Scarcity of Road Space in Urban Areas

A Case Study on the City of Darmstadt
Bachelor thesis by Taihao Zhang
Date of submission: 2 March 2021

Reviewer: [redacted]
Advisor: Jana Stahl, M.Sc.
Darmstadt

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In Memoriam

土豆儿

(Tudou)

Abstract

Long have population numbers been on the rise in cities, and especially Darmstadt has witnessed one of the fastest growths in Germany. This ever increasing population however demands mobility and thus space, which is a limited resource in urban areas. Motorised traffic, bicycle traffic, pedestrian traffic and public transit are considered the four most predominant modes of transport in a city. I conduct a spatial analysis of two select streets in Darmstadt, which reveals that one-third of road space is attributed to motorised traffic. I also discuss the specific needs of each subgroup, again focusing on the situation in Darmstadt. To close off, I identify needs for action and also recommend future actions.

Keywords road space allocation, space competition, sustainable city, Darmstadt

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Zusammenfassung

Seit geraumer Zeit steigen die Bevölkerungszahlen in Städten und Darmstadt verzeichnete einen besonders starken Wachstum unter deutschen Städten. Diese zunehmende Bevölkerung jedoch verlangt Mobilität und indes Fläche, welche in städtischen Regionen rar ist. Motorisierter, Fahrrad-, Fußgänger-, und öffentlicher Nahverkehr gelten als hauptsächliche Verkehrsmittel in der Stadt. Ich führe für zwei Darmstädter Straßen eine Flächenanalyse durch, die zeigt, dass ein Drittel der Straßenfläche dem motorisierten Verkehr zugeordnet wird; ferner erläutere ich die Anforderungen der Personengruppen in Bezug auf Darmstadt. Abschließend stelle ich Handlungsbedarf fest und konkretisiere mögliche Handlungsempfehlungen.

Schlagwörter Straßenflächenzuteilung, Flächenkonkurrenz, nachhaltige Stadt, Darmstadt

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1. Introduction

A city's available road space is mostly constrained to its inherent layout and properties, buildings set additional hard limits for roads they enclose. This means that while planning out urban development strategies, municipal governments bear the responsibility of ensuring fairness and sustainability, even more so when it comes to urban centres.

With that in mind, an emerging issue is the recent growth in population of those cities. Darmstadt's borough Innenstadt gained 16 000 residents from 2008 to 2018, an increase of 19 % (Wissenschaftsstadt Darmstadt 2020c). This figure is beyond tenfold the national average of Germany over the same period, which is only at + 1.2 % (Statistisches Bundesamt 2020). The same can be observed in a multitude of other cities in the country.

Diverge of interests In these very cities, a vast demographic spread within the populace leads to a variety of transport modes to coexist; members of these demographic groups all pursue different interests regarding road infrastructure (European Commission 2018, p. 11).

For instance, a cyclist is more inclined to continue their bicycling habit if their subjective perception of safety in traffic meets their standards (Bundesministerium für Verkehr und digitale Infrastruktur 2014, p. 24). Conversely, a car driver is interested in reaching their destination while retaining an average speed deemed comfortable. More concisely, they desire to encounter as little congestion as possible, and to spend as little time as possible waiting for traffic lights.

In the above, bicycles and motorised individual transport (MIT) are mere examples of many transport modes available. Likewise, the here mentioned interests are only two out of many. In the scope of intra-city transport, other modes of transport include public transit (bus and tramway in Darmstadt) and pedestrians; their needs will be discussed later on. (cf. § 4 *Results*, p. 21)

Motivation

The steadily diminishing amount of space as a public good poses a problem requiring the attention of people and government alike, and a variety of diverging interests clash together in this matter. Ultimately, this means that some sort of evaluation and prioritisation has to take place regarding the allocation of road space.

This thesis therefore seeks to answer two research questions primarily. One being how distribution of road space plays out in Darmstadt and which future possibilities are associated with it; the other being which demographics exist and what their interests regarding road space are.

The result of this work adds onto the discussion about road space in urban areas and how it can be distributed sustainably. This is achieved by providing a cross-sectional case study on the status quo of Darmstadt.

Structure

Relevant terminology and literature is presented in § 2, p. 3. The chapter also includes a qualitative comparison of methods that previous authors have used. § 3, p. 14 gives reasons for the choice of the study area and develops a methodology for measuring space distribution. This methodology is employed in § 4, p. 21, where findings are presented. The current space distribution is put side-to-side with an earlier one to demonstrate the changes in effect. In a second section of § 4, each major mode of transport is discussed in greater detail with respect to the study area. Especially each mode's characteristics, prevalence, and needs are points of discourse there. Lastly, § 5, p. 42 qualitatively discusses the previous findings and identifies critical points where action is needed.

2. Literature review

Prior to the writing of this thesis, a thorough search of the existing literature was conducted. An inquiry of the recency and topicality then helped narrow down the results to only the most relevant ones. This chapter describes the finding and filtering of literature, provides an overview of the current state of literature, and finalises by reviewing the methodology used by various authors in literature.

2.1. Terminology

Before engaging in more profound material, it is of considerable importance to first establish the terminology used, and to provide unambiguous definitions. Doing so ensures the key results presented in this thesis can be understood with ease. While this section iterates general terminology, more specific details regarding methodology remain to be particularised in § 3, p. 14 instead.

Road space *per se* As the one major focal point of the present thesis, the extent of *road space* is by no means well-defined. In the context onwards, it refers to public roads, car parks, pedestrian areas, and furthermore any traffic infrastructure constructed and maintained by municipal institutions – as opposed to privately held space (e.g. supermarket car parks), which is not subject to this study. While the argument can be made that supermarkets would size their car parks according to traffic volume and demand for such, this factor goes beyond the scope of this study and may be of interest in future studies instead.

Mode of transport Mode of transport, as hinted on earlier, describes any medium which facilitates mobility of the manoeuvring person and any number of passengers, if present (E. Schnieder and L. Schnieder 2013, p. 51; Ammoser and Hoppe 2006, pp. 30, 31). Specifically, the modes of transport which come to mind when referring to traffic in urban areas are the following:

- motorised individual transport, most prominently:
  - private and rental car
  - private and rental motorcycle
- mass transit
  - buses, mostly public but also includes privately operated ones
  - tramways
- bicycles

  including freight bicycles, which are gaining popularity in recent years (Bingener and Steppat 2020)
- pedestrians

Traffic participants Traffic participant is a term used to describe any individual partaking in traffic, regardless of whether their intention is involved. Naturally, car drivers and bicyclists fall under this category; yet in a broader sense, this notion includes various kinds of pedestrians (person pushing a pram, wheelchair users, children chasing a ball) (World Health Organisation 2013, p. 3).

Furthermore, traffic participants may be categorised by their motive of mobility. For instance, commuters regularly pursue the goal of getting to their workplace and returning to their home. Meanwhile, ordinary residents may participate in traffic to run errands such as to the grocery store. Another subgroup is seen in people who take part in traffic as a sheer leisure activity, to them, it sparks joy and relaxation (i.e. *going for a walk*, *going for a drive*).

Transport infrastructure Transport infrastructure refers to the stationary facilities of all forms which enable transport to come into existence (Ammoser and Hoppe 2006, pp. 23, 27, 28). Examples include, but are not limited to: carriageways, bicycle paths, pedestrian footpaths, car parks, traffic lights, bridges, and tunnels.

Trip A trip in the sense of transport planning is any continuous mobility by an individual with a set start and end point, and is not limited to a single mode of transport either. An intermodal trip is one where several different modes of transport were utilised in order to reach the destination.

Modal split Modal split refers to the relative amount of trips made using each mode of transport at any given reference date. Instead of the amount of trips, sometimes the amount of distance travelled is compared. The underlying data is usually obtained through interviews, and thus not always a comparable metric among individual regions or cities (Zukunft Mobilität 2018).

2.2. Literature research

In a first step, finding literature is quite simplistically achieved by querying pre-existing literature databases such as Google Scholar, ResearchGate, or Elsevier, as well as the university-provided engine TUfind using a string of keywords. Some examples of such keywords include `space allocation`, `space distribution`, or `road space urban area`.

The results found using this approach then need to undergo delicate filtering in order to reduce them to a more comprehensible amount which can be worked with. This filtering is done by investigating titles, subtitles, and abstracts. Also of importance in this step is the publishing entity (e.g. academic journal, institution).

Next, while reading some works in more detail, it comes to notice that there are authors whose contributions seem to be of major significance and who are cited quite frequently by other authors. Assuming that these authors' research specialises on the topic of road space allocation or similar, the aforementioned literature databases are then queried for their name in particular. In many cases, this leads to further relevant results.

Lastly, in close regard with the previous point, another method used while researching is the so-called *snowball method*. This well-tried method is implemented by consulting the references that the already found authors themselves are citing. In a sense, this method was also applied in an inverted way, such that papers which cite an interesting paper were consulted. Once again, these were determined with the help of literature databases.

2.3. Literature overview

A handful of authors have analysed cities or regions across Europe prior to this thesis. Though a reasonable amount of literature exists concerning the allocation of road space in general, Nello-Deakin (2019, p. 700) and Gössling et al. (2016, p. 661), however note that few academic papers have done explicit case studies and thus presented actual figures, which could be used to draw a meaningful comparison of space distribution present in different cities. The following section provides a review of literature, beginning with actual space distribution case studies and then proceeding with other related works on this topic.

2.3.1. Specific case studies on the distribution of space

Paris Colville-Andersen (2018), in contrast to the other papers which will be mentioned further down, is in its nature more geared towards popular culture, and thus criticised by Nello-Deakin (2019, p. 701) as a 'provocative piece of bicycle advocacy'. Said chapter in *Copenhagenize* anecdotally measures the fairness of space allocation at some intersections in Paris solely based off of aerial photographs, and subsequently counting the amount of vehicles, pedestrians, and bicyclists present at that point in time. Albeit the herein used method not being particularly rigorous, it does serve its purpose to an extent – to showcase the underlying issue of a disproportionate share of space being devoted to the car in urban areas, in this example Paris.

Berlin An earlier known example can be found in Agentur für clevere Städte (2014), which is a combined effort of an environmental protection agency and 20 students of a Berlin college. The authors realise that from 1998 to 2012, the share of bicycle traffic in Berlin has risen by 50 %. At the same time, they note, there is still a popular misconception that bicycles only amount to a negligible share of total traffic volume, and politicians are not taking action to improve bicycle culture. To strengthen their argument, students in groups have measured space distribution of near 200 streets on-site. Based on the aggregation of these findings, the Agentur concludes that 3 % of road space in Berlin is attributed to bicycle traffic and 58 % to parked and moving car traffic, while 15 % of trips are made by bicycle.

Freiburg Not much time later, Gössling et al. (2016) analyse the space distribution of four distinct neighbourhoods within the German city of Freiburg, which is widely regarded as one of the most bicycle-friendly cities in Germany, ranking 3rd in 2018 among cities with a population between 200.000 and 500.000 (Allgemeiner Deutscher Fahrrad-Club e. V. 2019, p. 2). Notwithstanding this pioneer status, the authors have still found that the share of trips made by bicycle and the share of space allocated to the bicycle cannot be considered proportionate (27 % and $\sim$ 4 %, respectively). To measure the space attributed to each transport mode, the authors processed satellite imagery by hand. Additionally, they remark that, at the time of their writing, 'there is a lack of research with a focus on actual space distribution in relation to transport mode use' (Gössling et al. 2016, p. 661), which is in line with findings of Nello-Deakin (2019, p. 700), and furthermore still applicable as of writing of the present thesis.

The Netherlands Also noteworthy at this point is Milieudefensie (2017), a case study by a Dutch environmental organisation, concluding the space distribution in 20 cities across the Netherlands. The authors make use of geographic information systems (GIS) to gather the relevant information about space distribution in these cities. Their results indicate that space allocated to bicycle infrastructure averages at about 21.5 %, while the share of space allocated to pedestrian traffic is at $\sim$ 57.8 % (among the topmost ten *districts* in each category, respectively (ibid., p. 13)).

Amsterdam Lastly, a recent paper in this field is Nello-Deakin (2019) itself. The author, a researcher at the University of Amsterdam, studies the space distribution in the Netherlands' capital and most populous city. According to their analysis, MIT and pedestrians have roughly the same space allocated to them, both being at $\sim$ 40 %, while 7 % of the available road space across the entire city of Amsterdam is claimed by bicyclists.

Conclusion Overall, current state of research involving case studies remains rather limited, with many of them bringing up the aspect of *fairness* of the road space distribution in their study area, in most cases as a direct result of how skewed space allocation is towards MIT; though this way of analytical conclusion does evoke criticism, as can be seen in Nello-Deakin (ibid.). Going further, these methods and their characteristics will be taken a closer look upon and discussed in greater detail in § 2.4, p. 10.

2.3.2. On space allocation in urban areas in general

In addition to the above literature which mainly focuses on observing space allocation within a specific area, i.e. a city, or in the case of Milieudefensie (2017) an entire country, also a number of academic articles have been published which elicit a broader, more general discussion.

Space allocation incorporating safety and construction cost

One fairly recent example of this can be found in Chen et al. (2020), in which the authors propose a statistical model to optimise road space allocation (in particular the width allocated to each mode) with respect to safety cost and agency cost, both of which being subject to minimisation. Safety cost, as proposed by Chen et al. (ibid.), refers to an estimate of monetary value assigned to human life and the costs which incur in consequence of a traffic accident, for instance. On the other hand, agency cost refers to the physical cost of constructing and maintaining road space. Several independent variables were taken into consideration, such as annual average daily traffic (AADT), traffic lane width, and footpath width among others.

Their results indicate that AADT is the main contributor of casualties – in pedestrians as well as in in-vehicle occupants. Furthermore, traffic lane width was found to bear a significant influence on the amount of accidents which involve pedestrian fatalities; while interestingly enough, this variable had no apparent effect on the number of in-vehicle occupant casualties. (§ 4.1 et seq., ibid.)

On another note, what may seem counterintuitive at first is their finding that an increase in footpath width correlates with an increase in pedestrian and in-vehicle occupant casualties. Though the authors elaborate that their model does not account for pedestrian volume, hence the footpath width possibly reflecting this missing quantity to an extent. Also they note that the more pedestrians are present, the more any given individual pedestrian is inclined to engage in reckless crossing. (§ 4.1 et seq., ibid.)

Chen et al. arrive at the conclusion that the optimal allocation of road space succumbs to these three major aspects:

1. Difference in construction and maintenance cost of paving materials, with pedestrian footpaths being much less expensive than asphalt used for streets

2. Prioritisation of safety cost versus agency cost, i.e. their relative weight

3. Total available width of any given road

In a stark contrast to the case studies discussed in the preceding subsection, Chen et al. do not take the bicycle as a major mode of transport into account, at all. Possibly this is omission was made due to the fact the city of Hong Kong is chosen herein as subject of study – a metropolis which in the past, just as in recent years, has not been perceived as particularly bicycle-friendly (Zhao 2012, p. 2; Tan and Martínez López 2018, p. 1).

Space-time as a more expressive quantity

A majorly different effort can be found in Will, Cornet and Munshi (2020), in which the authors propose to measure a conjunction of both space and time that any given mode consumes. It is argued that doing so allows for a more compelling comparison of transport modes, above all because this model imposes a hefty penalty on stationary traffic, as the product of space and time consumption is particularly high for parked cars.

As a result of an intricate analysis, the authors present that in the case of their study area of Rajkot City, India, investing more in non-motorised transport and public transport is more sustainable in the long term and can yield up to 20 times the space efficiency that MIT offers.

2.4. Comparison of methods in literature

As noted before, there exists a variety of methodology used in literature for the sole purpose of gathering and analysing space distribution related data of individual urban areas. In order to establish the foundation for a compelling analysis in this thesis, it is therefore imperative to set these methods side-by-side, alongside their respective advantages and shortcomings. The following discusses data acquisition methods and subsequently data evaluation methods which have proven to be the most prominent in previous research.

2.4.1. Data acquisition methods

The works presented in § 2.3.1, p. 6 have in common that their subject is a specific area. Naturally, the according data needs to be acquired first before it can be analysed. In this first step, there already cannot be determined one single methodology which all, or even a majority of authors tend to agree on.

As Agentur für clevere Städte (2014) is a collaborative effort, they apply a simple methodology where a group of two or three students measure widths of the street on-site using a rule. Arguably, this procedure is bound to have some level of gross inaccuracy as the difference in operation among the total of 20 students presents an observational error already. However, this type of error is alleviated in part because of their fairly large sample size and the weighted average they calculate (ibid., pp. 6, 7). This methodology, albeit being simple to apply, comes short when considering the amount of work that is expended, especially for a large-scale analysis such as Berlin. It can thus only be reasonably used within a large group of collaborating researchers.

Similarly, Gössling et al. (2016) also investigates street layouts on-site in their study area of Freiburg. However, these on-site visits only serve an auxiliary function in their work, while the principal data is acquired by means of manually analysing GIS data and satellite imagery. The authors however bring to attention that they 'only focused on four different city quarters, as the full digitalization of the whole city was beyond the scope of [their] project', indicating that this method also consumes its fair share of time (ibid., p. 662).

In their analysis of the Netherlands' largest 20 cities, Milieudefensie (2017) also make use of GIS data, though in a much more systematic approach. Their data is sourced from a database maintained by municipal and provincial administrations and contains specific information about the types of streets and their function in the form of GIS layers.[1] By conflating this with spatial data gained from dedicated software, the authors were able to determine the distribution of space per mode of transport (ibid., p. 7).

[1] Basis Grootschalige Topografie (BGT) is said to be 'the most detailed cartography of the Netherlands to date' (Nello-Deakin 2019, p. 702)

Akin to Milieudefensie (2017), Nello-Deakin (2019) also makes use of the same database in order to acquire street data of Amsterdam. Their data was then processed using software such as R.

In both cases, the authors' streamlined approach enabled their systematic analysis to cover a significantly larger area than their predecessors (Agentur für clevere Städte 2014; Gössling et al. 2016) did. Due to regional differences however, these kind of databases, as seen in the Netherlands, are not readily available everywhere.

2.4.2. Data evaluation methods

In a next step after acquiring the relevant data, it must be evaluated in such way that the results are meaningful and speak for themselves. Inevitably, this evaluation process is biased and depends on which point the individual author seeks to bring to attention. To some extent, a study's intended audience may also influence the way this data is presented.

Generally speaking, two major approaches are present in the existing literature. The share of space allocated to each mode can either be compared with its share of *distance travelled*, or with its share of *trips made*.[2] Either comparison will yield a vastly different result, as in any given area trips made and distance travelled are mostly not equivalent, by nature.

This disparity is illustrated in the following example, where share of pedestrian traffic (in Fig. 2.1) in Hesse is at a mere 3 % when the distance travelled by foot is being quantified. In contrast, when putting the amount of trips made into relation instead, this share rises to 24 %.

This goes to show that a quantification by trips made favours modes which are capable and conveniently suited for short trips, such as pedestrian traffic in the above example. As Nello-Deakin (2019, p. 706) also points out, a quantification by distance travelled instead favours modes which are capable of long-distance journeys in the first place (e.g. aggregated share of MIT taking up 75 % of the modal split by distance travelled).

[2] Irritatingly enough, both metrics are commonly referred to as *modal split*, though the latter metric appears to be the default when only *modal split* is mentioned. (cf. § 2.1 *Modal split*, p. 5)

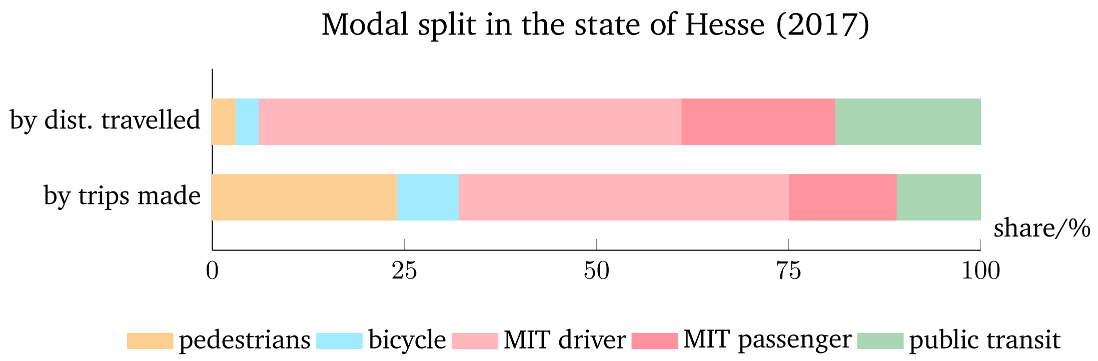


Fig. 2.1. *Difference in modal splits* [data: Brand et al. (2020, p. 39)]

Modal split as an underlying metric therefore can only be used for comparison within reasonable margin, and additional considerations need to be made when evaluating fairness of space allocation this way.

As indicated in § 2.3.2, p. 10, another very recent methodology developed by Will, Cornet and Munshi (2020) involves space-time as the literal product of space and time consumed by any mode. The main goal in this kind of analysis is to weight space consumption according to the span of time during which said space is occupied. Moreover, this weighted value accounts for the time intensity of parked cars, which play a substantial role in urban spaces.

3. Methodology

As prefaced in § 1 *Introduction* (p. 1), a cross-sectional case study on a select district within the city of Darmstadt will be subject to this thesis. This chapter aims to develop a comprehensive and conclusive methodology, which will be used throughout the case study. However the choice of the study area is reasoned first.

3.1. Area of study

The city of Darmstadt, as area of study in the present case study, was chosen for two major distinct reasons:

Firstly, the author resides here at the time of study and the overseeing university's facilities are also to a large part in the city's centre. Thus familiarity with Darmstadt's layout is at hand, while the general volume and climate of daily traffic in this city are well-known, as well.

Secondly, Darmstadt is one out of ten higher order settlements[3] in the state of Hesse (Hessische Landesregierung 2000). Therefore, especially its city centre is frequented by residents of surrounding smaller cities for various purposes, which results in traffic volume being above what Darmstadt itself would account for. Due to these circumstances, the city's streets are apt for the purpose of illustrating the underlying issue — which is scarcity of road space in urban areas.

[3] Christaller (1933) popularises the central place theory, wherein settlements of higher order provide goods and services (hospitals, higher education, entertainment, shopping) to circumjacent settlements of lower order.

3.1.1. Choice of Rheintor / Grafenstraße

Examining the centre of Darmstadt wholly, let alone all of its outer areas, steps beyond the scope of the present thesis. Consequently, it becomes necessary to determine a more specific subarea within Darmstadt for this case study to focus on.

In this decision, the choice of the statistical district[4] Rheintor / Grafenstraße (district `120` in Fig. 3.1) relies on several characteristics unique to this district. Foremost, this district is central to the city of Darmstadt and also serves as a direct connection between this city's major public square and transit hub Luisenplatz, and Darmstadt's main railway station (located in district `110` and district `250` in Fig. 3.1, respectively).

Perhaps because of its central location, the district itself offers many different sorts of services, too: restaurants, hotels, but also Darmstadt's clinic, to name some examples. This richness is also reflected in the different demographic groups that this district attracts. On a daily basis, locations in this district are many different people's destination.

In conclusion, Rheintor / Grafenstraße is particularly of interest and thus a prime study area thanks to its location in a macroscopic sense within Darmstadt, but also its own plurality in street types and usages of buildings. The demographic structure of this district holds some interesting properties, as will become clear in the following chapter.

3.1.2. Other districts

During the early phases of this thesis, a handful of other statistical districts were taken into consideration as candidates for a potential study area. Namely, these include Stadtzentrum (district `110`), and Martinsviertel (districts `220` and `230`, in Fig. 3.1). Wissenschaftsstadt Darmstadt (2020b) provides a comprehensive overview of boroughs and statistical districts located within Darmstadt proper.

[4] Statistical districts are used by municipal administration to partition a municipality into comprehensible districts. This aids collecting meaningful data for spatial planning, for example. Statistical districts also form the foundation for election districts, school districts, among other commonly encountered districts. While some statistical districts might coincide with colloquially known districts, Rheintor / Grafenstraße is not such.

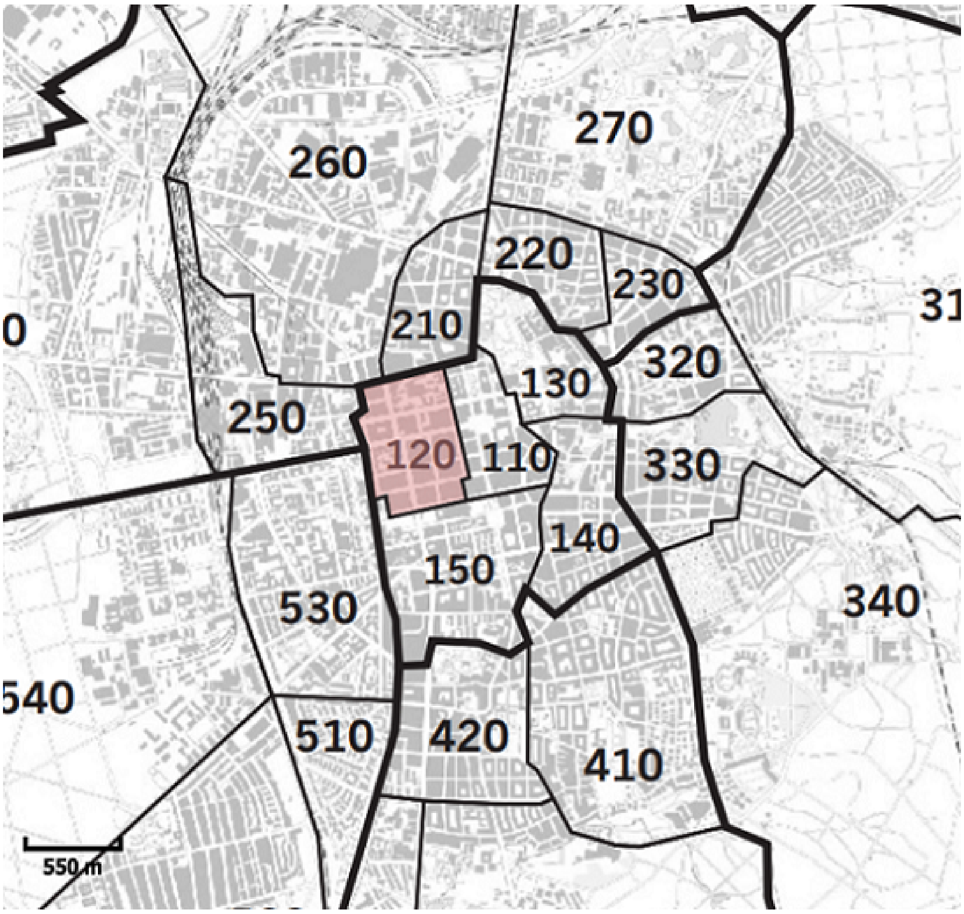


Fig. 3.1. *Location of Rheintor / Grafenstraße (district 120) in Darmstadt. North pointing map.* [map: Wissenschaftsstadt Darmstadt (2020b)]

However, after profound deliberation, these districts were disregarded with the main reason being that they do not offer the same breadth in street layout and building types that Rheintor / Grafenstraße does. Stadtzentrum, for example, consists to a large extent of pedestrian areas and shopping malls, with motorised traffic being relocated to several interconnected tunnels. Meanwhile Martinsviertel mostly comprises residential areas. In either case, the homogeneity is considered subpar in comparison to the diversity that Rheintor / Grafenstraße brings to the table.

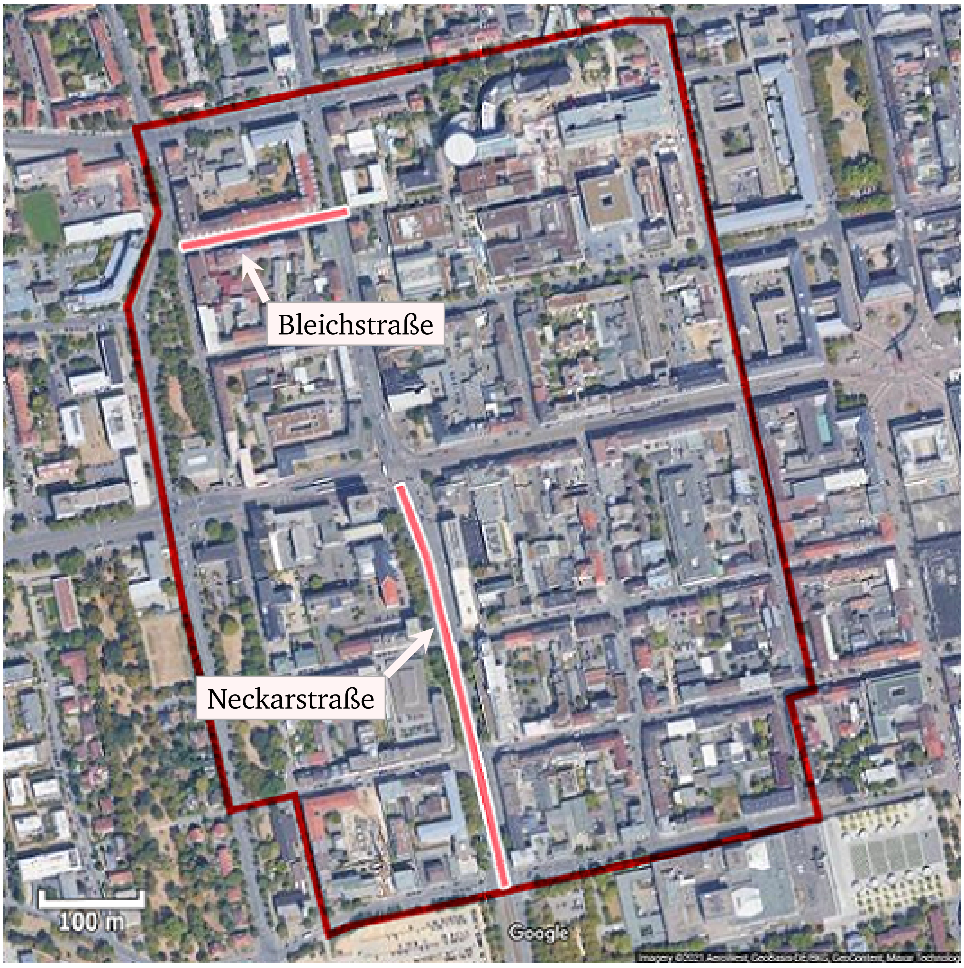


Fig. 3.2. *Location of sections of Bleichstraße and Neckarstraße in Rheintor / Grafenstraße. North pointing map.* [satellite imagery: Google Maps]

3.1.3. Bleichstraße and Neckarstraße

Specific sections of the two streets Bleichstraße and Neckarstraße (Fig. 3.2) are examined closer regarding their distribution of road space. The main motivation for choosing these is the availability of detailed maps (Wissenschaftsstadt Darmstadt 2020i,j,k), which allow for accurate results. Other streets would necessitate measuring with satellite imagery or conducting a tedious amount of on-site measurements.

The cross section of Neckarstraße is similar to that of Rheinstraße, both of which make up the two largest streets in the district. They both feature multiple carriageways with bidirectional tramway tracks in between.

The examined part of Bleichstraße is a rather small street where kerbside parking is legal. In that, it is similar to many other minor streets in the district.

3.2. Measurement

Measurements were carried out mainly using Photoshop®, which provides a ruler tool. Maps (Wissenschaftsstadt Darmstadt 2020i,j,k) were loaded into the program and then processed. Additionally, on-site visits with the purpose of completing and improving data were made.

3.2.1. Proof of concept

The following measurement of Darmstadt's Böllenfalltor soccer stadium serves as a proof of concept for this methodology. A standard soccer field, by rule, is 7140 m^2 in size, making this figure the 'optimal outcome' of the measurement process.
The scale of 20 m was determined to be 124.38 px in length. Next, the red area overlaid on top of the satellite image encompasses 272 978 px, which makes it equivalent to 7058 m^2.

The result deviates from the theoretical size of 7140 m^2 only by 1.1 %, proving this method to be highly accurate and reliable in this case. Appendix A describes this method further and includes more details to this example.

Limitations This method of measurement is dependent on the accuracy of the operator. Although the program does allow zooming in at a level where individual pixels can be seen clearly, it can still be ambiguous at which point the border needs to be drawn. The highest need for accuracy is in the initial step, which is to determine a unit length in pixels. For that, the scale can usually be understood as a well-defined unit length that is also easily measurable in pixels.

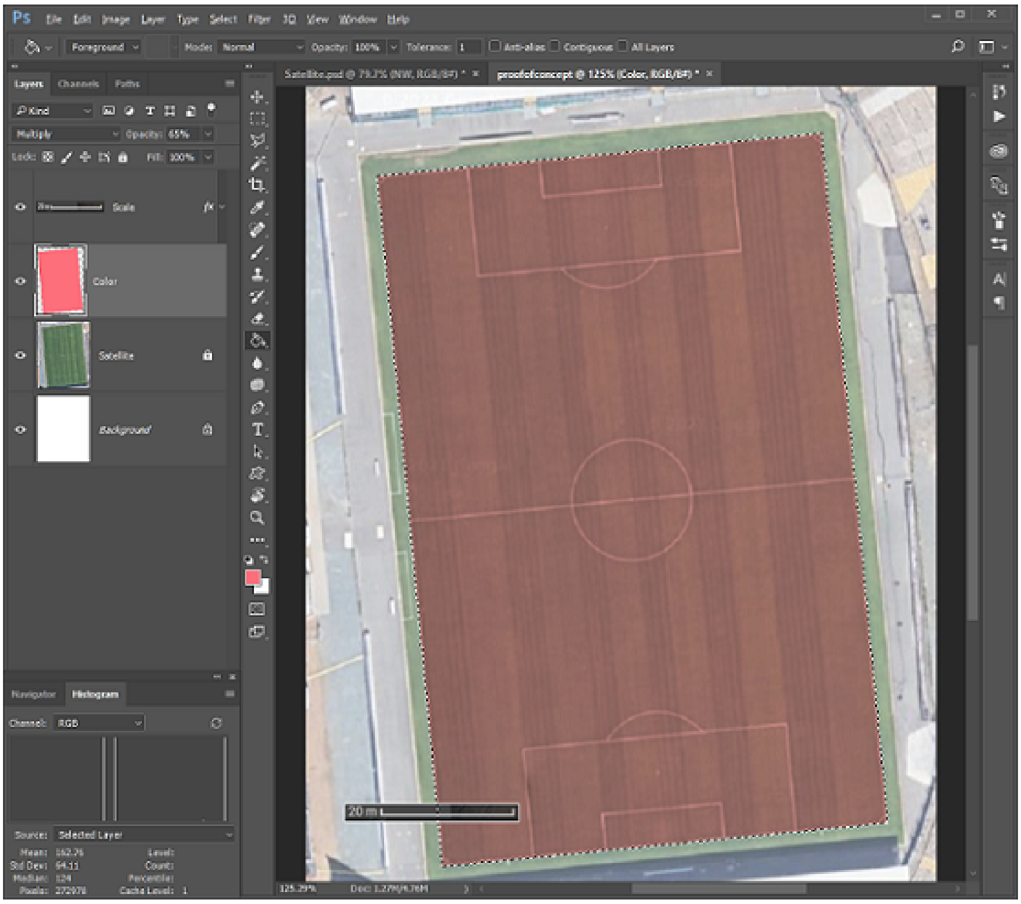


Fig. 3.3. *Proof of concept: Measurement of soccer field*

On-site visits On a few occasions, details in the maps were unclear or possibly outdated, and as such needed additional validation from on-site visits. For instance, during a visit a construction site marked in Wissenschaftsstadt Darmstadt (2020i) was found to no longer exist.

Visits were made in January and February 2021 during daytime. An ordinary commercially available folding rule of length 2 m was used to make measurements where necessary. Photos were taken with a DSLR camera to allow for reviewing later on.

(a) *Greenery between tracks*

(b) *Separator*

Fig. 3.4. *Categorisation of road space regarding public transit and bicycle space* [photos taken in February 2021]

3.2.2. Categorisation

For the purpose of this study, road space is categorised by the main mode of transport that occupies it, with respect to the direction of the street; such that at junctions, the cross traffic is not considered. Overall, this yields the following four main categories, which are similar to what Nello-Deakin (2019, p. 702) employs:

- **MIT** includes parking spaces
- **public transit** includes stops of public transit and greenery between tramway tracks (Fig. 3.4a)
- **bicycle** includes width of separation structures between bicycle paths and MIT carriageway (Fig. 3.4b)
- **pedestrian** includes greenery between pedestrian footpaths and bicycle or MIT area

4. Results

This chapter presents results in two regards. The allocation of road space in Bleichstraße and Neckarstraße is discussed first, before moving onto an analysis of the district's demographics and what's important to each subgroup, which comprises § 4.2, p. 27.

4.1. Space allocation

It must be duly noted that the following measurements were made during an ongoing trial project, which started in August 2020 (Wissenschaftsstadt Darmstadt 2021).

In the case of Bleichstraße, the bicycle path has been coloured and a separator has been put in place (cf. Fig. 3.4b) to deter vehicles from stopping there, which previously had led to bicycles being forced to dodge onto the carriageway (ibid.). The added structural separator aims to eliminate such endangering situations in the future.

For Neckarstraße, the outer of two carriageway lanes in each direction has been repurposed to serve bicycle traffic exclusively (cf. 1 in Fig. 4.1), also with a separator similar to Bleichstraße. Consequently, the previous bicycle paths now extend the pedestrian footpath (cf. 2 in Fig. 4.1 and Fig. 4.2).

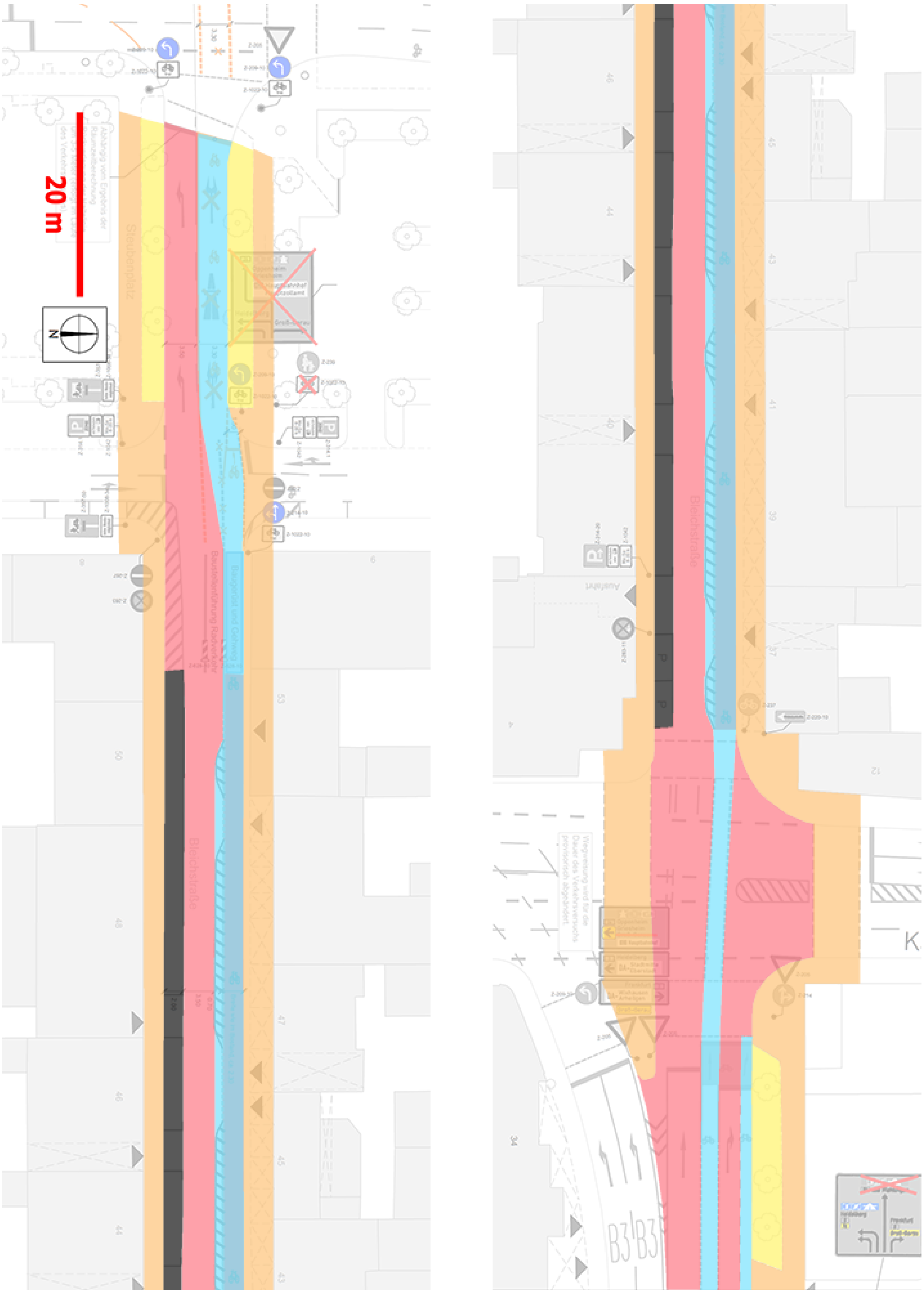
Results presented in this section therefore predominantly reflect the space allocation *during* these traffic trials. Whether they will be implemented permanently remains unknown at this time. The city administration is closely observing the effects of these trials and plans to make a decision in summer 2021 (ibid.).

Space allocation in Bleichstraße and Neckarstraße are quite dissimilar due to the physical size of both streets. The former only has one carriageway serving traffic westwards and no tramway tracks running parallel to the street.

Fig. 4.1. *New allocation of space* [photo taken in February 2021]

Fig. 4.2. *Former bicycle path now for pedestrian use* [photo taken in February 2021]

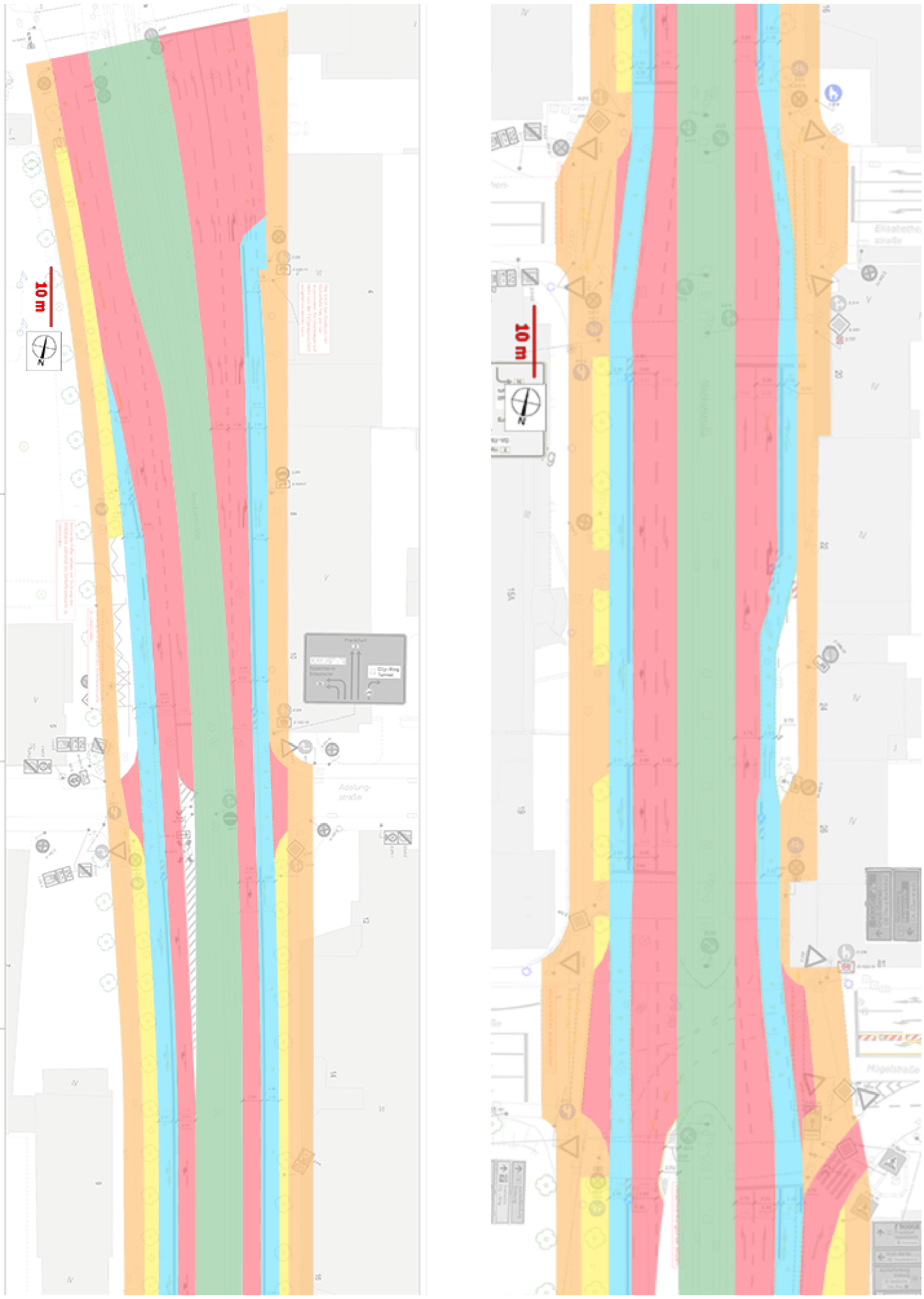
Bleichstraße In Bleichstraße, 39 % of road space is allocated to MIT, either in parking or moving form. Pedestrian footpath (37 % excluding greenery) is present on both sides of the street, and its width ranges from 2.2 m in the southeast, prior to the junction with Kasinostraße, to 3 m on the opposite side, in the northeast. Overall, the measured pedestrian area might be slightly inflated due to the way pedestrian crossings at the junction are measured, where the full width of the crossing controlled by the traffic light is taken into account (cf. junction in Fig. 4.3b). During the traffic trial, the right turning lane in the west has been reallocated for bicycle traffic, disallowing MIT to turn right (westernmost junction in Fig. 4.3a). In total, this currently puts bicycle space at 18 %.



(a) *West half*

(b) *East half*

Fig. 4.3. *Space allocation in Bleichstraße from Kasinostraße westwards to Steubenplatz* [cf. Fig. 4.5 for legend, map: Wissenschaftsstadt Darmstadt (2020i)]



(a) *North half* **(b)** *South half*

Fig. 4.4. *Space allocation in Neckarstraße from Rheinstraße southwards to Hügelstraße* [cf. Fig. 4.5 for legend, map: Wissenschaftsstadt Darmstadt (2020j,k)]

●MIT
●MIT / parking
●Public transit
●Bicycle
●Pedestrian
●Pedestrian / greenery

Fig. 4.5. *Legend to Fig. 4.3, Fig. 4.4, and Fig. 4.6*

Table 4.1. *Space distribution in Bleichstraße and Neckarstraße*

	Bleichstraße		Neckarstraße	
Mode	m^2	%	m^2	%
MIT	1333	33	4694	33
MIT / parking	251	6	–	–
Public transit	–	–	3333	23
Bicycle	715	18	2241	16
Pedestrian	1484	37	3344	23
Pedestrian / greenery	234	6	735	5
$\sum$	4016	100	14 347	100

Neckarstraße Interestingly, MIT also takes a third (33 %) of road space in Neckarstraße, just as in Bleichstraße. Difference being that Neckarstraße has no additional share of space intended for on-street parking, the whole width of the street is used for moving traffic. About a quarter of space (23 %) is allocated to public transit and pedestrians each. Tramway tracks are present in the middle of the street, between each direction's motor carriageway. Additionally, there is a small patch of greenery between each tramway track (cf. Fig. 3.4a). Pedestrian footpaths exist on both sides of the street, at times there is greenery separating it from the (now) bicycle path (previously motor carriageway). Bicycle paths, during the trial, are generally the same width as the neighbouring motor carriageway; however their share (16 %) is only about half of the share of MIT since bicycles do not have dedicated turning lanes.

Table 4.1 gives an overview of these results and compares both streets.

Estimate Since the space for the bicycle paths is essentially borrowed from former motor carriageways, it is not difficult to make an estimate regarding the original space distribution, which can help gauge the effects a permanent implementation of these changes could have.

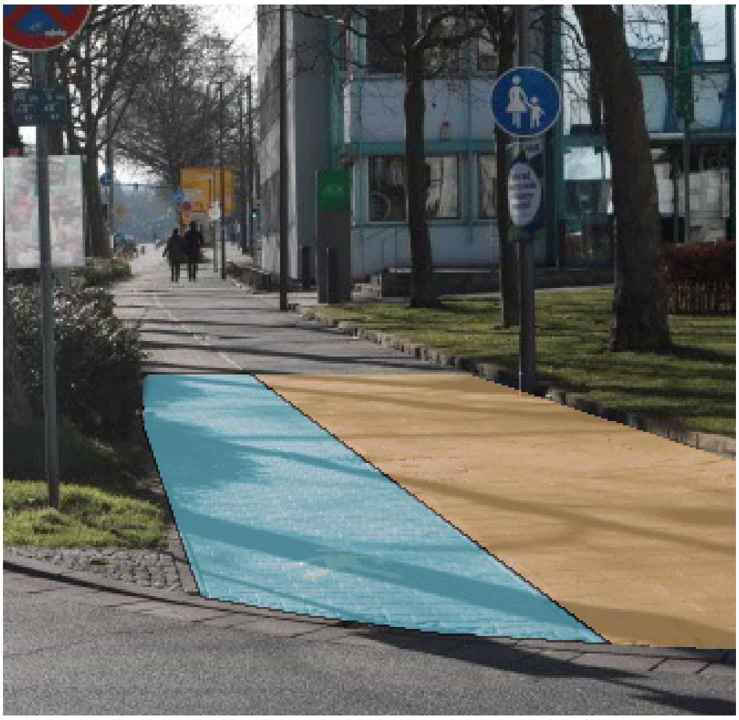


Fig. 4.6. *Bicycle and pedestrian space prior to the traffic trial*
[cf. Fig. 4.5 for legend, photo taken in February 2021]

For that, the entire area of bicycles is added 'back' onto that of MIT. Then, the current space of pedestrians is split in a 60/40 manner between pedestrians and bicycles. Based on observations made during on-site visits, this proportion roughly reflects the circumstances from before the traffic trial (Fig. 4.6).

The result of this estimate is presented in Table 4.2. Most notably, the share of MIT was 15 percentage points higher, at 48 %; making almost half of all available road space belong to MIT. At the same time, bicycle and pedestrian traffic were cramped in close proximity of each other, their share of space being 9 % and 14 % at the time, respectively.

Table 4.2. *Estimated space distribution in Neckarstraße prior to trial project*

	Neckarstraße est.	
Mode	m^2	%
MIT	6935	48
MIT / parking	–	–
Public transit	3333	23
Bicycle	1338	9
Pedestrian	2006	14
Pedestrian / greenery	735	5
$\sum$	14 347	100

Fig. 4.7 visualises this reallocation, with the diagram itself acting as an equivalent to the various lanes of traffic, in a way. It becomes clear how narrow the bicycle path and pedestrian footpath had previously been. To some extent, it can be seen how MIT carriageway consisted of three lanes, of which one is now devoted to bicycle traffic.

4.2. Modes of transport

§ 1 *Introduction* (p. 1) mentioned a fictitious cyclist and car driver, demonstrating how interests pursued by these two differ by a large margin and can even form a conflict of interest. As described before, these groups however are only two out of many.

In the following, this section aims to explore which groups contribute to the socio-demographic structure in Rheintor / Grafenstraße, which interests are of particular importance to each group and how these groups interrelate. This is done by glancing over different modes of transport in general and then discussing how their situation plays out in Rheintor / Grafenstraße each.

Since data specific to this district is oftentimes not available and cannot be reasonably obtained, it becomes necessary to extrapolate from other data, such as regional or state-wide statistics. It must also be kept in mind that Darmstadt

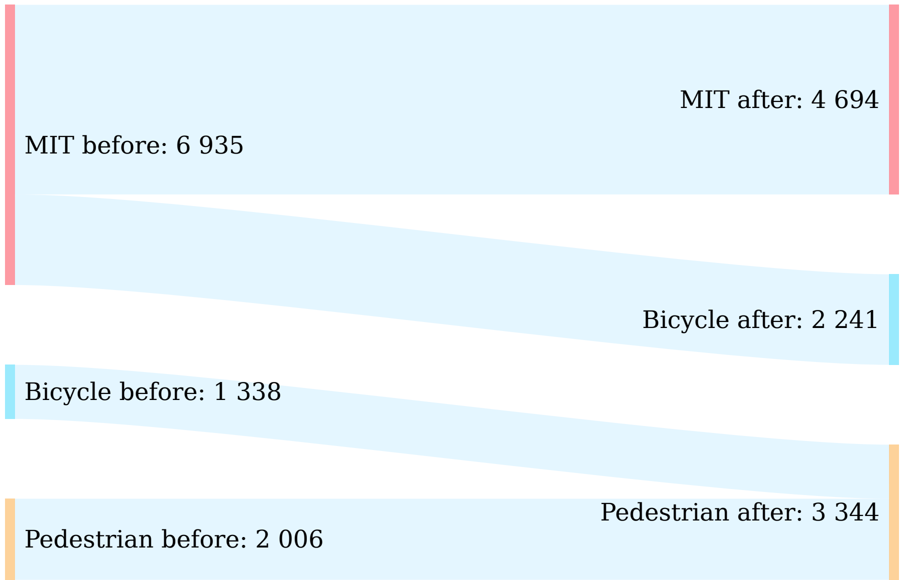


Fig. 4.7. *Reallocation of space during the traffic trial, based on estimates from Table 4.2.* [Not pictured are public transit and pedestrian greenery, as those did not change. Numbers in m^2.]

experiences a significant load of through-traffic (Gerike et al. 2020, pp. 103–126). However investigating population statistics still enables some initial insight into this district's traffic situation.

4.2.1. Motorised individual transport

To get a better understanding of the interests pursued by car drivers, it is vital to grasp what exactly motivates people to make that executive decision of owning and contingently driving a car, and which kind of people do so in particular.

Composition of motorists

A factor previous research has explored and quantitatively analysed is the link between household size and car ownership. In this matter, Jiang et al. (2017, pp. 528, 529) and Kwan, Sutan and Hashim (2018, p. 322) find that larger households, such as ones with children for instance, tend to utilise the private car rather than relying on other modes of transport.

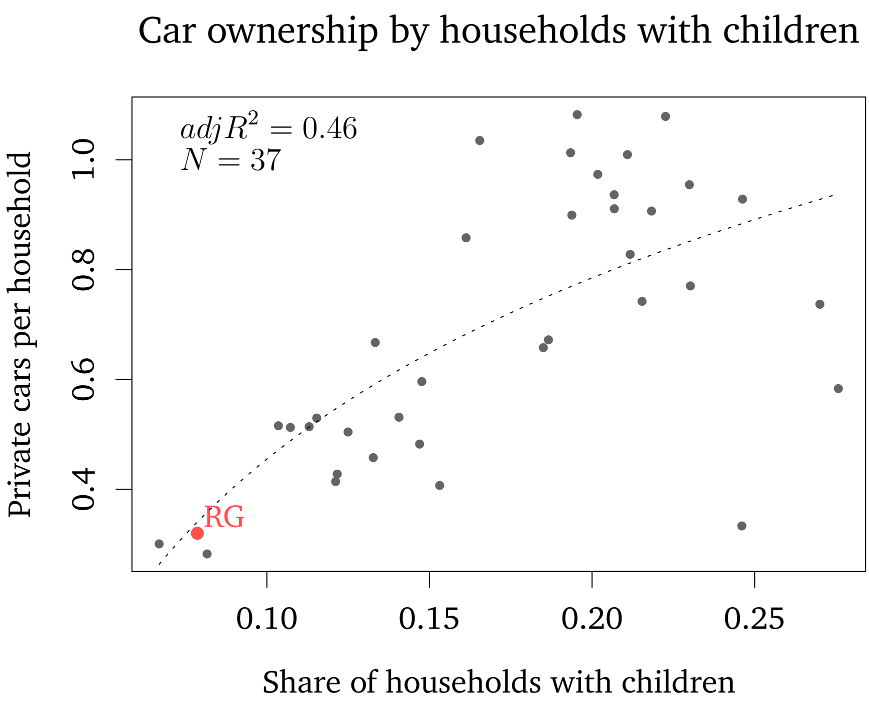


Fig. 4.8. *Private cars per household compared to the prevalence of households with children. Each dot represents a statistical district* $(N = 37)$.
[data: Wissenschaftsstadt Darmstadt (2020a,f)]

The following pages seek to investigate this relationship and discuss to which extent it exists in Rheintor / Grafenstraße. One may apply a linear regression model of the form

$$\text{cars}_i = \beta_0 + \beta_1 \cdot \log(\text{children}_i) + u_i,$$

where cars_i and children_i describe the private vehicles per household and the share of households with children in the ith district. The result of this regression (Fig. 4.8) reveals a strong positive correlation $(r = 0.69)$ between both variables, confirming that findings from previous studies also hold true in the case of Darmstadt's districts.[5] Taking a closer look, residents of Rheintor / Grafenstraße (RG in Fig. 4.8) are also much less likely to take on car ownership than most of the rest of Darmstadt. As expected, this observation coincides with the share of households with children in said district, which is Darmstadt's second-lowest at 7.87 %.

[5] Cf. Code B.2 for the detailed result.

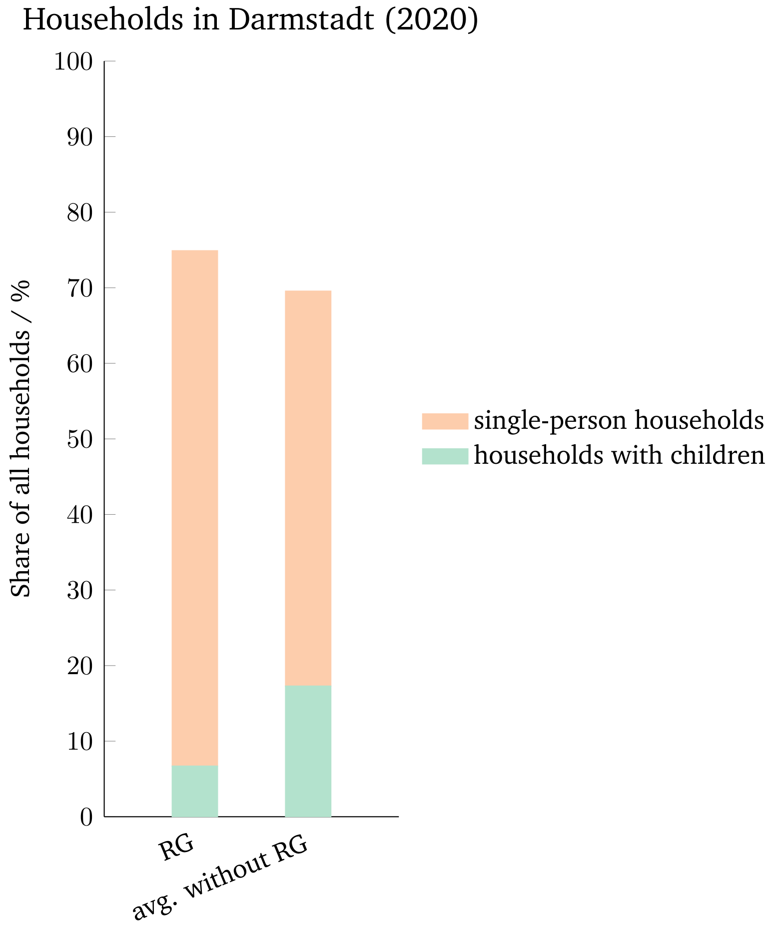


Fig. 4.9. *Comparing households in the district of Rheintor / Grafenstraße (RG) and Darmstadt's average without RG.* [Values missing to 100 % are households with two or more persons without children. Assuming no child forms a single-person household alone. data: Wissenschaftsstadt Darmstadt (2020e,f).]

Diverting attention to Fig. 4.9, one might, again, notice the few households with children (reiterated as); however, the graph also reveals the large share of single-person households () in this district. In both of these metrics, Rheintor / Grafenstraße is surpassed only by a single other district – its neighbouring one of Stadtmitte (cf. district 110 in Fig. 3.1), which has less households with children and more single-person households, relatively speaking (Wissenschaftsstadt Darmstadt 2020e).

Overall, the low share in private vehicles might be a consequence of Rheintor / Grafenstraße attracting a certain kind of residents. Persons who choose to reside in this part of the city might be ones pursuing work or a lifestyle which requires

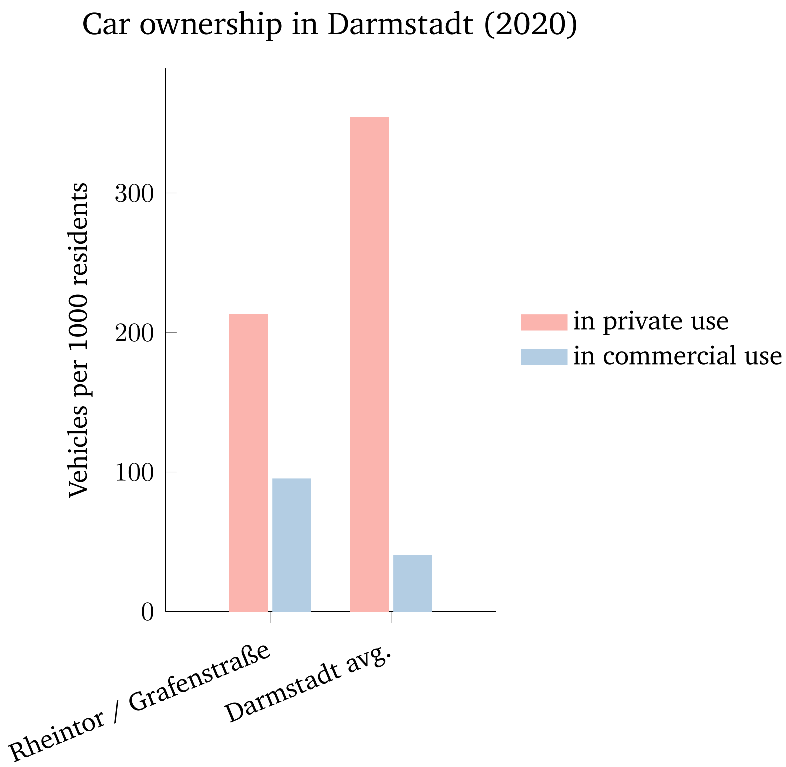


Fig. 4.10. *Private and commercial vehicle density in Rheintor / Grafenstraße and Darmstadt.* Average *of cars in both private and commercial use refers to the statistically robust median value.* [data: Wissenschaftsstadt Darmstadt (2020a,e)]

them to have little to no travel time to the city centre. Hence, they do not rely on private car ownership to supplement their daily mobility. Another plausible reason is that the rather high cost associated with vehicle ownership in such a central area burdens residents too much financially. With parking space being rare in the city, rental garages might not be a desirable option for everyone.

At the same time, analysing data from Wissenschaftsstadt Darmstadt (2020a,e) also suggests that a high percentage of vehicles in Rheintor / Grafenstraße is used commercially. In this context, both commercially registered auto vehicles and mid-size transporters are regarded as serving a commercial use. Across all 37 statistical districts of Darmstadt, there are on average[6] 40 commercially used vehicles per 1000 residents registered, while Rheintor / Grafenstraße records 95 per 1000 residents (in Fig. 4.10).

[6] Median average, cf. caption of Fig. 4.10

Motorists' needs

Getting an understanding of which groups of people contribute to demographic variety is an important step towards formulating each subgroup's specific needs.

On a much smaller scale than what Darmstadt's average might suggest, there might be persons who sustain a larger family and thus prefer mobility by car over public transit. As Kwan, Sutan and Hashim (2018, p. 322) point out, having children naturally raises the need for recreational journeys to farther locations, for which the private car is the preferred choice of transport mode in most cases (ibid., p. 322). Those same households could also utilise their car to run errands, as grocery shopping behaviour takes on a drastically different form than what would be the case for an alone-living person. Presumably, they are interested in their children experiencing a safe space when venturing outside and being able to stroll the streets without having the parents worried. Their own car ownership certainly contributes to traffic, however it can be argued that they drive out of necessity, to complete activities discussed above.

In summary, the majority of households in Rheintor / Grafenstraße consist of only a single person likely to utilise the many options for public transit available to them. Now making an educated guess and revisiting the regression from earlier, these single persons are not the main contributors to private car ownership in this district. Following that logic, albeit representing a small share, owners of private cars in Rheintor / Grafenstraße might be mostly families of two or more persons, especially ones with children. In those cases, allowing their children to grow up in a safe environment is their main stake.

Furthermore, the amount of commercially registered cars and mid-size transporters per 1000 residents is more than twice as high in Rheintor / Grafenstraße as the average of Darmstadt. This might be because of the many storefronts which can be found in the southeast of the district. Merchants rely on vehicles to transport goods from outside the district or to reach out to their clients and customers. Hence, their main concern might be spending as little time as possible in traffic, as any congestion or waiting encountered directly translates into a loss of resources.

Lastly, Rheintor / Grafenstraße entails some sections of *Bundesstraßen*, which are roads of national importance interconnecting localities all over Germany.

- B 3: Neckarstraße (N $\leftrightarrow$ S)
- B 26: Rheinstraße (W $\rightarrow$ E) / Bleichstraße (W $\leftarrow$ E)

Given the role these roads play not only in the local transport grid but also on a regional and national scale, it can be assumed that a sizeable share of motorised traffic there is represented by through-traffic and in no way related to the demographic of this district. Gerike et al. (2020) at least confirm that this is the case for Darmstadt as a whole.

4.2.2. Bicycle

Bicycling as a physical activity intrinsically attracts a wholly different demographic than MIT does. Data shows that no discernible difference in the relative size of the bicycling population exists across different grades of urbanisation. Meaning $\sim$ 59 % of residents rides in large cities (Frankfurt am Main, Wiesbaden, also Darmstadt and others), just as is the case in rural areas (Brand et al. 2020, p. 51). However, frequency of bicycling varies a lot. In large cities, 17 % of residents ride daily, while only 7 % do so in the most rural category. The highest share of daily cyclists, 23 %, is found in Frankfurt (ibid., p. 51).

Age is one of the most significant factors which influences bicycle usage patterns (Pucher and Buehler 2008a, p. 8). Brand et al. (2020, pp. 50–52) find that, in Hesse, bicycling is most common among persons aged 14 – 17 years. According to their research, 48 % of all teenagers in this age group indicate that they ride once a week or more often. In contrast, only about a fifth ($\sim$ 21 %) claim to ride never or near never. This share of non-users increases starting from persons aged 50 years upwards, and reaches its apex in the last age group, containing elderly persons of 75 years or older.

Further findings from Brand et al. (2020, p. 68) include a dependency of bicycle usage on income in Hesse: higher income households ride more than lower income ones. However other research suggests that this might not be the case everywhere. For instance, Pucher and Buehler (2008a, p. 8) note that income has near no influence on bicycling in Denmark and the Netherlands.

Reasons to bicycle

A major difference to MIT which cannot be overseen in this regard is that the bicycle is a so-called *active* mode of transport, meaning that travelling by bicycle requires significant physical effort. As such, bicycling inadvertently has a positive effect on health.

Likewise, bicycling creates no inherent pollution and thus does not pose a burden on the environment. Quite on the contrary, cyclists often find themselves in a situation where they are exposed to the pollution created by motorised traffic (Gössling 2020, p. 446). Barring this fact, paying an ever so small contribution to environmental protection might still be a motivating factor to some.

In practice however, these health and environmental benefits are frequently not the main point of consideration for cyclists (van Exel, de Graaf and Rietveld 2011, p. 395). Instead, the higher speed at which destinations within a city are reached is a main motivator to them (Tranter 2012, p. 57; Nello-Deakin and Nikolaeva 2020, p. 9). Additionally, Tranter (2012) focuses on *effective speed*, which refers to the time saved indirectly in terms of labour. They argue that, through bicycling, one spends less time at work earning money for car maintenance.

Situation in Rheintor / Grafenstraße

Purchasing, possessing, and use of a bicycle is in no way as regulated as is the case for motorised vehicles. Consequently, the city of Darmstadt does not issue detailed bicycle statistics on a per-district basis or much at all; any analysis and conclusions made here can only be of tentative nature.

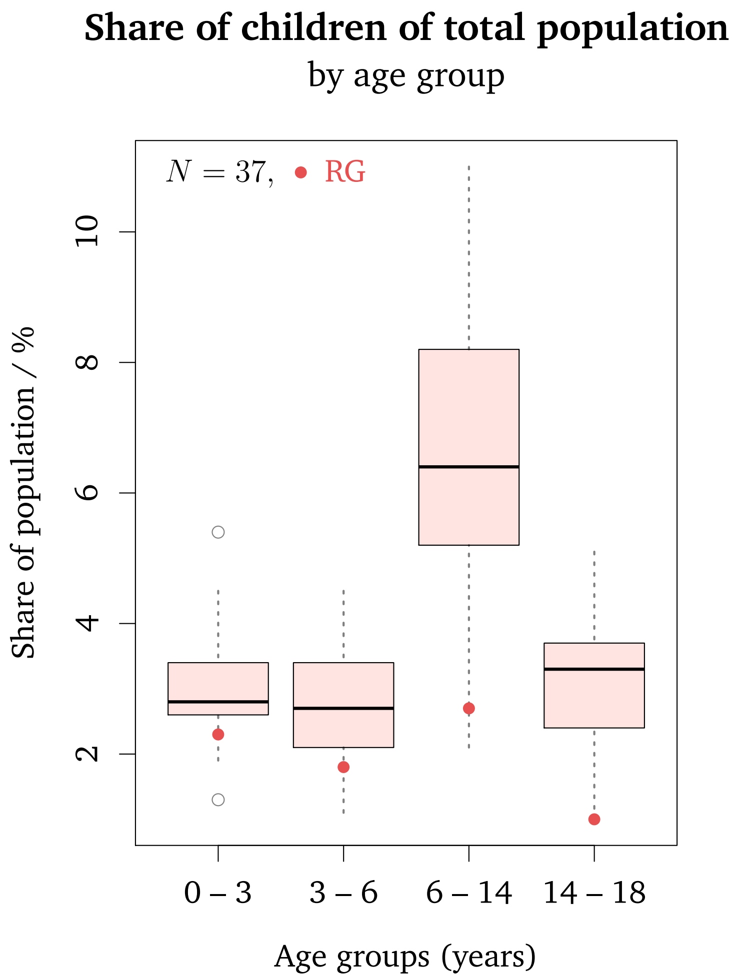


Fig. 4.11. *Share of children of total population by age group in Darmstadt's statistical districts in 2020. Rheintor / Grafenstraße emphasised in red.*
[data: Wissenschaftsstadt Darmstadt (2020l)]

As established before, age bears a significant influence on bicycle usage and teenagers between 14 and 17 years of age ride their bicycle the most. The following seeks to discuss the situation of bicycle culture in the case of Rheintor / Grafenstraße. Fig. 4.11 illustrates the distribution of children's age groups in Darmstadt. What has been a point of discourse in § 4.2.1, p. 28 further manifests itself here — not only does Rheintor / Grafenstraße have few children, moreover this district also has the lowest share of children aged 14 – 18, out of all statistical districts in Darmstadt.[7] This suggests that bicycle usage is considerably lower among residents of Rheintor / Grafenstraße in comparison to other districts.

Nonetheless, the presumably little bicycle usage in this district must not be misunderstood as bicycle traffic being of lesser importance than other transport modes. In fact, moving towards a more sustainable city, bicycling and its infrastructure are undeniably important and need to be expanded upon where necessary.

Additionally, Rheintor / Grafenstraße does not only contain motorised through-traffic, but likely also other forms of it, such as bicycle through-traffic. Thus, a low percentage of bicycle ownership and usage in this district might not be directly translatable into an overall low presence of bicycle traffic. Direct stakeholders regarding bicycle infrastructure are therefore not only residents of this district but also any other person passing through Rheintor / Grafenstraße. Due to its geographic location, one would err to think of the volume of such traffic as negligible.

Cyclists' needs

As noted before, a person's safety and their perception of safety while in midst of traffic is substantial to their decision regarding whether to bicycle regularly (Gössling 2013, p. 204; Jacobsen and Rutter 2012, p. 151). Additionally, academic literature has often come to the conclusion that concerns regarding safety are especially prominent among women and children (Pucher and Buehler 2008a; Garrard, Handy and Dill 2012; McDonald 2012). In comparison to the rest of Darmstadt, women and children are certainly underrepresented in the population of Rheintor / Grafenstraße (Wissenschaftsstadt Darmstadt 2020h,l). However, it is still important to consider cyclists' needs in this district, as many of them come from outside and pass through.

An effective way to ensure safety of cyclists is to separate the bicycle path from motorcar carriageway (Pucher and Buehler 2008b, p. 511). This is best done with the help of structural features instead of only a coloured marking (Pucher, Dill and

[7] Statistics in Brand et al. (2020) and Wissenschaftsstadt Darmstadt (2020l) differ in their definition of age groups. '14 – 17' and '14 – 18' are the closest equivalents.

Handy 2010, p. 107). In the case of Rheintor / Grafenstraße, such measures are experimented with at the time of writing and might see permanent implementation within the foreseeable future (Wissenschaftsstadt Darmstadt 2021).

4.2.3. Public transit

In any moderately large city, as is Darmstadt, public transit is an important mode of transport. Contrary to a private car, it has no acquisition costs or recurring maintenance fees, but instead features a ticket with a variable price. It comes short when needing to transport heavier or more sizeable goods, and of course does not provide the same level of privacy that a car does. Another disadvantage is the fact that public transit is constricted to the predetermined stops. In most cases, this means that public transit is unable to reach one's destination as closely as MIT or bicycles do.

Needless to say, popularity of public transit is only high where public transit exists in the first place. On a daily basis, residents of large cities utilise public transit more than eight times as much as rural residents (Brand et al. 2020, p. 49). Further, Brand et al. (ibid.) find that public transit usage declines steadily with age. Their data shows no apparent difference between male and female respondents' usage of public transit.

Stops in Rheintor / Grafenstraße

The district itself contains only three stops, of which two are at the boundary, as illustrated in Fig. 4.12. However, these stops are frequented by a multitude of different bus and tram lines. The stop Rhein- / Neckarstraße for instance is part of the route of 12 unique bus and tram lines, irrespective of direction of travel (Darmstadt-Dieburger Nahverkehrsorganisation 2020). All of these also halt at Luisenplatz immediately before or after, which acts as a central hub to Darmstadt's public transit grid; and 12 buses and trams stop in Kasinostraße. Interestingly,

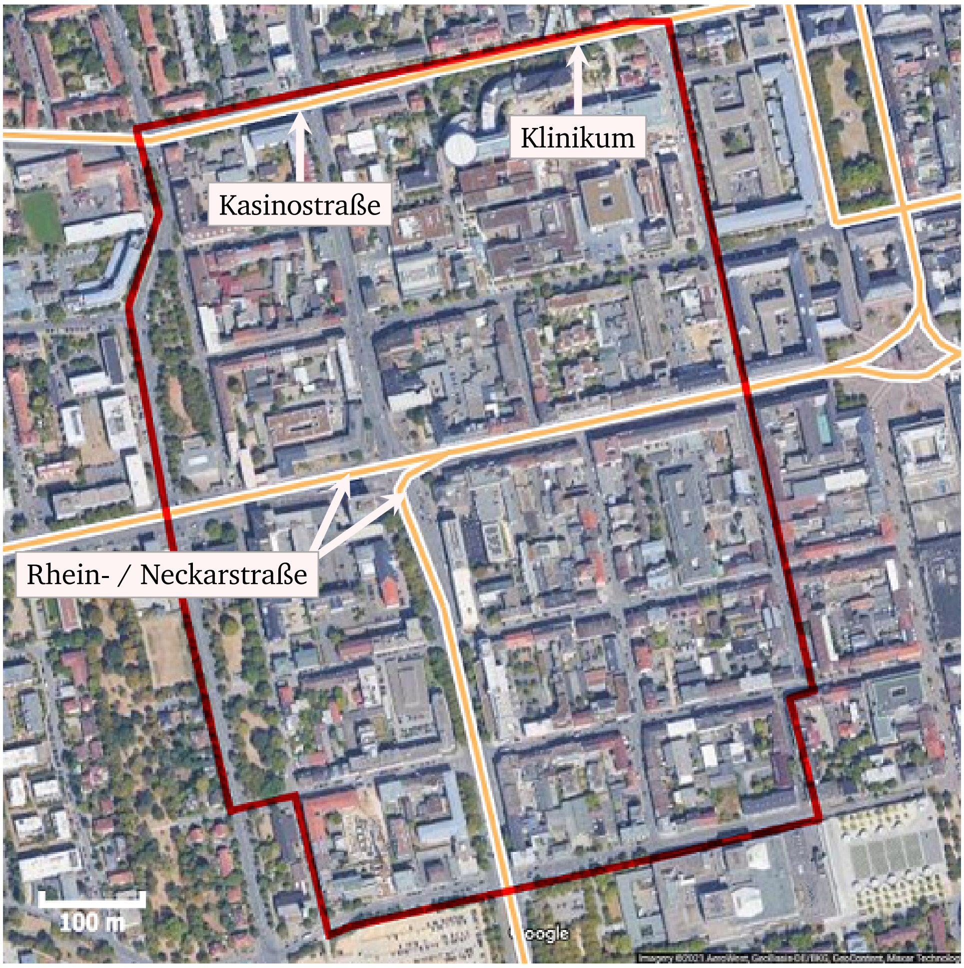


Fig. 4.12. *Stops of public transit in Rheintor / Grafenstraße. Orange lines indicate routes of at least one bus or tram. North pointing map.*
[data: Darmstadt-Dieburger Nahverkehrsorganisation (2020), satellite imagery: Google Maps]

while being right in-between Kasinostraße and another major stop, Klinikum gets skipped by the majority of bus lines and only one tram and one other bus stop there (Darmstadt-Dieburger Nahverkehrsorganisation 2020).

Residents of Rheintor / Grafenstraße

The availability and connectedness of public transit stops affects residents and their mobility. As established earlier, private car as well as bicycle ownership are low in this district. It follows that the share of pedestrian traffic and public transit usage must be higher than average among Rheintor / Grafenstraße's residents, which makes sense given how easily accessible stops of public transit are; even from the furthest point it takes no more than ten minutes to reach Rhein- / Neckarstraße by foot at a normal pace.

Needs of public transit

When discussing needs associated with public transit, a distinction must be made. For one, needs of passengers refer to the demands that individuals have, i.e. factors driving them to utilise public transit. In other words – aspects of the current situation deterring them from doing so and which changes could be made to improve the situation.

Accessibility is one of the main concerns of potential adopters of public transit. Having a public transit stop within short walking reach decreases odds of car ownership (Keller and Vance 2013, p. 255) and thus is likely to increase public transit usage. In the case of virtually all residents of Rheintor / Grafenstraße, one or more stops can be reached easily.

In addition, Tao, Fu and Comber (2019, p. 841) determine reliability, frequency, and cost to be of major interest to bus commuters. These aspects are likely to be transferable to passengers in general. No statement regarding reliability of public transit in Rheintor / Grafenstraße can be made with the available data. The frequency at which buses and trams arrive is rather high, especially at Rhein- / Neckarstraße and Kasinostraße. Lastly, cost of service cannot be evaluated adequately without engaging in more profound analysis. However, there are definitely voices advocating for less expensive transit.

Next, what is also of importance are needs that arise from the operation and maintenance of public transit. Those are particularly of interest to transit companies which administer public transit and oversee its operation.

From a certain standpoint, some needs of passengers are direct equivalents of the goals set forth by transit companies. For example, customers demand reliability and transit companies aim to provide that. More precisely, punctuality of buses and trams might be of interest because it is reflected strongly in an individual's perception of transit quality, and impacts their personal likelihood of habitual participation in public transit. Punctuality can be improved by having transit vehicles use dedicated transit lanes, which normal motor vehicles are prohibited from using. This method is being employed in many places in Darmstadt, also along Rheinstraße and Neckarstraße, where tram tracks in the centre of the street serve tram and bus only.

4.2.4. Pedestrians

Pedestrian traffic is similar to bicycle traffic as both implicate a physical activity and are thus described as active travel. At the same time, walking is different from other modes of transport as it requires no additional equipment or investment. To the abled population, walking is therefore the single most formless way of mobility, which regularly makes it the mode of choice for nearby destinations.

Further findings from Brand et al. (2020) include a stark tendency of the young (< 18 years) and the old (> 64 years) to walk daily. Also, among regularly walking persons, female respondents have indicated to walk more frequently than their male counterparts.

Similar to cyclists, pedestrians are also exposed to air pollution, which might be a disincentive to some extent (Gössling et al. 2016, p. 674).

Link to public transit

Public transit is intimately tied to pedestrian traffic and both are often combined especially within a city. Intermodal trips regularly begin and end with walks to and from public transit stops. In that sense, especially public transit in cities can be understood as a supplement to walking and extends mobility to destinations otherwise out of walking range (Zacharias 2020, p. 454).

Pedestrians in Rheintor / Grafenstraße

Within the study area, pedestrian footpaths are provided on all streets which facilitate walking. In support of pedestrian safety, major intersections feature traffic lights catered to pedestrians, minimising the risk when crossing roads. Nonetheless unsafe traversing, otherwise known as jaywalking, still occurs and happens even more likely in situations where a group of pedestrians is present (Will, Cornet and Munshi 2020, p. 227). Though the tram and bus stop Rhein- / Neckarstraße provides traffic lights, its position in the centre of the road might still cause disembarking passengers or passengers in need of catching a tram or bus to jaywalk.

In addition to usual footpaths at the side roads, there are parts in the southeast directly bordering pedestrian zones in Stadtmitte (district 110). Therefore, some share of pedestrian traffic might originate from these areas. Based on analyses and assumptions from § 4.2.1, p. 28 and § 4.2.2, p. 33, car and bicycle usage are underrepresented among the population of Rheintor / Grafenstraße, consequently putting pedestrian traffic more into focus. In fact, Brand et al. (2020, p. 52) find that residents in a city walk much more frequently than rural residents. They remark that this happens likely because daily destinations such as grocery stores are more within reach in urban areas.

Needs of pedestrians

A primary concern regarding pedestrian traffic is safety. Second only to car occupants, pedestrians form the largest group of road casualties (European Commission 2018, p. 40), however these accidents are preventable when given attention and action of policy-makers (World Health Organisation 2013, p. 5). Chen et al. (2020, p. 227) conclude that pedestrian safety can be improved by widening carriageway widths to a certain limit, which supposedly acts as a buffer between vehicle and pedestrian traffic. Similarly, Aljoufie and Tiwari (2021, p. 12) state that a lack of separation has an increasing effect on pedestrian fatality.

5. Discussion

The cross-sectional analysis of Bleichstraße and Neckarstraße, two streets in Rheintor / Grafenstraße, has shown that currently a third of road space is attributed to MIT. The share of bicycle space is similar in both streets, they both feature a separated bicycle path which takes up 18 % and 16 % of road space, respectively. Pedestrian space varies greatly from 37 % to 23 % in each street.

These values are by a large margin above what previous studies have found (§ 2.3.1, p. 6), however that is likely because these are only two streets and the data is by no means representative of the entire district. Another major reason is that the data was observed during ongoing traffic trials, which specifically reallocate MIT space for bicycle usage.

Many other streets, mostly residential ones, in Rheintor / Grafenstraße often allow kerbside parking, during which cars take up a significant share of space. Due to the large time effort it would require, this is a factor that could not be sufficiently explored in this thesis. It can be assumed however that a screening of the entire district lowers the share of non-motorised traffic's road space – especially that of bicycle traffic – noticeably, since many streets do not have dedicated bicycle paths.

The issue with 'fairness' of space distribution in this regard can only be answered partially. Surely the reallocated road spaces are *fairer* than before, especially considering how MIT took up nearly half of all space in Neckarstraße. Yet a comparison to Darmstadt's modal split would not give meaningful results in this instance, since the space allocation solely reflects two select streets. Additionally, Nello-Deakin (2019) criticises this popular approach of comparing space to modal split, stating that such comparisons are 'excessively simplistic' (ibid., p. 698) and gives reason that there is more to the 'fairness' of space than what numbers can describe.

5.1. Need for action

One might argue that a need for action has already been identified by the city of Darmstadt, given how numerous traffic trials with the purpose of improving bicycling culture are being conducted at the time of writing (Wissenschaftsstadt Darmstadt 2021). Current efforts are without doubt a major step towards achieving a goal of a more just space distribution.

However, the state of the art as such cannot be misunderstood as perfected already, and Darmstadt should always strive for further improvement. As any growth has its limits (Meadows 1972), the available space – and road space – in urban areas is bound to become scarcer and scarcer with time. At the current pace, the limit for space is drawing near faster than the limit for population is (Wissenschaftsstadt Darmstadt 2020g, p. 34).

With that, private car ownership cannot be the future of urban life, as the car is the most space-intense mode, while also being parked for a large portion of the day (Nello-Deakin 2019; Gössling 2020, p. 444). It is paramount that more 'green' ways of mobility move into the daily life of everyone involved. For that, the supporting infrastructure must be provided first (Gössling 2020, p. 445; Wissenschaftsstadt Darmstadt 2020g, p. 35).

In the case of Rheintor / Grafenstraße, residents of the district themselves rank very low in car ownership in comparison to the rest of Darmstadt, which however is counteracted by the heavy amount of through-traffic in this district. Within the mindset of prioritising local development over extra-regional development (Wissenschaftsstadt Darmstadt 2020g, p. 31), the needs of Rheintor / Grafenstraße's residents should be taken more into account. Currently, Rheinstraße is for its largest part a wide open road with two to three lanes in each direction and a speed limit of 50 km/h, which allows for a large volume of motorised traffic, but neglects bicycle and pedestrian traffic by giving them only a small margin of space to move within.

5.2. Recommended action

It is of great importance that ongoing traffic trials in Rheintor / Grafenstraße (and furthermore the rest of Darmstadt as well) receive permanent implementation this summer, since their presence fulfils a certain signalling function. It shows to the general population that a change in traffic culture is occurring and the need of such. Certainly, such a change is not welcomed by everyone (Gössling 2013, p. 203; Gössling et al. 2016, p. 672), but it can create momentum — momentum that is direly needed to serve as the foundation for future changes (Gössling 2013, p. 204; Nello-Deakin and Nikolaeva 2020, p. 19).

For example, this could allow for more streets to receive a dedicated bicycle path, such that cyclists are no longer forced to ride among motorised vehicles. One way of enacting this idea in narrower spaces is to make streets one-directional, which clears up one of the kerbs that were used for parking and opens up space for a dedicated bicycle path. This is a rather ambitious change that would surely be met with objection. Gössling et al. (2016, p. 672) still describes this as the most promising scenario, and offers to improve car-sharing programmes in order to reduce overall need for private car ownership, which subsequently reduces the demand for parking space.

Another concrete action step that could see implementation is the reduction of speed in places where it's possible. Where pedestrians and motorised traffic are confronted with each other, a speed limit of 30 km/h is considered appropriate and can reduce casualties by 25 % (European Commission 2018, p. 13). Further, lower speeds of MIT facilitate bicycling and also decrease the effective space demand of MIT (Garrard, Handy and Dill 2012, p. 227; Gössling et al. 2016, p. 673; Nello-Deakin 2019, p. 709; Will, Cornet and Munshi 2020).

It goes without saying that public transit achieves a higher space efficiency than the private car. Hence, policy makers should aim to make public transit more accessible, more affordable, more reliable, and – perhaps most importantly – more attractive. In the eyes of the population, public transit must not be considered 'worse' or 'lower-quality' than the alternative that is MIT (Buehler et al. 2019,

p. 115). In a similar vein, private car ownership as the largest contributor to space consumption *and* pollution among the herein discussed transport modes must be made less desirable. Gössling (2013, p. 203) finds that this is in fact best achieved by making alternate modes, such as bicycling, more desirable. Communication strategies utilised by policy-makers therefore do not show MIT in a bad light per se, but instead spotlight the benefits of bicycling (ibid.).

6. Conclusion and outlook

In Bleichstraße and Neckarstraße, one-third of the available road space was found to be allocated to MIT during the ongoing traffic trial. Bicycles occupied about 17 % and the share of pedestrian traffic ranged from 23 % to 37 %. In Neckarstraße where public transit was present, it took up near a quarter of road space. Parked cars were found to take up 6 % in Bleichstraße, where kerbside parking is allowed.

In comparison to other cities previous studies examined, the space distribution in these two individual streets is not as skewed towards MIT. However, a quantitative comparison shows that it had been significantly higher prior to the currently ongoing traffic trial, which specifically aims at improving bicycle culture. Similar reallocation of space may be thinkable in other parts of Rheintor / Grafenstraße as well, further fostering residents' awareness of green alternatives and paving the way for Darmstadt to become more sustainable in the future, as MIT solely cannot achieve that.

Previous authors note that households with children are significantly more likely to own a car than ones without. A regression analysis has proven this to also be true for Darmstadt. The study area has exceptionally few children, and thus also a low density of car ownership. Similarly, a tentative analysis suggests that bicycle ownership is also low. To residents, walking and public transit were determined to be the main modes of transport. However, the prevalence of through-traffic means that only taking local residents into account is not sufficient.

Future research might take an interest in quantifying space distribution in Darmstadt more comprehensively, which could not be achieved in this thesis due to time and resource limits. Such an analysis could provide deeper insight into how 'justly' space is distributed in the city and where further need for improvement exists.

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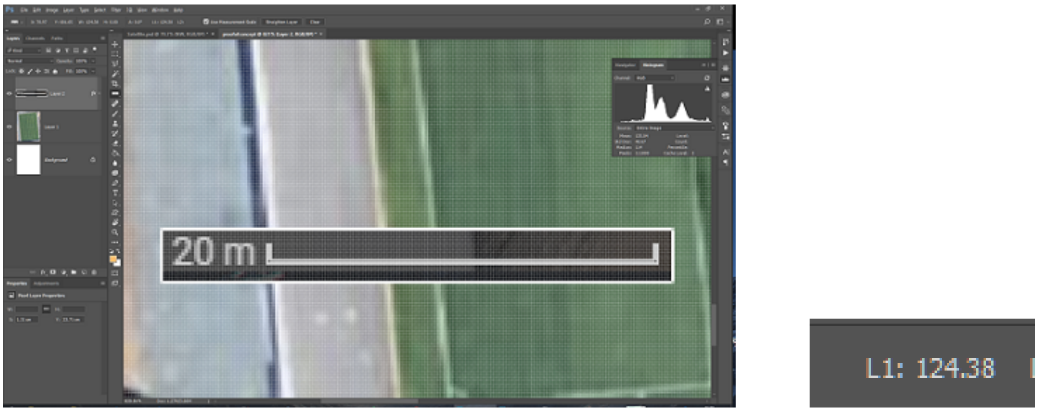
A. Measuring in Photoshop®

The following describes in great detail the measurement process in Photoshop®[1] using the same example of the Böllenfalltor soccer stadium that was briefly shown in § 3.2.1 *Proof of concept* (p. 18). The method is derived from Duck's Tech Blog (n.d.).[2]



(a) *Ruler Tool* **(b)** *Result*

Fig. A.1. *Measuring the scale*

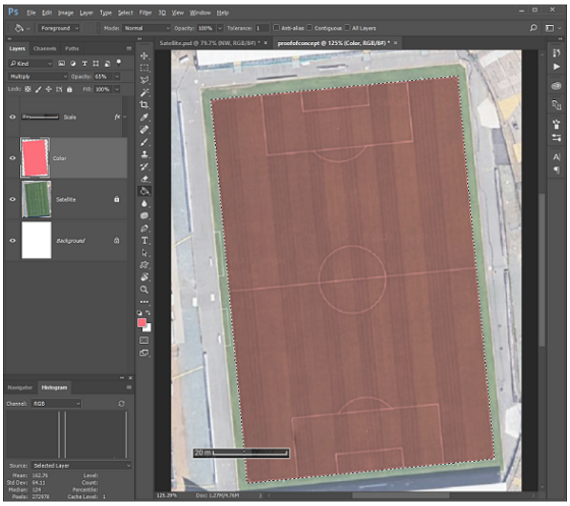
1. Measuring the scale (Fig. A.1) is done via the `Ruler Tool`, which outputs the length of any set distance in pixels. This value is noted down, as it will be used later.

2. Using the `Polygonal Lasso Tool` (Fig. A.2), the measure area is drawn over the base image, which allows filling it with a colour if desired.

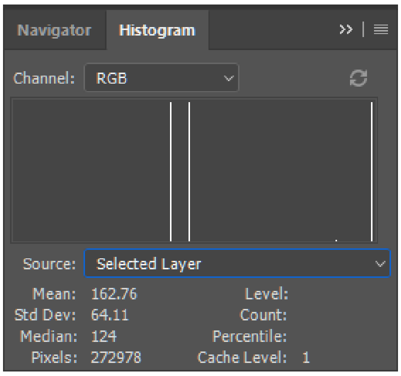
3. Finally, using the `Histogram`, the area can be read directly, in this example 272 978 px.

[1] Version: `2017.1.6 20180625.r.34 2018/06/25: 1178351 x64`

[2] Duck's Tech Blog (n.d.). *Measuring Area on a Map with Photoshop*. URL: https://blog.duklabs.com/measuring-area-on-a-map-with-photoshop/ (accessed on 2021-02-27)



(a) *Drawing the area*



(b) *Reading the result*

Fig. A.2. *Measuring area in pixels*

The scale $20\,\mathrm{m} \approx 124.38\,\mathrm{px}$ can be translated into $1\,\mathrm{m}^2 \approx 38.676\,\mathrm{px}$. Since pixel is essentially a unit of dimension $\mathbf{L}^0$, it need not to be squared to represent an area.

With that,

$$272\,978\,\mathrm{px} \cdot \frac{1}{38.676}\mathrm{m}^2\,\mathrm{px}^{-1} \approx 7058\,\mathrm{m}^2,$$

and the resulting error is

$$1 - \frac{7058\,\mathrm{m}^2}{7140\,\mathrm{m}^2} \approx 1.148\,\%.$$

Though it must be noted that there is no information on the actual size of the soccer field, and the 'optimal outcome' in this sense is purely theoretical. In practice, the areas measured are rarely a perfect rectangle like the soccer field in this example. This could also lead to further errors being introduced.

B. R Code

R was used in conjunction with the `tikzDevice`[3] library to generate code which could be compiled in LaTeX. At times, minor adjustments were then made to the generated code to improve quality of the resulting graph.

Each generating code therefore begins with `library(tikzDevice)` and a `tikz()` command specifying file location and dimensions, omitted in the following listings.

The raw values seen here are extracted from the source reference directly and have been formatted and aggregated using MS Excel and regular expressions. They are arranged by ascending district ID.

Code B.1 *Code used to generate Fig. 4.8, p. 29*

```
# Private cars per household in each district
privatecars <-
    c(0.3006, 0.3199, 0.4141, 0.5141, 0.5298, 0.5313, 0.4577, 0.4824,
        0.7423, 0.2823, 0.4070, 0.4277, 0.9736, 0.5157, 0.5127,
        0.6673, 0.8580, 0.5962, 0.8278, 0.3333, 0.6580, 1.0095,
        0.5044, 0.6722, 0.8993, 0.9067, 0.9284, 1.0130, 0.9109,
        0.9365, 1.0791, 1.0352, 0.5834, 1.0824, 0.9547, 0.7370, 0.7704)

# Share of households with at least one child out of all households
    in each district
children <-
    c(0.06688, 0.07865, 0.12115, 0.11303, 0.11535, 0.14063, 0.13273,
        0.14697, 0.21538, 0.08163, 0.15315, 0.12165, 0.20176, 0.10355,
        0.10725, 0.13333, 0.16127, 0.14765, 0.21173, 0.24607, 0.18501,
        0.21089, 0.12497, 0.18660, 0.19379, 0.21828, 0.24627, 0.19340,
        0.20685, 0.20680, 0.22259, 0.16546, 0.27575, 0.19544, 0.22994,
        0.27005, 0.23024)

df <- data.frame(children, privatecars)

plot(
```

[3] Sharpsteen, Charlie and Cameron Bracken (n.d.). tikzDevice: R Graphics Output in LaTeX Format. URL: https://CRAN.R-project.org/package=tikzDevice (accessed on 2021-02-18).

```
    privatecars ~ children, df,
    ylab = 'Private cars per household',
    xlab = 'Share of households with children',
    main = 'Car ownership by households with children',
    pch = 20 # small filled nodes
)

# Log regression
fitlog <- lm(privatecars~log(children), df)

# Draw regression line into plot
beta0 <- fitlog$coefficients[1]
beta1 <- fitlog$coefficients[2]
curve(beta0 + beta1*log(x), lty = 3, col = 'grey50', add = T)

# Add Rsquared and N to plot
r2 <- summary(fitlog)$adj.r.squared
legend(
  'topleft',
  bty = 'n',
  legend = c(
    paste('${adj R}^2 =', format(r2, digits = 2), '$'),
    paste('$N = ', NROW(children), '$')
  )
)

dev.off() # Somehow needed otherwise output will be cut off
```

Code B.2 *Result of the previous regression*

```
> summary(fitlog)

Call:
lm(formula = privatecars ~ log(children), data = df)

Residuals:
     Min       1Q   Median       3Q      Max
-0.55043 -0.08605  0.00680  0.10983  0.34044

Coefficients:
              Estimate Std. Error t value Pr(>|t|)
(Intercept)    1.55133    0.15706   9.877 1.17e-11 ***
log(children)  0.47613    0.08482   5.614 2.50e-06 ***
---
Signif. codes:  0 ‘’*** 0.001 ‘’** 0.01 ‘’* 0.05 ‘’. 0.1 ‘’  1

Residual standard error: 0.1819 on 35 degrees of freedom
Multiple R-squared:  0.4738, Adjusted R-squared:  0.4587
F-statistic: 31.51 on 1 and 35 DF,  p-value: 2.496e-06
```

Code B.3 *Code used to generate Fig. 4.11, p. 35*

```
# Ages in each district in %
# 0 - 3 years
age0 <- c(2.2, 2.3, 2.7, 2.8, 2.6, 2.6, 3.0, 3.4, 3.5, 1.3, 4.5, 2.6,
   2.8, 2.3, 2.0, 1.9, 2.7, 2.8, 3.8, 5.4, 3.3, 2.6, 2.6, 3.5, 3.3,
   2.8, 3.0, 3.4, 2.6, 3.0, 2.2, 2.0, 4.2, 2.8, 3.6, 3.4, 3.6)
# 3 - 6 years
age1 <- c(1.3, 1.8, 1.9, 2.3, 2.0, 2.3, 2.4, 2.7, 2.9, 1.1, 3.8, 2.0,
   3.5, 2.1, 2.1, 2.0, 2.3, 2.4, 4.2, 4.5, 2.6, 2.7, 2.1, 3.0, 2.7,
   3.4, 3.1, 2.8, 2.8, 3.5, 2.8, 2.2, 4.5, 3.4, 3.6, 3.7, 3.5)
# 6 - 14 years
age2 <- c(2.1, 2.7, 5.2, 4.4, 4.9, 6.3, 5.5, 5.8, 7.1, 4.3, 7.4, 5.6,
   8.2, 4.0, 4.9, 5.0, 6.1, 5.7, 9.7, 9.6, 7.4, 7.8, 4.9, 8.3, 7.2,
   8.0, 8.7, 6.4, 8.2, 7.9, 9.6, 6.3, 11.0, 5.9, 7.6, 10.9, 8.2)
# 14 - 18 years
age3 <- c(1.3, 1.0, 2.4, 1.8, 2.1, 2.4, 2.5, 2.6, 3.7, 2.3, 2.9, 2.0,
   3.3, 1.8, 1.8, 3.4, 3.2, 2.8, 4.0, 3.4, 3.3, 3.8, 2.7, 3.5, 3.5,
   3.7, 4.7, 3.5, 4.0, 3.6, 5.1, 3.2, 4.5, 3.4, 3.7, 5.1, 4.8)
data <- data.frame(age0, age1, age2, age3)
```

```
boxplot(
  data,
  main = 'Share of children of total population',
  xaxt = 'n', # No x axis ticks
  xlab = 'Age groups (years)',
  ylab = 'Share of population / $\\%$',
  col = 'mistyrose',
  whisklty = 3,
  whisklwd = 2,
  staplelty = 0,
  whiskcol = 'grey50'
)

# Custom x axis
axis(1, at = 1:4, labels = c('0 -- 3', '3 -- 6', '6 -- 14', '14 --
   18'))

# Emphasise RG
points(c(1,2,3,4), c(2.3,1.8,2.7,1), col = 'red', pch = 16)

legend(
  'topleft',
  bty = 'n', # no box around legend
  legend = c(paste('$N =', NROW(data), ',$'), 'RG'),
  col = c('white', 'red'),
  text.col = c('black', 'red'),
  pch = c(1, 16),
  horiz = T
)

dev.off()
```

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I dedicate this work to 土豆儿 (Tudou). Though no longer among us, your companionship and blissfulness will be kept in remembrance always. God bless your little heart.

Erklärung zur Arbeit
gem. § 22 Abs. 7 und § 23 Abs. 7 APB TU Darmstadt

Hiermit versichere ich, die vorliegende Bachelorarbeit ohne Hilfe Dritter und nur mit den angegebenen Quellen und Hilfsmitteln angefertigt zu haben. Alle Stellen, die Quellen entnommen wurden, sind als solche kenntlich gemacht worden. Diese Arbeit hat noch keiner Prüfungsbehörde vorgelegen.
Mir ist bekannt, dass im Falle eines Plagiats (§ 38 Abs. 2 APB) ein Täuschungsversuch vorliegt, der dazu führt, dass die Arbeit mit 5,0 bewertet und damit ein Prüfungsversuch verbraucht wird.

Darmstadt, den 2. März 2021

Zhang

Taihao Zhang