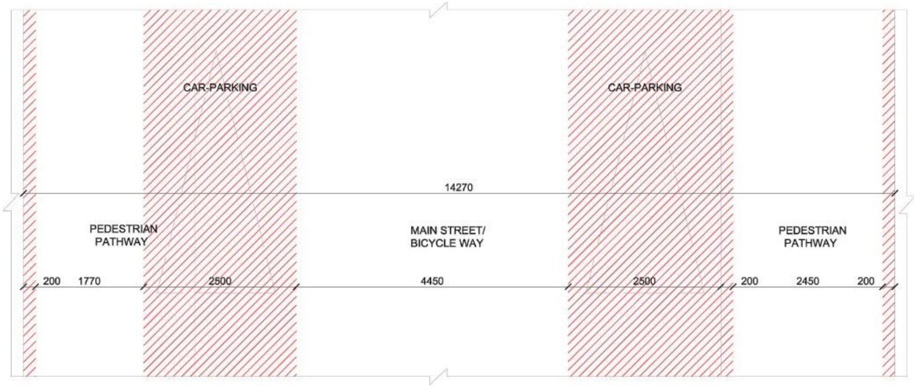

Figure 214: Street width and buffer spaces (in mm) for Gateway 12 in the area surrounding Offenbach am Main Hauptbahnhof

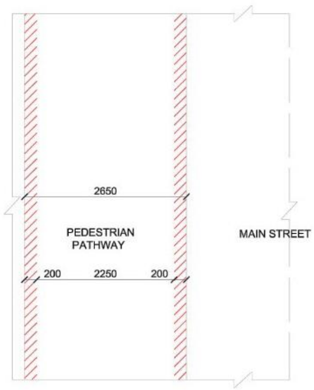

Figure 215: Street width and buffer spaces (in mm) for Gateway 13 in the area surrounding Offenbach am Main Hauptbahnhof

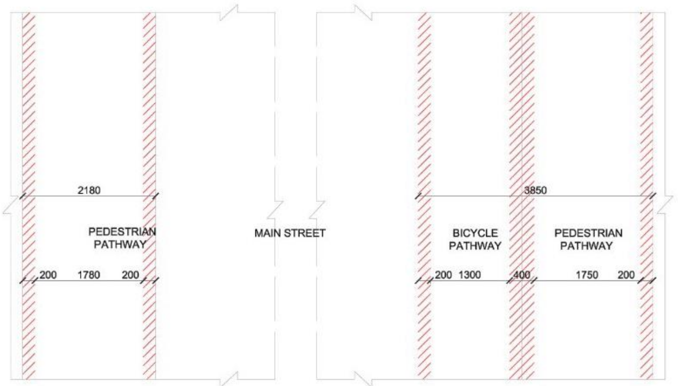

Figure 216: Street width and buffer spaces (in mm) for Gateway 14 in the area surrounding Offenbach am Main Hauptbahnhof

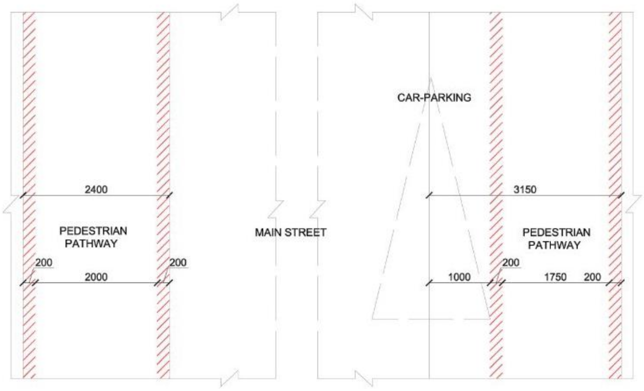

Figure 217: Street width and buffer spaces (in mm) for Gateway 15 in the area surrounding Offenbach am Main Hauptbahnhof

The street widths and buffer spaces (in red) for the area surrounding the city centre in Offenbach am Main are as follows:

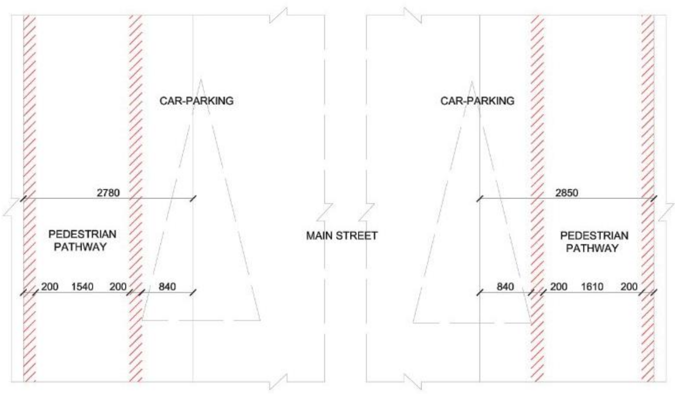

Figure 218: Street width and buffer spaces (in mm) for Gateway 1 in the area surrounding Marktplatz in Offenbach am Main

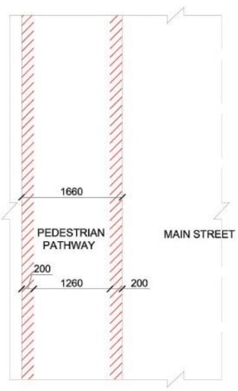

Figure 219: Street width and buffer spaces (in mm) for Gateway 2 in the area surrounding Marktplatz in Offenbach am Main
Note: The street included on-going construction work on the adjacent pedestrian pathway (which is not taken into crowding calculation)

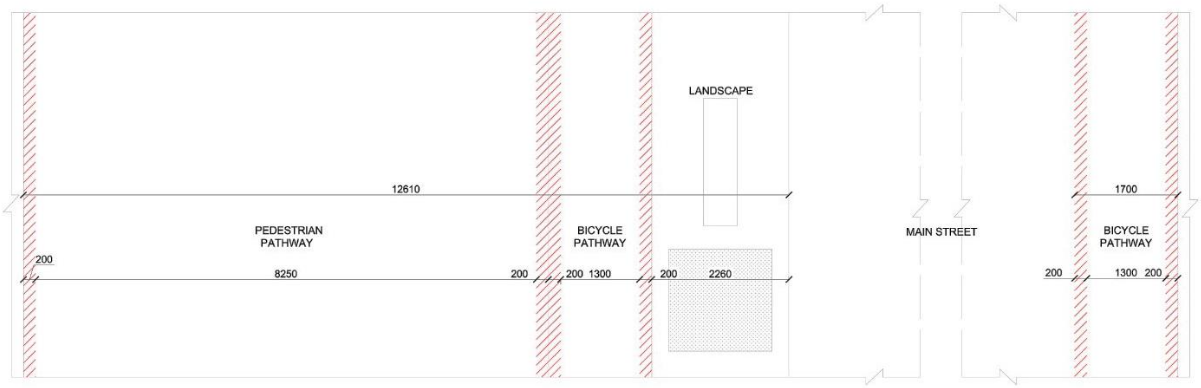

Figure 220: Street width and buffer spaces (in mm) for Gateway 3 in the area surrounding Marktplatz in Offenbach am Main
Note: The street included on-going construction work on the adjacent pedestrian pathway (which is not taken into crowding calculation)

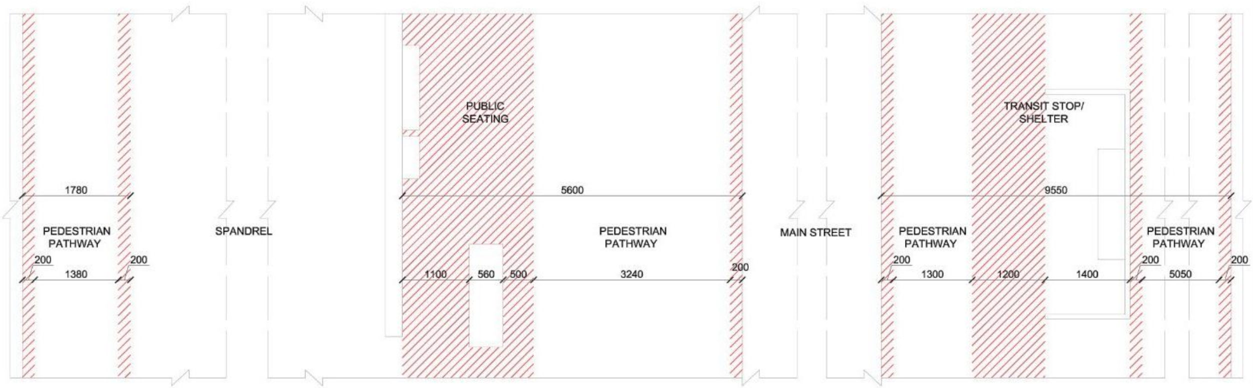

Figure 221: Street width and buffer spaces (in mm) for Gateway 4 in the area surrounding Marktplatz in Offenbach am Main

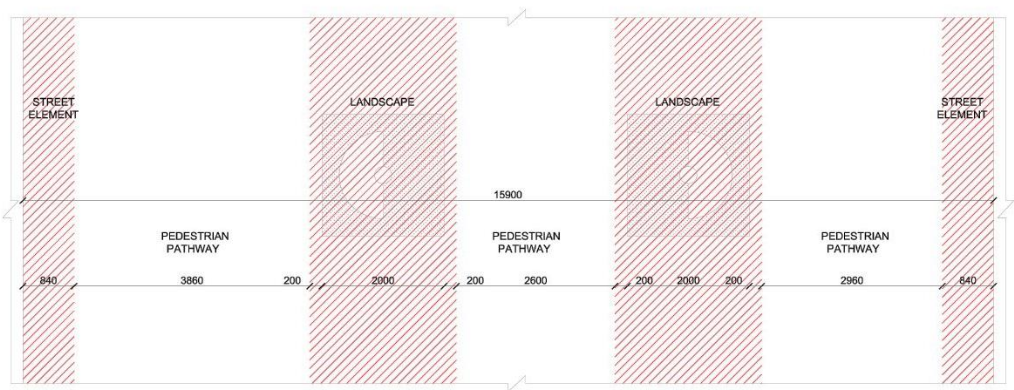

Figure 222: Street width and buffer spaces (in mm) for Gateway 5 in the area surrounding Marktplatz in Offenbach am Main

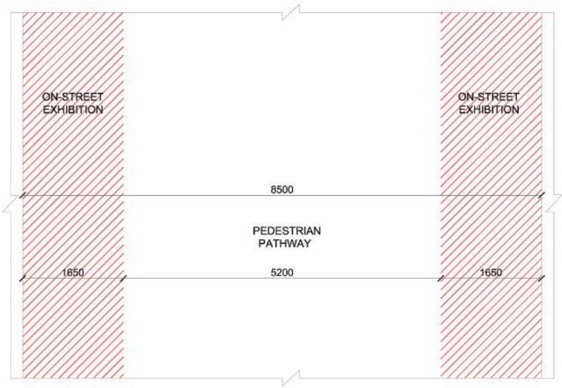

Figure 223: Street width and buffer spaces (in mm) for Gateway 6 in the area surrounding Marktplatz in Offenbach am Main

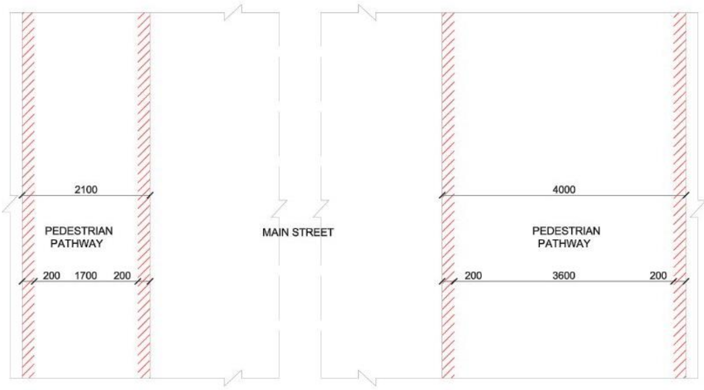

Figure 224: Street width and buffer spaces (in mm) for Gateway 7 in the area surrounding Marktplatz in Offenbach am Main

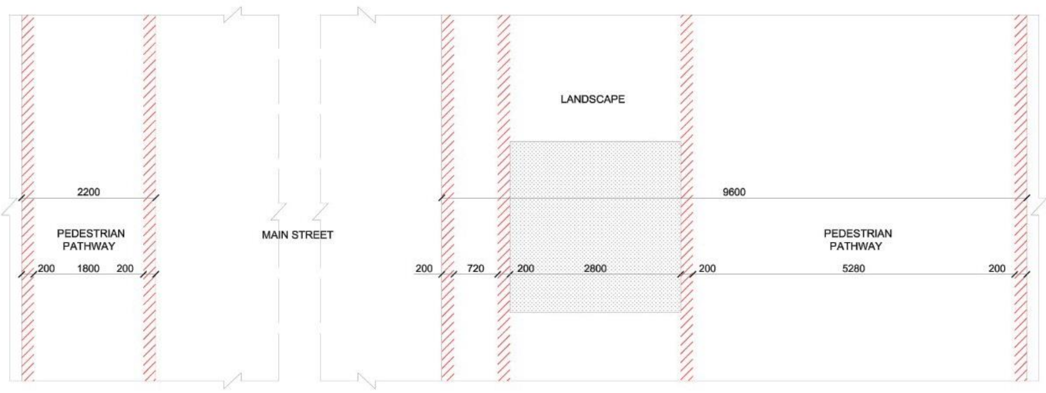

Figure 225: Street width and buffer spaces (in mm) for Gateway 8 in the area surrounding Marktplatz in Offenbach am Main

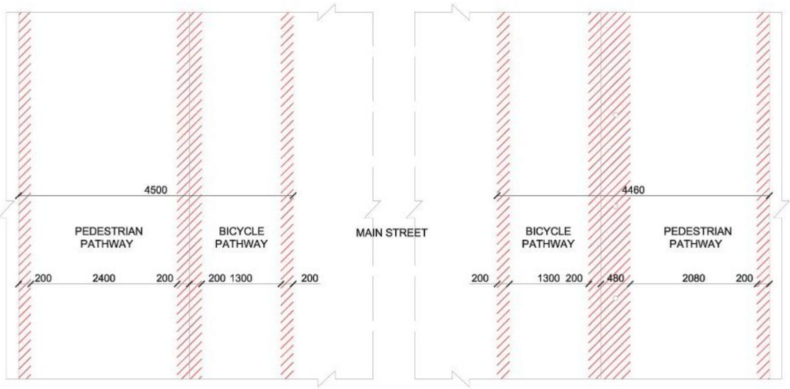

Figure 226: Street width and buffer spaces (in mm) for Gateway 9 in the area surrounding Marktplatz in Offenbach am Main

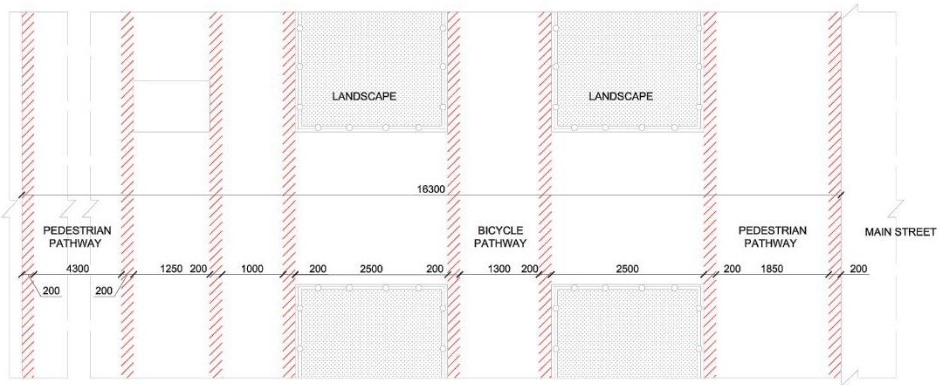

Figure 227: Street width and buffer spaces (in mm) for Gateway 10 (on the southern side of the main street) in the area surrounding Marktplatz in Offenbach am Main

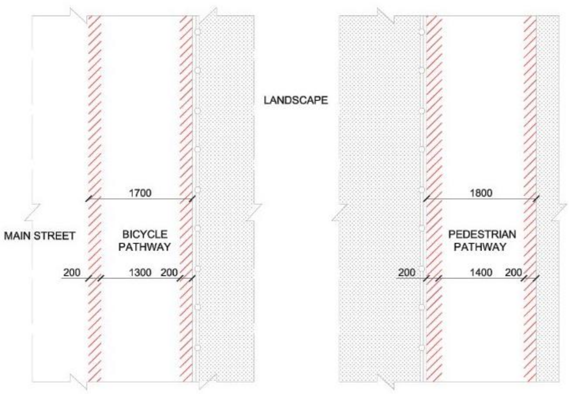

Figure 228: Street width and buffer spaces (in mm) for Gateway 10 (on the northern side of the main street) in the area surrounding Marktplatz in Offenbach am Main

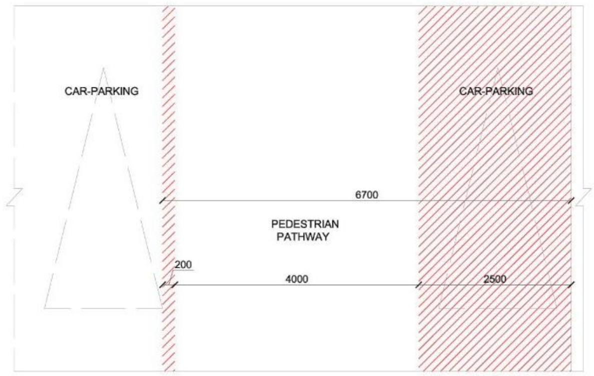

Figure 229: Street width and buffer spaces (in mm) for Gateway 11 in the area surrounding Marktplatz in Offenbach am Main

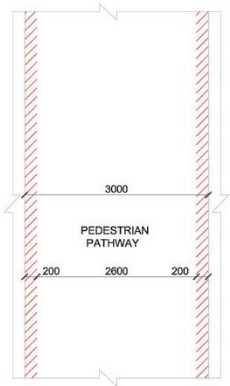

Figure 230: Street width and buffer spaces (in mm) for Gateway 12 in the area surrounding Marktplatz in Offenbach am Main

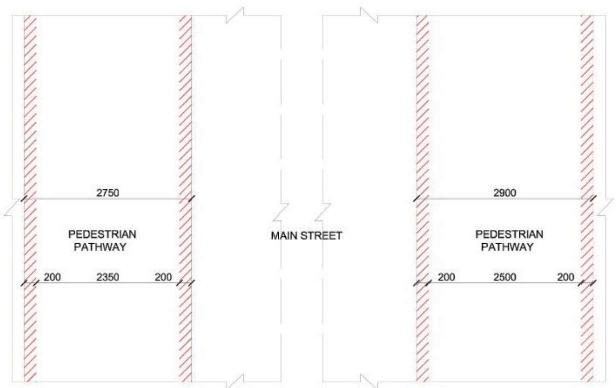

Figure 231: Street width and buffer spaces (in mm) for Gateway 13 in the area surrounding Marktplatz in Offenbach am Main

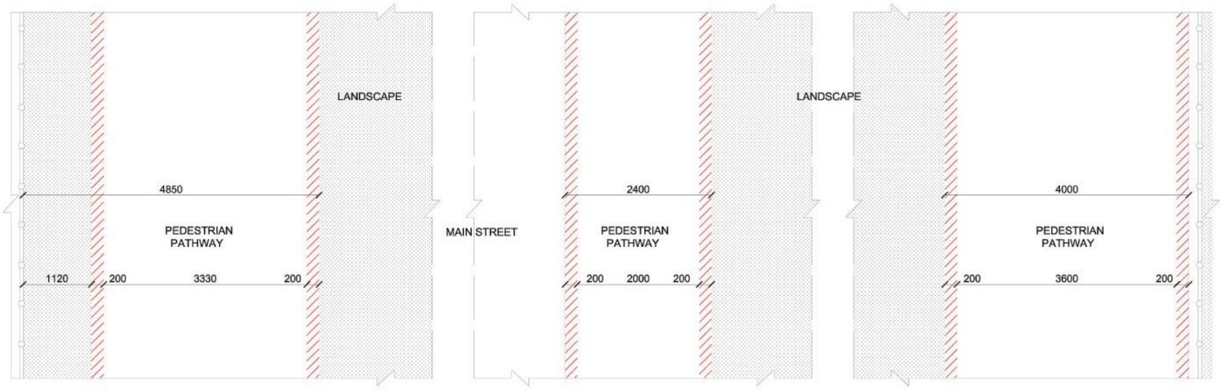

Figure 232: Street width and buffer spaces (in mm) for Gateway 14 in the area surrounding Marktplatz in Offenbach am Main

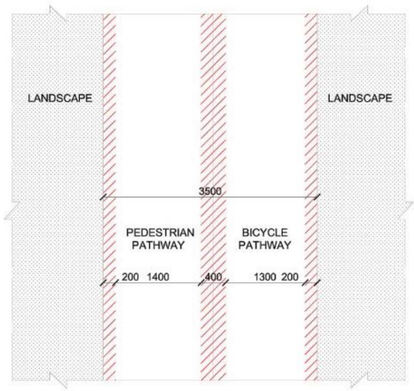

Figure 233: Street width and buffer spaces (in mm) for Gateway 15 in the area surrounding Marktplatz in Offenbach am Main

APPENDIX IV

Priority survey for public perception

A4.1 Preface

This appendix includes the public survey focusing on selected multimodal accessibility parameters in the Rhein-Main area. The priority survey is designed with an intention to understand how people in the Rhine-Main region perceive accessibility and prioritize different aspects catering towards accessibility within their urban surroundings. The survey is utilized to bring in the public perspective to the five equally weighted parameters (or performance measures) for the subjective ranking of urban areas and other mobility aspects. The accessibility parameters were identified and studied through different urban areas within the cities of Darmstadt, Frankfurt and Offenbach prior to the undertaking of the survey. The public survey was distributed through two languages i.e. in English and German for better reach of participants from the urban agglomeration.

A4.2 Priority survey description

The survey was divided in three sections, where the first section is utilized to describe the selected five parameters in a simplified manner which is easy to understand for public and user-groups participating in the survey. This is followed by two sections, where the first section focuses on the demographics and urban areas, while the later section focuses on pair-wise comparison of the different aspects of the multimodal accessibility to be prioritized. The latter two sections are introduced, including the description of selected five parameters, as follows:

Section A

1. Under which age group do you fall under?
    a. 18-30
    b. 31-40
    c. 41-50
    d. 51-60
    e. 61 and above

2. Are you a person with a mobility impairment (or other kind of disability)?
    a. Yes
    b. No

3. Which city do you live in Rhein-Main agglomeration?
    a. Frankfurt
    b. Darmstadt
    c. Offenbach
    d. Other

4. Which neighbourhood would you categorize your place of residence to be in?
    a. City Centre
    b. Residential
    c. Transit area (e.g. close to main station of the city)
    d. Other

5. What is the postal code (5-digit number) of your neighbourhood?
    a. _____

6. Which mode of mobility do you prefer to travel in general?
    a. Walking
    b. Cycling
    c. Public Transport
    d. Car
    e. Other

The selected five aspects for upcoming questions:

GOOD NETWORK OF STREETS (S)

This relates to a good walking network of streets with sufficient pedestrian pathways, junctions, short block lengths and many ways to go from A to B around a place or neighbourhood, offering freedom of choice for people to move. A good network of streets would help promoting walking in neighbourhoods.

ACCESS TO PUBLIC TRANSPORT (PT)

This relates to ease of accessing a public transport service (including trams, buses, trains etc.) based on its frequency of services and its distance from a point of origin. Higher access to public transport would mean closeness to public transport stations and less waiting time at the station for trams (or buses, trains etc.).

ACCESS TO BICYCLE ROUTES (B)

This relates to good network of bicycle routes in the city, which are quick, direct and less time consuming to reach a destination. Access to more direct routes for cyclists from the point of origin to destination would make the overall mobility network of neighbourhoods (or cities) more efficient.

EASE OF MOVEMENT (M)

This relates to ease of moving around in a pedestrian space without too many obstructions or barriers (e.g. parking spaces, street furniture etc.). The ease of movement also relates to having good width of space to move, without too many people occupying the space at the same time.

EASE OF NAVIGATION (N)

This relates to the ability of a person to pinpoint their location in an urban space which helps in navigation and movement. A navigable space is easy to understand and move around in the city.

7. How would you rate the 'Network of Streets' (S) in your neighbourhood?
    a. 1 (Very Poor)
    b. 2
    c. 3
    d. 4
    e. 5 (Very Good)

8. How would you rate ‘Access to Public Transport' (PT) in your neighbourhood?
    a. 1 (Very Poor)
    b. 2
    c. 3
    d. 4
    e. 5 (Very Good)

9. How would you rate ‘Access to Bicycle Routes’ (B) in your neighbourhood?
    a. 1 (Very Poor)
    b. 2
    c. 3
    d. 4
    e. 5 (Very Good)

10. How would you rate ‘Ease of Movement’ (M) in your neighbourhood?
    a. 1 (Very Poor)
    b. 2
    c. 3
    d. 4
    e. 5 (Very Good)

11. How would you rate the ‘Ease of Navigation' (N) in your neighbourhood?
    a. 1 (Very Poor)
    b. 2
    c. 3
    d. 4
    e. 5 (Very Good)

Section B

This section deals with pair-wise comparison of aspects related to accessibility in urban areas. The sample demonstration for the comparison is as follows:

Question:
Which aspect is of a more priority to you between ‘X’ and ‘Y’?

Options:
a. X9 (Extreme priority for ‘X’)
b. X7
c. X5

d. X3
e. 1 (No priority / Neutral)
f. Y3
g. Y5
h. Y7
i. Y9 (Extreme Priority for ‘Y’)

- If you ‘extremely’ prioritize X over Y, then choose X9 (and vice versa).
- If you ‘very strongly’ favour X over Y (but not as extremely), then choose X7 (and vice versa).
- If you ‘strongly’ favour X over Y, then choose X5 (and vice versa).
- If you ‘slightly’ favour X over Y, then choose X3 (and vice versa).
- If you cannot prioritize between the two, then choose 1 (i.e. neutral).

12. Which aspect do you prioritize the most?
    a. Network of Streets (S)
    b. Access to Public Transport (PT)
    c. Access to Bicycle Routes (B)
    d. Ease of Movement (M)
    e. Ease of Navigation (N)

13. Which aspect is of a more priority to you between ‘Good network of streets (S)’ and ‘Access to Public Transport (PT)’?
    a. S9 (Extreme priority for 'Good network of streets')
    b. S7
    c. S5
    d. S3
    e. 1 (No priority / Neutral)
    f. PT3
    g. PT5
    h. PT7
    i. PT9 (Extreme Priority for ‘Access to Public Transport’)

14. Which aspect is of a more priority to you between ‘Good network of streets (S)’ and ‘Access to Bicycle Routes (B)’?
    a. S9 (Extreme priority for 'Good network of streets')
    b. S7
    c. S5
    d. S3
    e. 1 (No priority / Neutral)
    f. B3
    g. B5
    h. B7
    i. B9 (Extreme Priority for ‘Access to Bicycle Routes’)

15. Which aspect is of a more priority to you between ‘Good network of streets (S)’ and ‘Ease of Movement (M)’?
    a. S9 (Extreme priority for 'Good network of streets')
    b. S7
    c. S5
    d. S3
    e. 1 (No priority / Neutral)
    f. M3
    g. M5
    h. M7
    i. M9 (Extreme Priority for ‘Ease of Movement’)

16. Which aspect is of a more priority to you between ‘Good network of streets (S)’ and ‘Ease of Navigation (N)’?
    a. S9 (Extreme priority for 'Good network of streets')
    b. S7
    c. S5
    d. S3
    e. 1 (No priority / Neutral)
    f. N3
    g. N5
    h. N7
    i. N9 (Extreme Priority for ‘Ease of Navigation’)

17. Which aspect is of a more priority to you between ‘Access to Public Transport (PT)’ and ‘Access to Bicycle Routes (B)’?
    a. PT9 (Extreme priority for 'Access to Public Transport)
    b. PT7
    c. PT5
    d. PT3
    e. 1 (No priority / Neutral)
    f. B3
    g. B5
    h. B7
    i. B9 (Extreme Priority for ‘Access to Bicycle Routes’)

18. Which aspect is of a more priority to you between ‘Access to Public Transport (PT)’ and ‘Ease of Movement (M)’?
    a. PT9 (Extreme priority for 'Access to Public Transport)
    b. PT7
    c. PT5
    d. PT3
    e. 1 (No priority / Neutral)
    f. M3

g. M5
h. M7
i. M9 (Extreme Priority for ‘Ease of Movement’)

19. Which aspect is of a more priority to you between ‘Access to Public Transport (PT)’ and ‘Ease of Navigation (N)’?
    a. PT9 (Extreme priority for 'Access to Public Transport)
    b. PT7
    c. PT5
    d. PT3
    e. 1 (No priority / Neutral)
    f. N3
    g. N5
    h. N7
    i. N9 (Extreme Priority for ‘Ease of Navigation’)

20. Which aspect is of a more priority to you between ‘Access to Bicycle Routes (B)’ and ‘Ease of Movement (M)’?
    a. B9 (Extreme priority for ‘Access to Bicycle Routes’)
    b. B7
    c. B5
    d. B3
    e. 1 (No priority / Neutral)
    f. M3
    g. M5
    h. M7
    i. M9 (Extreme Priority for ‘Ease of Movement’)

21. Which aspect is of a more priority to you between ‘Access to Bicycle Routes (B)’ and ‘Ease of Navigation (N)’?
    a. B9 (Extreme priority for ‘Access to Bicycle Routes’)
    b. B7
    c. B5
    d. B3
    e. 1 (No priority / Neutral)
    f. N3
    g. N5
    h. N7
    i. N9 (Extreme Priority for ‘Ease of Navigation’)

22. Which aspect is of a more priority to you between ‘Ease of Movement (M)’ and ‘Ease of Navigation (N)’?
    a. M9 (Extreme priority for ‘Ease of Movement’)
    b. M7
    c. M5
    d. M3

e. 1 (No priority / Neutral)
f. N3
g. N5
h. N7
i. N9 (Extreme Priority for ‘Ease of Navigation’)

A4.3 Added survey outcomes

This subsection showcases the added survey outcomes discussed in Chapter 6, which includes the age group of survey participants in the three cities along with the pairwise comparison for the subjective weightage based on the AHP.

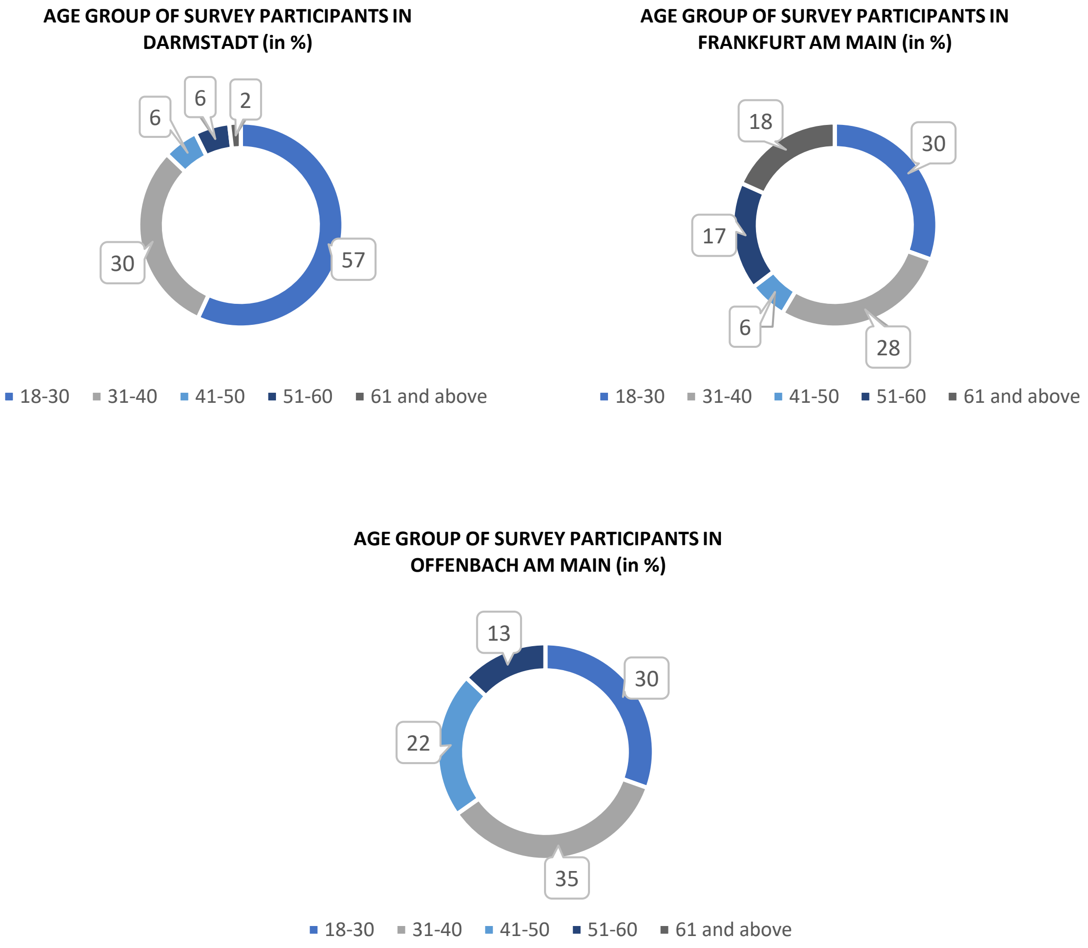

Figure 234: Age group of survey participants in Darmstadt, Frankfurt am Main and Offenbach am Main (in %)

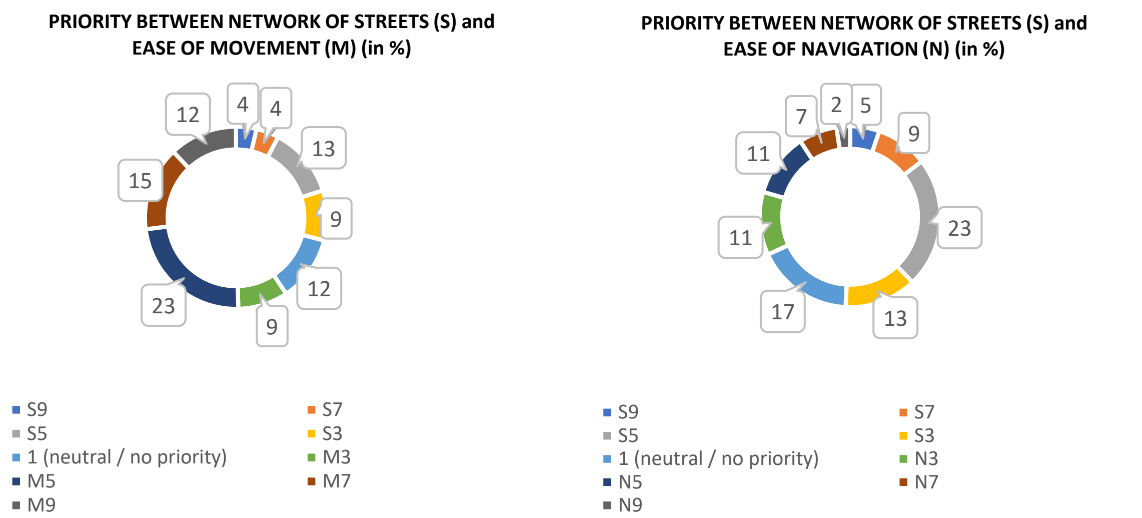

Figure 235: Pair-wise comparison graphics between 'network of streets' and 'ease of movement' (left), and 'network of streets' and 'ease of navigation' (right) within AHP

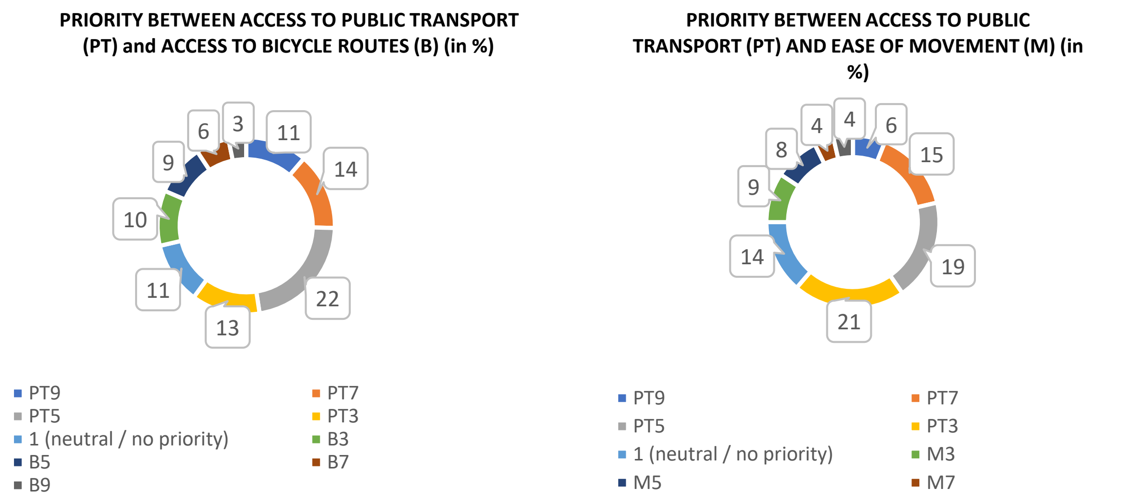

Figure 236: Pair-wise comparison graphics between 'access to public transport and 'access to bicycle routes' (left), and 'access to public transport' and 'ease of movement' (right) within AHP

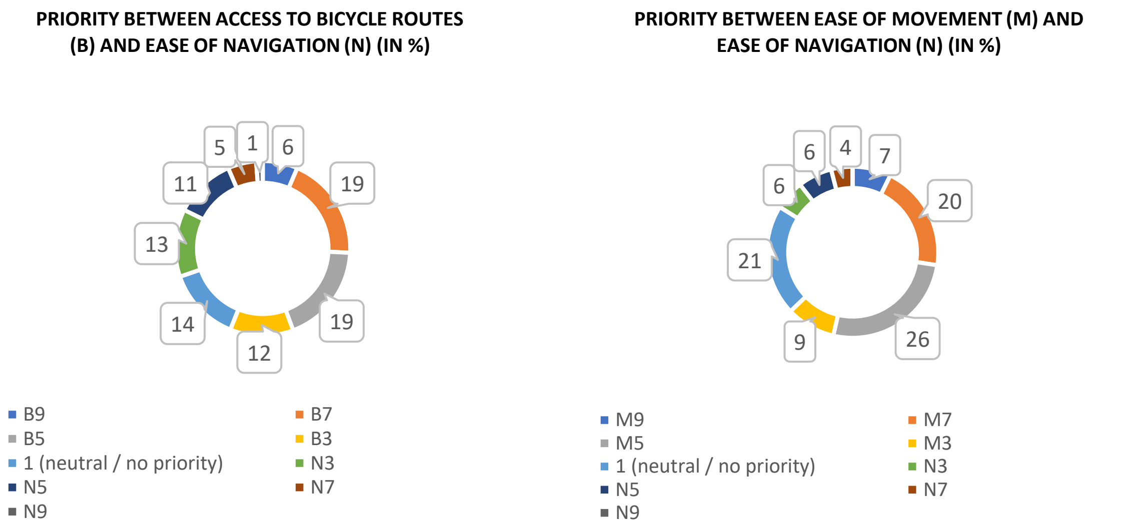

Figure 237: Pair-wise comparison graphics between 'access to bicycle routes' and 'ease of navigation' (left), and 'ease of movement' and 'ease of navigation' (right) within AHP

APPENDIX V

Agglomerative Hierarchical Clustering

A5.1 Urban Clustering and Interpretation

Based on the objective accessibility characteristics of the selected nine urban areas in Rhein-Main agglomeration, the agglomerative hierarchical clustering methodology (via XLSTAT n.d.) is adopted to cluster areas showing similar homogenous characteristics.

Evolution of indices:

Number of clusters	**2**	3	4	5
Silhouette index	0.388	0.294	0.245	0.201
Hartigan index (H)	3.895	2.683	1.655	1.167
H(k-1) - H(k)	**4.443**	1.211	1.028	0.488
Calinski & Harabasz index	8.338	7.840	7.587	6.850

Table 43: Evolution of the Silhouette index, the Hartigan index, and the Calinski & Harabasz index for different number of clusters ranging from 2 to 5

The measure of an object (or an urban area in this study) showing more similarity within its own cluster than other clusters via Silhouette index shows the highest number for cluster 2 (see Table 43). It also shows the evolution of Hartigan index and the difference between the clustering of k clusters and k-1 clusters (XLSTAT n.d.). The greater difference on third row under ‘2’ clusters, indicates the number of clusters to be created.

___

XLSTAT n.d., Agglomerative Hierarchical Clustering (AHC) in Excel, accessed on 15.11.2022. Retrieved from https://www.xlstat.com/en/