Multi-criteria and Multi-modal Evaluation of Traffic Signal Control

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Abstract

Traffic signal systems are an essential tool for traffic management in road networks. For the design of traffic signal control, it is not only necessary to address the diverse requirements from different road users but also to consider the various impacts on traffic flow quality, traffic safety, environment, and economic efficiency. However, current evaluation methods for road traffic signal control, such as the assessment of the level of service in guidelines and performance indices in optimisation methods, often evaluate from the one-dimensional perspective - mainly traffic-related aspects. Decisions made accordingly often lack a fair balance of different impacts on all road user groups.

Therefore, this thesis aims to address this gap by developing an evaluation method for road traffic signal control that incorporates multidimensional criteria for various road users in a unified framework, hereby termed as "Darmstadt Method of Traffic Signal Evaluation (D-MoTSE)". Its applicability is analysed through case studies. As a basis for the method development, the basics of traffic signal control and evaluation methods were reviewed and discussed. The literature review concentrates on answering three questions: how to design a traffic signal program, which criteria and road user groups are relevant and how they are considered in the existing evaluation methods.

Multiple parameters corresponding to traffic flow quality, traffic safety and environmental impacts are selected as the evaluation criteria in the developed evaluation method. The traffic-related parameters are distinguished for different traffic modes. The multidimensional evaluation criteria are first determined using appropriate simulation or calculation methods. Later on, they are converted into monetary values using established cost rates, and further aggregated to calculate the total cost. During the aggregation, particular weighting factors can be applied to reflect the political or planning preferences for specific criteria or road user groups. The cost and weighting factors can be adjusted dynamically under different situations. Superordinate effects that are of high significance at a macroscopic level can be taken into consideration as and when necessary and in the case that the relevant data are available.

The developed evaluation method was applied to four individual traffic signal systems in the City of Darmstadt, Germany, as case studies. The results show that the number of persons that are present at a traffic signal system has a significant impact on the design of traffic signal control. The distribution of the related cost components differs significantly depending on the type of intersection and the traffic signal program. Furthermore, energy consumption and environmental costs take up at least one-third of the total cost, and therefore, should not be neglected in the evaluation of traffic signal control.

The evaluation results can be used for comparing alternative traffic signal programs and selecting the optimum solution among them. Recommendations for designing traffic signal control can be derived accordingly. At signalised pedestrian crossings, integration into the coordination with neighbouring intersections can significantly reduce the delay costs for motorised private transport but may lead to higher costs for crossing pedestrians (and cyclists). A signal program with coordination is the optimum solution under the equal weighting of all evaluation criteria. Higher particular weight for pedestrians (and cyclists) is necessary to further reduce the delays for crossing pedestrians (and cyclists). However, it should be emphasised that generally particular weights should only be adjusted moderately in special cases with the support of plausible planning or political reasons. At signalised intersections, it can be observed that public transport priority can but does not necessarily cause disadvantages for the whole traffic. Instead, it leads to a shift of delays from public transport to other modes. The case studies revealed that no general recommendations can be provided for the design of traffic signal control at signalised intersections. The appropriate solution varies from case to case.

A further implementation of the developed evaluation method in practice can assist transport engineers and authorities with the development, optimisation, revision and quality management of traffic signal control, both in the planning and operation stage. The chances and the challenges for its implementation are discussed in this thesis.
Zusammenfassung


Das entwickelte Bewertungsverfahren wurde an vier einzelnen Lichtsignalanlagen in der Stadt Darmstadt als Fallbeispielen angewendet. Die Ergebnisse zeigen, dass die absolute Anzahl der Personen, die in verschiedenen Verkehrsmitteln auftreten, eine erhebliche Bedeutung für die Gestaltung der Lichtsignalsteuerung hat. Es wurde festgestellt, dass die Verteilung der Kostenkategorien je nach Knotenpunkttyp und ausgewähltem Signalprogramm signifikant variiert. Der Anteil der Kraftstoff- und Umweltkosten liegt in der Regel bei mindestens einem Drittel der Gesamtkosten und ist bei der Bewertung auf keinen Fall zu vernachlässigen.

keine allgemeingültige Aussage zur Eignung einzelner Varianten getätigt werden. Es muss von Fall zu Fall untersucht werden, wie die Lichtsignalsteuerung zu gestalten ist.

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1 Introduction

1.1 Background and Motivation

Road traffic signals are an important instrument of traffic management and operation, which are widely used in road networks, corridors and intersections. The design of traffic signal control has serious impacts not only on traffic flow quality but also on other aspects including traffic safety, environmental quality and economic efficiency. Poor design of signal timing can cause more delays and more air pollution emissions as well as make the signal system less safe and less efficient. Statistics indicate that approximately 40% of total traffic accidents, approximately 80% of vehicles delays on urban roads, and approximately 20% of vehicle emissions occur at signalised intersections (FHWA, 2016; Kan et al., 2018; WHO, 2016 as cited in Tang et al., 2019). There is a need to design and assess traffic signal control in a multi-criteria way by comprehensively considering its various impacts.

At signalised intersections, multiple road users from various directions are interacting with each other. Traffic signal systems regulate the road user behaviour by releasing and stopping different traffic streams in sequence in order to reduce conflicts between them (FGSV, 2015b, p. 9). Most common road user groups include pedestrians, cyclists, public transport, motorised private transport and heavy transport. The first three road user groups belong to the environmental alliance as they emit no or low air pollution during travel. While designing and assessing the traffic signal control, it is necessary to consider the impacts on different road user groups.

Last but not least, there are also indirect effects of traffic signal control on modal shifts that appear in the middle term and long term. However, other measures without negative environmental impacts, such as pricing, regulatory policies and information, should be chosen to affect people's mode choices (Boltze and Jiang, 2017).

Conflicts of interest can occur between the above-mentioned aspects since the available time and space are limited at traffic signal systems. A fair balance is required to deal with goal conflicts while designing traffic signal control. As an example, the members of environmental alliance are often prioritised in traffic signal control in order to encourage people to travel more frequently with these modes. Priority for them may lead to disadvantages for other modes at the same time. Motorised vehicles may wait longer before stop lines and emit more air pollution locally. Trade-offs are necessary to compare the gained benefits with the resulted losses.

Proper consideration of various criteria and traffic modes in the evaluation of traffic signal control is a crucial topic which has not yet been investigated in depth in the existing literature. The current evaluation methods, such as the guidelines for assessing road infrastructures and the performance indices in optimisation methods, reflect the above-mentioned features only limitedly while still, the focus of these methods lays mainly on traffic-related aspects. Although there are brief descriptions about the importance of evaluating other aspects, there is a lack of comprehensive and quantitative analysis about how to integrate them into the same evaluation framework together with traffic-related aspects. Rules to value and to weight the different impacts still need to be defined. There is no tool to present the trade-offs between different goals and road users comprehensively and transparently.

An evaluation of traffic signal control is widely conducted in both the planning and operation stage. The necessity to integrate multiple criteria and traffic modes into the evaluation has not only raised an awareness in the academics but also among governments that are managing the urban road transport in practice. In the year 2015, the city council of Darmstadt has published a decision about promoting a comprehensive consideration of different effects on multiple road users in organising traffic signal
systems (Magistrat der Stadt Darmstadt, 2015). The main content of this decision was also published as a suggestion for the transport political framework concerning the design of the traffic signal control in cities (Boltze and Jiang, 2017). It is the primary motivation for a research project, in which part of the research in this dissertation was conducted, which is then widened and enriched.

1.2 Research Questions and Objectives

This thesis aims to develop an evaluation method for traffic signal control that integrates multiple goals and traffic modes into one framework and investigate its applicability. Since the study is conducted in the City of Darmstadt, Germany, the new evaluation method is termed as "Darmstadt Method of Traffic Signal Evaluation (D-MoTSE)". The research questions addressed in this thesis are listed as follows.

- What is the current status of research on road traffic signal control and its evaluation methods?
- What is the goal system for traffic signal control?
- Which criteria are relevant to the evaluation of traffic signal control?
- Which measurement methods are suitable for valuing the evaluation criteria quantitatively in different phases?
- Which traffic modes are relevant to the evaluation of traffic signal control?
- How to develop alternative traffic signal programs for evaluation?
- How to integrate the multidimensional criteria for different traffic modes into a uniform evaluation framework?
- How to reflect the possible attitudes towards specific goals and traffic modes in the evaluation framework? What are their effects on designing traffic signal control?
- How to treat superordinate effects on a macroscopic level in the evaluation of traffic signal control?
- How to aggregate all the essential features to an overall evaluation result?
- How to apply the evaluation method on case studies and furthermore in practice?
- Which evaluation results can be obtained through the case studies?
- What recommendations for traffic signal control can be given accordingly?
- What are the potential application areas of the developed evaluation method?
- What chances and challenges are faced with in the application?

D-MoTSE focuses only on evaluating the performance of traffic signal control regarding multiple goals and traffic modes. Due to the constraint of this thesis, the following two aspects are not included in the framework of D-MoTSE:

- The hardware and software for operating traffic signal systems
  The reliability and the price/performance ratio can vary between different kinds of hardware and software for operating traffic signal systems. Since D-MoTSE focuses only on the design of traffic signal control, the hardware and the software are not considered in its framework.

- The installation, operation and maintenance costs for traffic signal systems
  The more complex the traffic signal system is, the higher are the installation, operation and maintenance costs. They are one of the factors that governments consider while planning traffic signal systems, especially when there is a limited budget. However, these three cost components can not reflect the performance of a traffic signal program regarding improving traffic flow quality, increasing traffic safety or reducing environmental impacts. Therefore, they are not directly considered in D-MoTSE that is described in this thesis.
1.3 Methodology and Outline of the Thesis

Figure 1 shows the outline of the thesis. In the beginning, Chapter 1 introduces briefly the background information to the study, defines the research objectives and the research questions, and describes the outline of the thesis.

The development of a new evaluation method is, first, based on a comprehensive understanding of the existing knowledge. In Chapter 2 and 3, a search for relevant studies was conducted. Their findings were reviewed and summarised.

The main topic of Chapter 2 is road traffic signal control. It explains the legal framework and technical guidelines, the multi-criteria and the multi-modal features of traffic signal control, the elements of traffic signal programs and the necessity of their situation-responsiveness.

The keyword of Chapter 3 is the evaluation. It compares, analyses and summarises the existing evaluation methods in transport planning and, more specifically, for evaluating traffic signal control. The obtained essential information can be further used for developing a new evaluation method in the upcoming chapter.

After the literature review, a new evaluation method for traffic signal control D-MoTSE was developed and explained step by step in Chapter 4. In the beginning, the general issues of the evaluation method are explained. Later on, each work step is concretised in detail using the gathered existing findings as a reference. At the end, an overview of the developed evaluation is shown and a discussion on its benefits and constrains is given.

In the next step, D-MoTSE was applied on four exemplary case studies to verify its applicability and to analyse its effects on designing traffic signal control, as illustrated in Chapter 5. In the case studies, data
were collected from the responsible authorities, including data about the geometric design of test sites, the traffic volumes, the traffic accidents and the current signal programs. In addition, manual traffic counts were conducted to collect the traffic volumes that were unavailable from the authorities. Then for each case study, several alternative signal programs were developed and compared using D-MoTSE. The microscopic traffic flow simulation and the emission modelling were conducted in order to measure the evaluation criteria. The measured values of the traffic-related and the emission criteria as well as the traffic accident data were further quantitatively analysed in order to compare the alternative traffic signal programs. Recommendations for traffic signal control at each test site were derived based on the evaluation results. In the end, sensitivity analyses were conducted to examine the robustness of the results.

Chapter 6 describes how to implement the evaluation in practice. An qualitative analyse was conducted on the potential application areas. The opportunities and the challenges in the application were discussed.

Chapter 7 summarises all the findings in the last chapters and discusses the possibilities for the further development of the evaluation method.
2 Basics of Road Traffic Signal Control

2.1 Introduction

This thesis aims at developing a multi-criteria and multi-modal evaluation method for road traffic signal control. As an important basis for further research, the basic issues of road traffic signal control are explained in the following sections.

The design of traffic signal control should conform to the corresponding legal framework and technical guidelines, which are explained in Section 2.2. Under the legal and technical framework, traffic signal systems are designed to achieve multiple goals, which are illustrated together with their relevant parameters in Section 2.3. How to measure these parameters is further explained in Section 2.4. In addition to the multi-criteria character, D-MoTSE aims to have another major feature that it takes various traffic modes and their corresponding road user groups into consideration. During the design of traffic signal control, priority may be given to specific road user groups due to political or planning reasons. Section 2.5 provides an overview of not only the relevant traffic modes but also their priority at traffic signal systems. Rules for controlling traffic signals are documented as a traffic signal program, which is briefly explained in Section 2.6. An essential feature of traffic signal control is its dynamic response to real-time situations, in order to guarantee its performance over a long period. Section 2.7 explores this concept and gives some examples of the research projects and practical examples with regards to its implementation.

2.2 Legal Framework and Technical Guidelines

2.2.1 Legal Framework

The basic law on road transport in Germany is the Road Traffic Act, original German title "Straßenverkehrsgesetz (StVG)". It is supported by four ordinances, which give more detailed regulations to implement the rules given by StVG. Among these ordinances, the Road Traffic Regulation, original German title "Straßenverkehrs-Ordnung (StVO)" is most relevant for traffic signal control, since it mainly regulates the behaviour of road users on streets. It contains two parts: general traffic rules; traffic signs and road facilities.

The StVO defines the basic rules for traffic signal systems (§37). The colour sequences of the light signal and the meaning of each colour are defined. Symbols for several road user groups or modes, e.g. pedestrians, cyclists, public transport vehicles are regulated, as well.

The StVO provides rules for the regulation of road traffic. According to §45, road authorities have the right to constrain or reroute traffic, to organise traffic or to improve safety. Moreover, a constraint and a rerouting of traffic can be approved due to other reasons, such as:

- to protect residents against noise and air pollution
- near hospitals and nursing homes
- in case of cultural events (limited in certain places and at certain times)

Common ways of constraining or rerouting traffic are to reorganise the road space and to use traffic signs. Traffic signal control is another crucial supportive tool for that. The regulations mentioned above provide the basis for dynamic traffic control under changing situations.
Additionally, the operation of trams is regulated by another law - Ordinance on the Construction and Operation of Trams, original German title "Verordnung über den Bau und Betrieb der Straßenbahnen (BOStrab)". In annexe 4 of BOStrab, the unique signals for controlling trams are defined.

2.2.2 Technical Guidelines

The Road and Transportation Research Association, original German name "Forschungsgesellschaft für Straßen- und Verkehrswesen (FGSV)", has published various guidelines about traffic signal control and traffic control measures. The following paragraphs give a summary to those that are most relevant to the topic of this thesis.

The Guidelines for Traffic Signals, original German title "Richtlinien für Lichtsignalanlagen (RiLSA)", contains detailed knowledge and suggestions for the design and the operation of a traffic signal system in Germany (FGSV, 2015b). RiLSA covers several topic areas, among which the most relevant for this thesis are:

- basic principles
- the signal program design
- impacts of traffic signal control on the intersection layout
- control strategies
- the quality management

In the beginning, RiLSA (FGSV, 2015b, pp. 9-10) defines the basic principles for the use of a traffic signal system. Those relevant for this thesis are summarised here. Traffic signal systems could, not only improve traffic safety and flow, but also, have valuable meaning to reduce air pollution emissions in (sub-)networks or corridors. The main criteria for its implementation are, therefore, traffic safety, traffic flow quality, fuel consumption and emissions. In addition to these criteria, the requirements of various road users should also be taken into consideration. In particular, the non-motorised traffic and public transport need some special considerations. Appropriate priority measures could significantly improve their quality. There exists usually conflicts between different goals, such as high traffic safety, good traffic flow quality, acceleration of public transport vehicles, low fuel consumption and minimum environmental impacts. A fair balance between these conflicting goals is necessary while designing traffic signal control. Following RiLSA, the evaluation method developed later in this thesis helps to promote these basic principles in research and practice.

RiLSA (FGSV, 2015b, pp. 13-50) covers a wide range of issues on the design and the operation of traffic signal systems. Terms and rules defined in RiLSA are used throughout this thesis. More details can be found in Section 2.6.

At last, RiLSA (FGSV, 2015b, pp. 78-84) elaborates the quality management of traffic signal systems in all stages of their lifetime. Although the performance measurement is highly related, it goes beyond the scope of this thesis. The method proposed in the upcoming chapters can be part of the performance measurement both in the planning and operation stage of traffic signal systems, as briefly explained in Chapter 6.

The German Highway Capacity Manual, original German title "Handbuch für die Bemessung von Straßenverkehrsanlagen (HBS)", is another important guideline about traffic signal control. It proposes methodologies to assess the performance of different road facilities with regards to traffic flow quality (FGSV, 2015a). The methods and the values in the HBS are a good reference for developing D-MoTSE in the framework of this thesis. Detailed information is explained in Section 3.4.

Traffic signal control is closely related to the geometric design of intersections or other road facilities. There are various guidelines about this topic area, including:
2.3 Main Goals and Relevant Parameters

In general, there are four main goals for traffic management, including traffic flow quality, traffic safety, energy consumption and emissions, as well as improvement of economic efficiency (Boltze, Dinter, and Schöttler, 1994; Boltze and Jiang, 2017). The first three goals are also given in the RiLSA (FGSV, 2015b, pp. 9-10) as the main criteria for the usage of traffic signal systems. Besides, due to the limited resources and space (especially in an urban area), economic efficiency is an important aspect to consider during the design and the operation of traffic signal systems.

2.3.1 Satisfaction of Mobility Needs

A primary motivation to install a traffic signal system is to improve traffic flow in order to better satisfy the mobility needs of road users and residents. The accessibility of a city determines its attractiveness for not only residents but also the economy (Boltze and Jiang, 2017).

Road traffic congestions have become a significant urban problem all over the world. They are increasing in many urban areas and in locations where populations and economies are growing (ECMT, 2007, p. 14). FHWA (2004, pp. 2-4) identified the poor signal timing as one of the leading causes for congestions in urban areas. It is necessary to optimise traffic signal control in order to reduce delays and to improve traffic flow.

The parameters related to traffic flows are (Boltze and Jiang, 2017):

- the delay for vehicles (motorised and non-motorised)
- the delay for individuals
- the number of stops
- queue lengths
- comfort

Delays are the most common indicator to measure traffic flows at signalised intersections. The delay is defined as the additional travel time experienced by a driver, passenger, cyclist, or pedestrian beyond that required to travel at the desired speed (TRB, 2010, pp. 9-5). Delays can be further distinguished between the delay for vehicles and the delay for individuals. With regards to the delay for vehicles, one vehicle is used as a unit, no matter how many people sit or stand inside. The total delay is calculated by multiplying the average delay for vehicles with the number of vehicles. On the contrary, the delay for individuals considers each person that passes an intersection. Calculation of the total delay requires not only information on the number of vehicles but also the occupancy rates of different traffic modes. One exception is the cycling mode, because, usually only one person rides a bicycle.

The number of stops is another important indicator of traffic flows. According to FGSV (2012a, p. 57), a stop means the break of a trip, which is not caused by the traffic condition or a traffic rule. However, this
definition is not applicable for the stops of vehicles at a signalised intersection due to the signal program. The definition according to TRB (2010, pp. 9-8) fits better. Here, a stop is defined as the slowing of a vehicle to less than 5 mi/h (about 8 km/h). The average number of stops that vehicles experience at a signalised intersection is related not only to the energy consumption and emissions but also to the comfort of road users.

A reason for delays and stops is queues that exist at the approaches of signalised intersections. A queue is defined as a line of vehicles waiting to be served due to traffic control, a bottleneck or other causes (FGSV, 2012a, p. 58; TRB, 2010, pp. 9-15). The queue length is calculated as the distance between the upstream and downstream ends of the queue. The potential queue length is an important factor to consider for the dimension of intersections. Enough spaces should be provided so that different traffic streams do not hinder each other. Extreme long queues may also influence the traffic flows at neighbouring intersections.

There is no standard definition for comfort in the guideline about traffic signal control. It is an overall personal perception of road users, which is related to various aspects, such as delays, stops or the availability of seats (for public transport vehicles only). A quantification of comfort is difficult.

2.3.2 Increase of Traffic Safety

A traffic signal system can significantly increase traffic safety. While in some developed countries, major improvements in traffic safety have already been accomplished in the last decades, many other countries are still suffering from severe traffic safety problems (Boltze and Jiang, 2017). Statistics from WHO (2018a) have shown that the global number of road traffic deaths was 1.35 million in 2016 and has been rising steadily in the last years. Significant differences between countries can be observed from the statistics. With an average rate of 27.5 deaths per 100,000 population, the risk of a road traffic death is more than three times higher in low-income countries than in high-income countries where the average rate is 8.3 deaths per 100,000 population. There has also been more progress in reducing the number of road traffic deaths among middle- and high-income countries than low-income countries. In Germany, the number of deaths in road traffic accidents has been continuously decreasing since the 1990s, from a total number of 8758 deaths in 1996 to 3275 deaths in 2018 (Bundesministerium für Verkehr und digitale Infrastruktur, 2019, p. 157). Despite this significant achievement, further improvement is still necessary to protect road users and residents from traffic-related accidents. The traffic safety issue remains, therefore, an important criterion.

The parameters related to safety are (Boltze and Jiang, 2017):

- number of traffic accidents
- number of slight injuries
- number of serious injuries
- number of deaths

The definitions related to road accidents vary from country to country. FGSV (2012a, p. 112) gives the definitions for the above-mentioned terms in Germany. Slight injuries are injured people that do not immediately require medical treatment in a hospital. Serious injuries are injured people that immediately require medical treatment in a hospital but do not die in less than 30 days after a traffic accident due to its consequences. Road traffic deaths are people that die in less than 30 days after a traffic accident due to its consequences.

2.3.3 Reduction of Environmental Pollution

Environmental pollution from road traffic has become a growing concern since the past few years. Road traffic produces not only noise but also air pollution, which can both harm human health and cause
diseases (or even early deaths). WHO (2018b) estimated that the outdoor air pollution in both cities and rural areas caused about 4.2 million deaths worldwide in 2016. Among all sectors, the transport sector is one of the major contributors to the air pollution disease burden globally (Anenberg et al., 2019, p. i). It was estimated in this study that the global vehicle tailpipe emissions contributed to about 361,000 premature deaths from ambient PM$_{2.5}$ and ozone in 2010 and 385,000 in 2015, which corresponds to 5.43 deaths per 100,000 population in 2010 and 5.35 deaths per 100,000 population in 2015. In Germany, the German Environment Agency linked an average of about 44,900 yearly premature deaths to the ambient particle pollution in the period from 2007 to 2015 (Umweltbundesamt, 2017a).

To protect human health, the following parameters related to environmental pollution should be considered (Boltze and Jiang, 2017):

- emissions of air pollutants
- ambient air quality
- noise level
- energy consumption and CO$_2$ emissions

Road traffic emits various kinds of air pollution. Among those, particulate matters (PM) and NO$_x$ are particularly of serious concern.

Globally, the problem of outdoor particle pollution is rising. Statistics from WHO (2016, p. 31) showed a global increase of 8% in the annual mean concentration of PM$_{2.5}$. Despite a decreasing trend in high-income countries of the Americas, Europe and Western Pacific, other regions have a rise in the pollution level. The annual mean concentrations in those regions are also at a high level, which is around 5 - 10 times of the guideline level concentration given by World Health Organisation. Road transport is one of the main contributors to particle pollution. In Germany, it is responsible for 14% of the total PM$_{10}$ emissions and 19% of the total PM$_{2.5}$ in 2017 (Umweltbundesamt, 2017b). Traffic-related particles come not only through the combustion process, but also from the resuspended road dust and wear of tires and brake linings.

NO$_x$ is becoming a great concern for environmental protection in the traffic sector in Germany. Despite a significant progress in reducing particle concentrations, the NO$_2$ concentration only shows a slightly decreasing trend in the past years (Minkos et al., 2016, pp. 9-10). The statistics have shown that the pollution level remained beyond the legal threshold value at more than half of the traffic-oriented monitoring stations in Germany in the past years. Road traffic is the largest contributor to NO$_x$ emissions, which took up around 34% of the total emissions in Germany in 2017 (Umweltbundesamt, 2017b).

Both, emissions of air pollutant and ambient air quality, are parameters to describe air pollution level. Emissions of air pollutants are defined as the amount of air pollutants that is emitted by a mobile or stationary source (FGSV, 2012a, p. 34). The ambient air quality means the quality of outdoor air. The emissions of air pollutants from a source will disperse, react and suspend in the air, thus influencing the ambient air quality in the surrounding environment.

The negative effects of noise on human health are, for example, cardiovascular disease, cognitive impairment, sleep disturbance, tinnitus and annoyance (Europe, 2011, p. 3). Among those, the sleep disturbance and the annoyance, most related to road traffic, comprise the main burden of environmental noise (Europe, 2011, p. v). Statistics from that study show that at least one million healthy life years are lost every year from traffic-related noise in the western part of Europe.

To prevent climate change and to save resources, energy consumption and CO$_2$ emissions are another two important aspects that need consideration. CO$_2$ is a typical greenhouse gas, which is emitted in combustion processes. These two parameters have a close relationship and it is necessary to reduce both (Boltze and Jiang, 2017).
2.3.4 Improvement of Economic Efficiency

The parameters related to the economic efficiency of traffic signal control are (Boltze and Jiang, 2017):

- **average travel speed**
- **saturation degree of green times**

The average travel speed is defined as the quotient of the travel distance to the travel time (FGSV, 2012a, p. 55). An increase of the average travel speed of vehicles can improve economic efficiency, since, higher mobility can support economic activities better (Boltze and Jiang, 2017).

Another aspect of efficiency is that the infrastructures and vehicles should be utilised efficiently (Boltze and Jiang, 2017). At intersections, the saturation degree of green times can be used to measure whether the time is appropriately distributed among different stages. Since time is limited, a low saturation degree would indicate a waste of green time that could be potentially used by other streams to pass the intersection.

2.4 Methods to Measure Parameters

For a quantified evaluation of traffic signal control, it is necessary to estimate or measure the values of the parameters identified in Section 2.3. The impact estimation should be conducted, on the one hand, before the implementation of any traffic signal control in order to optimise its effects. On the other hand, it should be conducted continuously during the operation to verify its practical performance.

A variety of methods are available for the impact estimation both before and during the operation. They can be classified into four groups. The two main groups of methods in the planning stage are calculation and modelling methods. During the operation, the parameters can be either measured using techniques or estimated by modelling approaches with the support of online data.

Table 1 shows an overview of the parameters and their corresponding estimation or measurement methods. A brief description of the methods can be found in Appendix A. Parameters that belong to the same goal can sometimes be estimated using the same method. For example, traffic parameters such as delays for vehicles and individuals, queue lengths and the number of stops can all be measured using the traffic flow simulation.

The efforts for implementation and the accuracy of results are estimated roughly according to experiences and statements in the literature. The efforts for implementation are classified into three levels:

- **Low effort**: The method is a standardised method with a low requirement for input data. The input data are either available or can be gathered with little time or expense.
- **Medium effort**: The method needs to be adapted in each case. It has a medium requirement for input data. The input data can be gathered with a medium level of time or expense.
- **High effort**: The method needs to be adapted in each case. It has a high requirement for input data. The input data can be gathered with significant time or expense.

The accuracy can be classified into three levels as well:

- **Low accuracy**: The parameters are estimated roughly.
- **Medium accuracy**: The parameters are estimated using calculation or modelling methods. The results are, in most cases, not validated or have a certain degree of uncertainty.
- **High accuracy**: The parameters are either measured with measuring instruments or estimated with validated models.
<table>
<thead>
<tr>
<th>Main goal</th>
<th>Parameters</th>
<th>Before implementation</th>
<th>Under operation</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mobility</strong></td>
<td></td>
<td>Calculation</td>
<td>Modelling</td>
</tr>
<tr>
<td></td>
<td>Delay for vehicles</td>
<td>Method in HBS 2015</td>
<td>Traffic flow simulation</td>
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<tr>
<td></td>
<td>Delay for individuals</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>Queue lengths</td>
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<td></td>
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<tr>
<td></td>
<td>Number of stops</td>
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<td></td>
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<tr>
<td></td>
<td>Comfort</td>
<td></td>
<td>Derivation from delays and stops</td>
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<tr>
<td><strong>Traffic safety</strong></td>
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<td></td>
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<tr>
<td></td>
<td>Number of traffic accidents</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>Number of slight injuries</td>
<td>Method in HVS (draft)</td>
<td>Accident analysis with data under similar situations</td>
</tr>
<tr>
<td></td>
<td>Number of serious injuries</td>
<td>Evaluation of safety level using point system (qualitative)</td>
<td>Modelling of accident frequency</td>
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<tr>
<td></td>
<td>Number of deaths</td>
<td></td>
<td></td>
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<tr>
<td><strong>Emissions</strong></td>
<td>Emissions of air pollutants</td>
<td>Emission modelling(^a)</td>
<td>Measurement runs</td>
</tr>
<tr>
<td></td>
<td>Ambient air quality</td>
<td>Method in RLS-19(^d)</td>
<td>Modelling of ambient air quality with dispersion models or with statistical models</td>
</tr>
<tr>
<td></td>
<td>Noise level</td>
<td>Method in RLS-19(^d)</td>
<td>Measurement at roadside</td>
</tr>
<tr>
<td></td>
<td>Energy consumption</td>
<td></td>
<td>Emission modelling(^b)</td>
</tr>
<tr>
<td><strong>Economic efficiency</strong></td>
<td>Average travel speed</td>
<td>Traffic flow simulation</td>
<td>Use of measurement devices Vehicle pattern recognition Automatic Licence Plate Recognition (ALPR) Analysis of Floating Car Data (FCD)</td>
</tr>
<tr>
<td></td>
<td>Saturation degree of green times</td>
<td>Method in HBS 2015</td>
<td></td>
</tr>
</tbody>
</table>

\(^a\) Handbook for the Evaluation of Traffic Safety on Roads, original German title "Das Handbuch für die Bewertung der Verkehrssicherheit von Straßen (HVS)" (Bark et al., 2008)

\(^b\) low effort only in case of exiting traffic flow simulation models

\(^c\) Directives to Determine Ambient Air Quality at Roads without or with Loose Surrounding Buildings 2012, original German title "Richtlinien zur Ermittlung der Luftqualität an Straßen ohne oder mit lockerer Randbebauung (RLuS) 2012" (FGSV, 2012e), only applicable for roads without buildings or with low-density buildings

\(^d\) Directives for Noise Protection on Roads, original German title "Richtlinien für den Lärmschutz an Straßen (RLS-19)" (FGSV, 2019)
2.5 Main Traffic Modes and their Priority at Traffic Signal Systems

2.5.1 Traffic Modes

Traffic signal systems serve users of different traffic modes. The classification of traffic modes in this thesis is generally according to the fundamental research in Boltze and Jiang (2017). Citizens can generally choose between four main traffic modes: walking, cycling, public transport (PuT) and motorised private transport (PrT). In addition to these four modes, the heavy transport, which is mainly composed of heavy duty vehicle (HDV), needs special consideration.

The terms used here are based mainly on FGSV (2012a). English definitions in TRB (2010) are used as a reference additionally. Following definitions of the traffic modes are used in this thesis:

- **Walking**: a travel mode under which a trip (or part of a trip) is made on foot along a roadway or a pedestrian facility.
- **Cycling**: a travel mode under which a bicycle is used on a roadway or a pathway.
- **Public transport**: a travel mode in which vehicles (including buses and trams) stop at regular intervals along the roadway to pick up and drop off passengers. It is generally accessible for all citizens.
- **Motorised private transport**: a travel mode that includes motor vehicle traffic using a roadway that relates to passenger transport. It includes such vehicles as motorcycles and passenger cars.
- **Heavy transport**: a travel mode for heavy traffic that transports goods and materials or delivers services other than public transport.

Although light commercial vehicles (LCV) transport goods and have different operating characteristics from passenger cars, both vehicle types are similar in the size, the shape and emissions. Therefore, light commercial vehicles are considered as part of motorised private vehicles but separated from vehicles such as passenger cars.

2.5.2 Modal Split and its Influencing Factors

Travellers can choose for their trips between various travel modes, except for heavy transport mode, which is mainly for transporting goods. The distribution of travellers using different traffic modes is defined as modal split (FGSV, 2012a, p. 23).

The mode choice is a complex issue. Various factors affect an individual's mode choice for a trip and the modal split on a macroscopic level (e.g. on a city or country level). Table 2 shows a summary of the factors influencing mode choice that are identified from previous literature. Among these, traffic signal control can influence only some part of the transport-related factors. The focus of the following paragraphs lays mainly on these factors. The socio-economic and demographic characteristics, spatial development patterns, national cultures, individual preferences and the other factors are independent of how traffic signal control is designed and therefore not explained in detail.

**Travel time** is an important factor which is traditionally considered in mode choice models. Pez and Janßen (2017) proved, based on a questionnaire, that the travel time of different traffic modes can be perceived by road users and correlate to their mode choices. Frank et al. (2007) investigated how relative associations between the travel time, costs, and land-use patterns impact the mode choice. It was found that the travel time was the strongest predictor among those. The significant effect of the travel time on the mode choice is also confirmed by Anwar and Yang (2017) for the case of new public transport policies for university commuters and by Satiennam et al. (2016) for the case of planning Bus Rapid Transit systems. However, Idris, Nurul Habib, and Shalaby (2015) drew a different conclusion.
Table 2: Factors affecting the mode choice and the modal split (own illustration)

<table>
<thead>
<tr>
<th>Categorisation of factors</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Group 1: Socio-economic and demographic characteristics</strong></td>
<td>Ko, Lee, and Byun (2019); Keyes and Crawford-Brown (2018); Satienam et al. (2016); Driscoll et al. (2013); Santos et al. (2013) Buehler (2011); Scheiner and Holz-Rau (2007)</td>
</tr>
<tr>
<td>• income</td>
<td></td>
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<tr>
<td>• car ownership</td>
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<tr>
<td>• household composition</td>
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<td>• life cycle</td>
<td></td>
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<tr>
<td>• gender</td>
<td></td>
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<tr>
<td>• age</td>
<td></td>
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<tr>
<td><strong>Group 2: Spatial development patterns</strong></td>
<td>Mendiola, González, and Cebollada (2014); Santos et al. (2013); Buehler (2011); Frank et al. (2007)</td>
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<tr>
<td>• urban form</td>
<td></td>
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<tr>
<td>• land use</td>
<td></td>
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<tr>
<td>• residential density</td>
<td></td>
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<tr>
<td><strong>Group 3: Transport-related factors</strong></td>
<td>Anwar and Yang (2017); Pez and Janßen (2017); Song, Preston, and Ogilvie (2017); Idris, Nurul Habib, and Shalaby (2015); Comendador, Monzón, and López-Lambas (2014); Satienam et al. (2016); Driscoll et al. (2013); Santos et al. (2013); Tyrinopoulos and Antoniou (2013); Buehler (2011); Frank et al. (2007)</td>
</tr>
<tr>
<td>• travel time</td>
<td></td>
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<tr>
<td>• trip distance</td>
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<td>• travel costs</td>
<td></td>
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<tr>
<td>• infrastructure supple</td>
<td></td>
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<tr>
<td>• quality/service level of transport systems</td>
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<tr>
<td>• speed limits</td>
<td></td>
</tr>
<tr>
<td><strong>Group 4: National cultures or individual preferences</strong></td>
<td>Keyes and Crawford-Brown (2018); Idris, Nurul Habib, and Shalaby (2015); Buehler (2011)</td>
</tr>
<tr>
<td>• travel habit</td>
<td></td>
</tr>
<tr>
<td>• attitudes towards transport modes</td>
<td></td>
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<tr>
<td>• life style</td>
<td></td>
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<tr>
<td><strong>Group 5: Others</strong></td>
<td>Pike and Lubell (2016); Liu, Susilo, and Karlström (2015)</td>
</tr>
<tr>
<td>• weather</td>
<td></td>
</tr>
<tr>
<td>• social networks</td>
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</tbody>
</table>

The results of comparing different kinds of mode choice models showed that the traditional attributes (e.g. travel costs and time) are of lower importance to mode switching behaviour than behavioural factors (e.g. the habit formation towards car driving) and other transit service design attributes (e.g. the crowding level, the number of transfers and schedule delays). The importance of other influential factors is highlighted in that study.

The service quality or service level of transport systems is another factor that impacts the modal split significantly and can be strongly influenced by traffic signal control, as stated in Idris, Nurul Habib, and Shalaby (2015). They concluded that enhancing the public transport service performance is essential to increase modal shifts. Tyrinopoulos and Antoniou (2013) has identified crowding as the most important factor that discourages respondents from the use of public transport, but could not find significant impacts from a high fare, a lack of public transport information and the bad accessibility to the transit network in the particular situation in their research.
Travel costs are another significant factor that influences the mode choice (Frank et al., 2007). A modal shift away from cars can be encouraged by transport policies to increase car operating costs, such as fuel costs, automobile registration fees, tolls and parking costs (Buehler, 2011; Creutzig, 2014; Idris, Nurul Habib, and Shalaby, 2015). Decreasing public transport fares is likely to increase the public transport share (Santos et al., 2013). Public transport fares can be influenced indirectly due to changes in operation costs of public transport. Among all different travel costs, traffic signal control can influence fuel costs.

In most western European cities, motorised private transport is still dominant in road traffic. It is considered not environment-friendly in comparison to the travel modes like walking, cycling and public transport since cars generally emit more air pollutants (on per person basis with respect to public transport). Therefore, there is usually no priority measure for motorised private transport at traffic signal systems. The following paragraphs introduce the priority measures for other travel modes in detail.

### 2.5.3 Walking and its Priority at Traffic Signal Systems

Walking is a non-motorised traffic mode that brings many benefits, such as basic mobility, affordable transportation, access to other motorised modes, physical fitness and enjoyment (Litman, 2015, p. 2). Besides, there are no fossil fuels consumed and no emissions made by the pedestrian mode, which makes it sustainable and environment-friendly.

Pedestrian behaviour has some unique characteristics, which need to be considered in designing traffic signal control from a multi-modal point of view. An important aspect is the violation of traffic signals. Many influencing factors influence pedestrians to decide whether they comply with traffic signals or walk on red. Ni (2009, pp. 12-15) summarised six groups of factors that influence the non-compliance behaviour of pedestrians, including:

- human factors such as the gender, the age, mobility impairments, socio-demographic factors and psychological factors
- background factors such as the area, the size, the land use, weather and time
- traffic factors such as traffic volumes and time gaps
- the intersection geometry and layout factors such as the road width, the existence of a central island and the stop stations nearby
- signal control factors that influence waiting time
- traffic education and law enforcement factors

Pedestrians are sensitive to a long waiting time. The share of pedestrians who violate signals would significantly increase after waiting for 40 s (FGSV, 2002a, p. 23). In this case, the accident risk for pedestrians increases. However, the non-compliance behaviour of pedestrians is also influenced by other factors mentioned above and very situation-responsive. Therefore, it is difficult to isolate the influence of waiting time and conduct a quantitative analysis between the number of accidents and the signal setting.

In Germany, the basic phase sequence of a pedestrian signal is green-red-green, as regulated in p. 19 StVO. When a signal turns from green to red, pedestrians on the road must finish crossing it in a hurry. However, this leads to a problem that pedestrians are still crossing the road when the signal shows red. Previous studies (as cited in Alrutz, 2012, p. 9) pointed out that it may cause the confusion between vehicles and pedestrians since the turning vehicles may think it as the violation of traffic regulations and do not pay enough attention to the pedestrians or even drive more aggressively. Alrutz (2012) has evaluated the traditional pedestrian signal and other forms of pedestrian signals, including the display of remaining green or red time and the introduction of amber or flashing green to display clearance time. However, the conclusion is that the traditional phase sequence has the advantage of the relative good acceptance and the safe crossing.
Pedestrian crossings can be installed at the midblock location. Its form and facility depend on the pedestrian demand, the motorised traffic demand and the surrounding road situation (FGSV, 2002a, pp. 19-20). According to this guideline, when there are more than two lanes for motor vehicles, a pedestrian signal is necessary to avoid the conflicts between vehicles and pedestrians and to improve traffic safety. A pedestrian crossing can also be installed to avoid the detour between intersections or as access to the public transport station on the median. The pedestrian signal at the midblock location is generally operated as an actuated signal, at which green time for pedestrians is granted based on their requests (FGSV, 2015b, p. 15). Pedestrians need to press the push button so that their requests are registered and signal control system will jump to the green phase for pedestrians after some time. This time depends on signal settings and the real-time traffic situation.

A critical goal of the pedestrian signal is to reduce pedestrian delays. It is more uncomfortable for pedestrians, who wait at the roadside without protection against weather, than for drivers, who sit inside cars. FGSV (2002a, p. 23) suggested that pedestrians should be granted a green signal as soon as possible (after 7 s) at such kind of actuated controlled pedestrian crossings. In a green wave, the suggested value can extend to 30 s.

Another important aspect to consider is the relationship between coordination (green wave) and pedestrian signals, especially the midblock pedestrian signals. FGSV (2015b, p. 15) requires an integration of the pedestrian signals in the green wave. If there is a massive delay for crossing pedestrians due to long cycle time, the green wave is to be disrupted when necessary to protect crossing pedestrians (FGSV, 2015b, p. 15). However, the disruption may lead to more vehicle stops as well as higher fuel consumption and emissions.

At signalised intersections, pedestrian signals are usually embedded in the signal control program. Here, the pedestrian signal control can be divided into four categories (McLeod, Hounsell, and Rajbhandari, 2004):

- full pedestrian stages, where pedestrian signals for all directions are green at the same time
- parallel pedestrian stages, where pedestrian movements run in parallel with vehicles
- staggered pedestrian crossings, where the crossing movement is divided into two parts at streets with a central island
- displaced pedestrian crossings, where the crossing is set back away from the junction

The concept of the pedestrian signal priority rarely appears in research. It is similar to the control strategies that mainly serve to reduce pedestrian delays. McLeod, Hounsell, and Rajbhandari (2004) proposed a method to prioritise pedestrian flows by extending the pedestrian phase, up to a pre-set maximum value, for as long as there is continued pedestrian presence at the roadside. Results showed that this method could reduce both pedestrian delays and vehicle delays simultaneously at pedestrian crossing sites. Its main drawback was the need for the directional detection of pedestrians. There were signal control systems developed to increase safety and reduce delays for pedestrians, such as pedestrian light-controlled crossing (PELICAN), high intensity activated crosswalk (HAWK) and pedestrian user-friendly intelligent (PUFFIN) in the United Kingdom.

Previous studies have also contributed to the optimisation of pedestrian phases at intersections or midblock locations. Yu et al. (2015) proposed an optimisation model for quantity, locations and signal settings for mid-block crosswalks to achieve an optimal tradeoff between pedestrian costs including the detour distance and the delay at signalised crosswalks and vehicular costs measured by maximum bandwidths. M. Li, Alhajyaseen, and Nakamura (2010) developed a traffic signal optimisation strategy to minimise the average person delay, which is a weighted vehicle and pedestrian delay.
2.5.4 Cycling and its Priority at Traffic Signal Systems

Similar to walking, cycling is another active traffic mode that belongs to the environmental alliance. It has similar benefits with the walking mode, including improving public fitness and environmental friendliness. Cyclists can travel a longer distance than pedestrians. With the introduction of cycle highways in some cities, bicycles can be even used for trips up to 20 km (Spapé, Fuchs, and Gerlach, 2015). Another significant trend in the past years is the increased use of e-bikes and pedelecs. It supports the spread of the cycling mode as well.

The popularity of cycling differs significantly between countries. In the well-known cycling countries, such as Netherlands and Denmark, the share of cycling can reach 18 to 27% of all trips, while in other countries, the share is far below this value (Pucher and Buehler, 2008). In Germany, cycling is not as popular as in Netherlands and Denmark. However, it is gaining higher importance in transport and environmental politics in Germany as can be seen in the 2020 National Cycling Plan and the cycling promotion plans of multiple federal states (Rainer et al., 2010). Infrastructure, regulatory and management measures are planned to enhance the usage of cycling.

The signalisation of cycling has three basic forms: the shared signal with motor vehicles, the separate signal for bicycles and the shared signal with pedestrians (FGSV, 2015b, pp. 19-20). The application of different forms depends on bicycle facilities, traffic signal programs and the geometric design of intersections.

Priority for cyclists is often applied at signalised intersections along cycle highways. Cycle highways are high qualitative, direct and high-performance cycle routes between regions, cities and in the urban area (Spapé, Fuchs, and Gerlach, 2015). This study has reviewed the facilities of cycle highways in the Netherlands, Denmark, Great Britain and Germany. It was found out that cyclists are given priority at signalised intersections along cycle highways to reduce their delays. Possible measures are:

- the green wave for cyclists
- the extension of green time for cyclists
- the cyclists recognition through detectors

However, Gwiasda and Erler (2015) emphasised that the needs of other road users should not be ignored while planning a cycle highway.

The green wave for cyclists is a useful tool to reduce delays for them at signalised intersections. Similar to the green wave for motorised traffic, the signal timing of neighbouring intersections is coordinated with each other, so that road users (here cyclists) can pass them without stops and delays. The progression speed of cyclists is between 16 - 20 km/h, significantly lower than the preferred progression speed of motorised vehicles, which is between 40 - 50 km/h in the urban area (FGSV, 2015b, pp. 44-46). Therefore, the green wave for cyclists may have disadvantages for motorised vehicles and result in higher delays, more stops and therefore, more emissions. However, Gwiasda and Erler (2015) has found out from a case study that motorised traffic may not be influenced negatively from the green wave for cyclists if the road is so congested that vehicles can only drive with a low speed.

2.5.5 Public Transport and its Priority at Traffic Signal Systems

Public transport is another important member of the environmental alliance. It presents many benefits for the society, including environmental sustainability and the reduction of fossil fuel usage; the building of a strong economy by transporting people to and from work; the maintenance and the creation of jobs; congestion prevention; and the provision of access for all ages (Stjernborg and Mattisson, 2016).
According to FGSV (2015b, p. 15), trams are normally signalised with light bar signals defined in BOSstrab, as explained in Section 2.2. Buses can be signalised using the same signals if there are separate phases to prioritise them at traffic signal systems.

To promote the usage of public transport, acceleration measures are widely implemented to reduce its travel time and improve its service quality in general. One important measure at intersections is the public transport signal priority. The traffic signal program would be designed to favour a public transport vehicle and grant sufficient green time for it to pass smoothly. According to FGSV (2018b, p. 26), the following traffic control measures can be employed in order to provide priority to public transport vehicles:

- the green extension or the early green to prioritise public transport
- the stage rotation to prioritise public transport
- a demand stage
- the queue clearance while public transport vehicles approaching
- the assurance of clear access to nearside stops
- block the following vehicles at farside stops

As defined in FGSV (2018b, p. 22), acceleration measures can achieve different impacts on the operation of public transport: from a minimum reduction of delays for public transport to a free flow of public transport vehicles regardless of the intervention time. In this thesis, it is defined as conditional priority if priority is granted to public transport under certain traffic conditions. The latter is defined as absolute priority, which means a free flow of public transport vehicles is desired. For the conditional priority, the following parameters can be considered while defining the conditions when the priority is granted to public transport vehicles (Diakaki et al., 2015):

- parameters related to public transport, such as the headway and schedule adherence, the occupancy of public transport vehicles, passenger delays, the passenger waiting time at stops
- parameters related to motorised private transport, such as the saturation degree, traffic volumes at approaches, queues, delays in motorised private transport

Although they are not mentioned in the studies, parameters related to pedestrians and cyclists can also be considered, if relevant. Axon (2017) and Hildebrand (2017) introduced practical examples for applying such kind of conditional priority.

The direct benefit of applying public transport signal priority is a reduction of person delays for passengers at traffic signal systems. A reduction of delays would further improve the service quality and the attractiveness of public transport, which promotes its usage in lieu of motorised private transport. However, despite the benefits, public transport signal priority would possibly disbenefit general traffic locally and have negative impacts on other road users as well as local air pollution emissions, as stated in Dion and Rakha (2005), N. Fischer and B. Friedrich (2003), FGSV (2018b), and Wijayaratna et al. (2013). FGSV (2018b, pp. 22-24) identified the goal conflicts that may arise between public transport priority and other aspects:

- minimum green and red time
- maximum delays
- the coordination of motorised private vehicles
- conflicting public transport streams
- interventions with higher priority
- the coordination on the crossing roads
- the available space for queueing vehicles
- the saturation degree
- the mixed lane use with other vehicles or bicycles
It is, therefore, recommended to assess the **counter-effects** of public transport acceleration measures on other road users. Davies (2014) identified the importance to consider the expected costs and the expected benefits for implementing public transport signal priority, as well.

### 2.5.6 Heavy Transport and its Priority at Traffic Signal Systems

Although **heavy transport** is only a small part of the total traffic, it still needs a particular consideration because of its distinct differences in characteristics from other vehicles. The vehicle characteristics of heavy transport are different from those of cars due to the greater length, the greater mass and the lower power-to-mass ratio (Ramsay and Bunker, 2005). Besides, a HDV emits more air pollutant emissions and produces more noise than a car.

**Priority can be given to heavy transport** at intersections in order to promote efficient and safe transport of goods and to reduce emissions in the heavy transport system. Previous studies have proposed several measures for heavy transport priority at intersections, such as Blanco et al. (2010, p. 28); Ramsay and Bunker (2005):

- HDV detection or priority request: HDV can either be detected using detection technologies or send requests when approaching an intersection.
- Green time extension: The current green time can be extended to allow a HDV to pass without stopping.
- Signalised corridor offset specification: The offset can be set to favour the progression of HDV.
- The selection of appropriate minimum green time, cycle time and gap time: The parameters mentioned above can be adapted to favour HDV.

There are few studies about the **application of heavy transport signal priority**. Saunier, Sayed, and Lim (2009) presented a prototype heavy transport priority system which uses video sensors to detect, identify and track HDV. A false alarm rate below the 0.5% value was measured. Pluvinet et al. (2012) have applied signal priority measures for heavy transport to optimise energy efficiency along with the measure of speed advice for heavy vehicle drivers at three test sites. It was found out that the application of the measures has positive effects on increasing the speeds of heavy vehicles as well as reducing their number of stops and air pollutant emissions. Zhao and Ioannou (2016); Zhao and Ioannou (2019) have also proposed a traffic control system with truck priority and observed benefits for both trucks and passenger cars through the case study. Besides, the overall fuel consumption and vehicle emissions are reduced as a result. In general, the heavy transport signal priority is not widely implemented in practice.

### 2.5.7 Multi-modal Signal Priority

In traditional priority strategies for a single road user, the demands from other road users are often not fully considered. However, traffic signal control should be designed to serve all road users who are using a traffic signal system. Therefore, when several priority requests come from different road users simultaneously, the consideration of their trade-offs can improve the overall benefits for all. The concept of **multi-modal signal priority** was introduced under this circumstance.

As a basis for this concept, a **multi-modal assessment of traffic signal systems** evaluates their performances from the perspective of all traffic modes. Hunter, Wolfermann, and Boltze (2011) has proposed a methodology that evaluates the overall level of service (LOS) of a traffic signal system under consideration of the LOS of each traffic mode and the number of travellers in each mode as well as the route importance of the intersection with respect to the individual modes.

The **multi-modal signal priority** could be implemented both offline and online. For **offline implementation**, the priority level for different road users could be considered in the selection process by assigning
different weights. Some previous studies have proposed such kind of methodology and evaluated its effects. Lo, Medina, and Benekohal (2013, pp. 1-2) has applied a multi-attribute decision making method to combine the effects on four modes of transport (automobiles, buses, pedestrians, and bicycles) in selecting the most appropriate signal timing setting at an intersection. Three methods were used: Simple Average Weighting, Analytic Hierarchy Process and Technique for Order Preference by Similarity to Ideal Solution. The assigned weights reflect the priority levels for different road users. The case study has proved the potential application of the multi-attribute decision making methods in multi-modal traffic signal control.

The multi-modal signal priority can also respond online to the real-time priority requests from multiple road users. Zamanipour, Head, and Ding (2014) has used a mathematical optimisation model to deal with the priority requests from multiple road users. It was assumed that different road users could send their priority requests to infrastructures based on a modern wireless communication system. The relative importance of different road users needs to be defined by the responsible operating agency. The system has been developed and tested using both microscopic traffic simulation model and in a live network in Arizona using emerging technology developments in connected vehicle systems. A similar issue has also been investigated in He, Head, and Ding (2014) using a request-based mixed-integer linear program. The proposed signal plan could adjust itself to serve multiple priority requests from different road users and be responsive to the real-time actuation of non-priority demand using traditional vehicle actuation logic at the same time. The simulation experiments have shown the effectiveness of the proposed control model on reducing the waiting time of multiple road users. An American standard, "NTCIP Signal Control and Prioritization Standard" has established a general architectural framework for multiple road users to send priority requests at intersections.

2.6 Design of Traffic Signal Programs

Signal programs determine the signalisation of all traffic streams at an intersection or a crossing over time (Boltze, Nakamura, and Tian, 2019, p. 8). The important terms related to traffic signal programs are listed as follows. The translation and the definition of terms refer to FGSV (2015b, pp. 12-50), FGSV (2012a) and Wolfermann (2009, p. 4).

- **Stage** is a state where the signalisation remains unchanged.
- **Stream** denotes a traffic movement with unique origin and destination at an intersection.
- **Signal group** is a group of signals where all signals show the same indication at all times.
- **Stage transition** is the time between the end of one stage and the beginning of another.
- **Transition time** is the time of transition signals (yellow or yellow-and-red).
- **Intergreen time** is the time between the end of the green time of one stream and the beginning of the green time of a subsequent conflicting stream.
- **Cycle time** is the time of a single run of traffic signal program.
- **Green time** is the time when the signal shows green.
- **Red time** is the time when the signal shows red.

When designing a traffic signal program, one important step is to design the signal structure, which includes four components (FGSV, 2015b, pp. 12-21):

- stage design
- number of stages
- stage sequence
- stage transition

The **stage design** and the **number of stages** show how streams are signalised and how they are assigned to stages. The **stage sequence** tells in which sequence the stages appear in one run of a traffic signal program. The **stage transition** shows how signals change during the time between two stages. There
are many possibilities for the stage design. RiLSA (FGSV, 2015b, pp. 12-21) describes different forms to signalise left-turning streams, right-turning streams, public transport, walking and cycling. They should be considered while designing stages. Although more stages can allow a safer traffic operation, they may also increase the number of stage transitions and the cycle time and thus reduce the capacity of the intersection (Boltze, Nakamura, and Tian, 2019, p. 10). While in North America ring-barrier structure is a standard practice, the concept of intergreen time is widely used in Europe (Boltze, Nakamura, and Tian, 2019, p. 10).

Another important step to design a traffic signal program is the calculation of signal timing parameters, which include transition time, intergreen time, cycle time, green time and red time. Depending on situations, the corresponding transition time is already given in RiLSA (FGSV, 2015b, p. 21). The intergreen time depends on the geometry design and the layout of the intersection as well as the clearing or entering speeds of road users. RiLSA (FGSV, 2015b, pp. 21-26) proposes a complex method to calculate it.

There are different kinds of traffic signal programs depending on the changeability of the stage design and signal timing parameters. The changeable components are the cycle time, the stage sequence, the number of stages, the green time and the offset (FGSV, 2015b, p. 37). A fixed-time program means that all the components remain unchanged. In a traffic-actuated program (or rule-based program), the changeable components are adapted or built up following a predefined control logic. The decisions for signal programs and related actions depend directly on collected parameters in the real-time situation. An adaptive traffic signal program (or a model-based signal program) bases not directly on the collected parameters, but uses the processed values from models to derive the suitable stage design and signal timing parameters.

Coordination (or green wave) is a form of signal program where the green time of neighbouring signal systems is coordinated with certain offsets (FGSV, 2015b, p. 43). It aims to enable the smooth progression of road users along a sequence of traffic signals without stops. Thus, it is usually implemented to reduce travel time, energy consumption and vehicle emissions (FGSV, 2015b, p. 43). Burdens on road users can be the long delays for minor streams (or added delays) and a lack of responsiveness, particularly when there is high demand on conflicting movements (Urbanik et al., 2015, pp. 7-2).

This thesis focuses mainly on the German method for designing traffic signal programs since it is conducted in Germany. If D-MoTSE is conveyed to analyse traffic signals in other countries, their specialities should be considered.

2.7 Situation-responsive Traffic Signal Control

Measures of traffic management can be activated using different strategies: permanent (statically), according to a fixed time plan (time-dependent) and under certain traffic or environmental situations (situation-responsive) (Boltze, Krüger, and Balluff, 2012, p. 9). The traffic signal control can also be situation-responsive in the way that the signal plan corresponds to not only variable traffic situations but also other environmental conditions such as air quality and weather conditions.

Although a permanent implementation of traffic measures can have stronger effects, the ineffectiveness of such activation strategy was identified in Boltze, Kohoutek, and Krüger (2011). With an experimental calculation under many assumptions, the study estimated the potential of situation-responsive interventions in traffic signal control to reduce NOx and PM emissions so that the threshold values of the annual average concentrations can be fulfilled. Four situations according to the air quality level and queue lengths at intersections were identified. The results showed that a large percentage of the effects by permanent activation can already be achieved if interventions are activated in certain situations that only occur in a small part of the whole period.
There were previous studies that proposed situation-responsive traffic control systems or measures. Diegmann (2014) gave an overview of the case studies about situation-responsive traffic control measures which was targeted at reducing air pollutant emissions. The review of twelve case studies in German cities has identified the potential of reducing NO\textsubscript{x} pollution level to be between several per cents and almost 30\% and that of PM\textsubscript{10} to be up to 10 exceedance days. The potential effects depend strongly on the activation rate. Besides the air quality level, weather conditions can also be considered in the dynamic adjustment of traffic signal control. Setälä, Kosonen, and Luttinen (2008) proposed a traffic and weather responsive adaptive signal control system to enhance an existing intelligent signal control system. The system has been tested using simulations. Results showed improvements in the performance of intersections as well as in safety.

2.8 Conclusions

This chapter gives an overview of the relevant aspects of road traffic signal control. The literature review identifies the following principles that guide the development of the evaluation method for traffic signal control in the framework of this thesis:

• **Traffic signal control has impacts on multiple criteria that need to be considered in its design.**
  
  In general, there are four main goals for traffic signal control, including traffic safety, traffic flow quality, fuel consumption and emissions as well as economic efficiency. Conflicts of interest can exist between different goals and their related criteria. An assessment of traffic signal control from a multi-criteria point of view is necessary.

• **Traffic signal systems serve users of different traffic modes that need to be considered in its design.**
  
  Various traffic modes share the space at intersections, including walking, cycling, public transport, motorised private transport and heavy transport. There are priority measures that prefer a specific traffic mode in order to reduce its delays at a traffic signal system. However, that may result in disadvantages to other traffic modes. A multi-modal evaluation of traffic signal control is recommended.

• **A fair balance between multiple criteria and different traffic modes is necessary while designing and evaluating traffic signal control.**
  
  Conflicts of interest may occur not only between different criteria but also between various traffic modes. The evaluation of traffic signal control should be able to deal with the goal conflicts and to make the trade-off process comprehensive and transparent.

• **The basic terms related to traffic signal programs will be used while designing alternative signal programs for evaluation.**
  
  The signal structure and signal timing parameters need to be defined while designing traffic signal programs. Depending on their changeability, traffic signal programs can be divided into fixed-time, traffic-actuated and adaptive programs. Besides, coordination is a special form of signal programs, which is widely implemented. All the related terms will be used while designing alternative signal programs for evaluation.

• **It is proposed to consider the situation responsiveness in the evaluation of traffic signal control.**
  
  The traffic signal control can be designed situation-responsive in the way that the signal plan corresponds to not only variable traffic situations but also other environmental conditions. It helps to improve the performance and the efficiency of traffic signal control, and in the meantime, reduce the frequency of interventions.
3 Basics of Evaluation Methods

3.1 Introduction

The keyword of this chapter is evaluation. In the beginning, Section 3.2 defines the term evaluation and establishes its basic principles. Further on, the focus of the next section (Section 3.3) lays more specifically on the evaluation methods in transport planning. Finally, the existing evaluation methods for traffic signal control are reviewed in Section 3.4.

3.2 General Issues about Evaluation Methods

Evaluation is an important procedure in various fields of scientific and social research. Despite the differences in details, various evaluation methods for different purposes share some similar basic issues or principles, as explained in the following sections.

Definition of evaluation

In a broad meaning, evaluation means the process of judging something's quality, importance, or value (Cambridge dictionary 2017). A similar definition is given in the standards for evaluation published by the German Evaluation Society (original German name: Gesellschaft für Evaluation (DeGEval)). Evaluation is defined here as a systematic investigation of the quality or utility of a target of evaluation. It has the following characteristics (DeGEval, 2016, p. 13):

- It is a comprehensive systematic approach based on empirically gained data.
- It should be transparent and follow certain criteria.
- The targets of evaluation can be various, e.g. projects, measures and other intervention, organisation, products as well as the evaluation itself.

These characteristics are emphasised in the definition of evaluation methods for some specific targets as well. Rossi, Lipsey, and Freeman (2006, p. 17) defined the program evaluation as the use of social research methods to systematically investigate the effectiveness of social intervention programs. It was emphasised that the concept of evaluation should entail not only a description of the performance of the evaluated entity but also some standards or criteria for judging the performance (Rossi, Lipsey, and Freeman, 2006, p. 17). In FGSV (2012c, p. 5), the evaluation of transport-related measures was defined as a systematic analysis and interpretation of information to assess the implementation and impacts of measures.

Objectives of evaluation

An evaluation is a decision support tool and an important component of the trade-off process (FGSV, 2012c). The evaluation aims mainly to (DeGEval, 2016, p. 13):

- improve the evaluation target
- enable the decisions about the evaluation target
- gain knowledge about the evaluation target
- support the learning and the dialogue about the evaluation target
- report about the evaluation target
Time to conduct evaluation

The evaluation is an integrated component of the planning process (FGSV, 2018a, p. 13). It can be conducted not only in the planning process but also during the operation of projects, measures or other processes (FGSV, 2012c, p. 7).

General process of evaluation

Depending on the complexity, evaluation methods can be grouped into non-formalised, partially formalised and formalised procedures (FGSV, 2018a, p. 33). The processes can vary for different groups of evaluation methods, and even for different methods in the same group. Fornauf (2015, pp. 52-56) reviewed different evaluation methods and summarised the possible processes as shown in Table 3.

Table 3: Description of the general processes for evaluation (source: Fornauf, 2015, pp. 52-56)

<table>
<thead>
<tr>
<th>Process</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Definition of a goal system</td>
<td>The goal system is a structured system of relevant goals that evaluation targets aim to achieve. The priority of goals can be defined.</td>
</tr>
<tr>
<td>Definition of evaluation criteria</td>
<td>The evaluation criteria are parameters that can be used to judge the performance of evaluation targets to achieve the defined goals.</td>
</tr>
<tr>
<td>Formulation of constraints</td>
<td>The constraints related to the evaluation targets need to be defined, which may involve physical, budgetary, legal, administrative or political aspects.</td>
</tr>
<tr>
<td>Development of alternatives</td>
<td>The evaluation method can target at several alternative programs to compare their performance.</td>
</tr>
<tr>
<td>Definition of MOEs</td>
<td>The Measures Of Effectiveness (MOEs) are quantifiable and correspond to the evaluation criteria.</td>
</tr>
<tr>
<td>Data collection</td>
<td>Data collection provides important data basis for the measurement of parameters.</td>
</tr>
<tr>
<td>Weighting of criteria</td>
<td>Weighting can be used to reflect the priority of different criteria.</td>
</tr>
<tr>
<td>Discounting</td>
<td>For long-term projects, future costs need to discounted to the present value.</td>
</tr>
<tr>
<td>Measurement of criteria values</td>
<td>The measured values serve as basis for further steps. In general, parameters can be qualitatively or quantitatively measured.</td>
</tr>
<tr>
<td>Assessment of performance</td>
<td>The measured values can be compared with guidance values, reference values or threshold values to assess the performance of evaluated targets to achieve the predefined goals.</td>
</tr>
<tr>
<td>Normalisation of criteria values</td>
<td>The multidimensional values shall be normalised to the same scale.</td>
</tr>
<tr>
<td>Aggregation</td>
<td>The multiple criteria shall be transformed or aggregated following certain rules to derive the overall evaluation result. This overall result is especially useful for comparing alternatives.</td>
</tr>
<tr>
<td>Ranking of alternatives</td>
<td>The evaluation results can be used to rank the alternatives with regards to their performance to achieve the predefined goals.</td>
</tr>
</tbody>
</table>
Not all these processes are obligatory for all evaluation methods. Some of the steps can be irrelevant for certain methods. Therefore, it is necessary to define the actual procedure while developing the evaluation method for traffic signal control. This is described in detail in Section 4.2.

**Standards for evaluation**

A good evaluation method should fulfil certain standards in order to ensure qualified and generally acceptable results. The standards can be grouped into four groups: utility, feasibility, fairness and accuracy (DeGEval, 2016, pp. 17-31; Yarbrough, 2011).

**Utility** seeks to ensure that the evaluation methods can achieve their goals and serve to provide the users with the required information. **Feasibility** seeks to ensure that an evaluation is realistic, prudent, diplomatic and frugal. **Fairness** seeks to ensure that the persons and groups, which are involved in the evaluation, are treated respectfully and fair. **Accuracy** seeks to ensure that an evaluation reveals appropriate and comprehensive information and results about the evaluation targets or questions (DeGEval, 2016, pp. 17-31; Yarbrough, 2011). Table 4 demonstrates the concrete standards that belong to each group.

<table>
<thead>
<tr>
<th>Group</th>
<th>Single standard</th>
</tr>
</thead>
</table>
| Utility | • Identification of stakeholder  
          • Clarity of purposes  
          • Credibility of evaluator  
          • Selection and scope of information  
          • Transparent values  
          • Complete and clarified report  
          • Timely evaluation  
          • Use of evaluation |
| Feasibility | • Appropriate method  
                  • Practical procedure  
                  • Efficiency of evaluation |
| Fairness | • Formal agreements  
               • Protection of individual rights  
               • Comprehensive and fair assessment  
               • Neutral implementation and reporting  
               • Disclosure of findings |
| Accuracy | • Description of evaluation targets  
                • Context analysis  
                • Description of purposes and procedures  
                • Disclosure of information sources  
                • Validated and reliable information  
                • Systematic error check  
                • Appropriate analysis of qualitative and quantitative information  
                • Justified evaluations and conclusions  
                • Meta-evaluation |
Fornauf (2015, pp. 47-52) has defined the following criteria to select the appropriate evaluation methods for dynamic transport management strategies: effort, the availability of data, understandability, objectivity, transparency, reliability, comparability, accuracy and validity. In comparison to the standards in Table 4, these criteria are more abstract. However, the basic principles are similar. Developing and implementing the evaluation method for traffic signal control should pursue the standards mentioned above.

### 3.3 Existing Evaluation Methods in Transport Planning

Evaluation methods in transport planning can be categorised into three groups: **non-formalised**, **partially formalised** and **formalised methods**. Fornauf (2015, pp. 56-72) reviewed different kinds of evaluation methods and concluded that the more formalised a method is, the higher is its degree of quantification. He noted that the non-formalised methods only deliver argumentative and qualitative results while formalised methods provide quantitative results, which help to compare alternatives directly. Partially formalised methods require a combination of quantitative and qualitative analysis (Fornauf, 2015, pp. 56-72). The estimated quantitative effects of transport projects can serve as the basis for a qualitative decision-making procedure, e.g. a pairwise comparison or a strength-weakness-profile (FGSV, 2010b, p. 15).

These methods are mainly applicable for the evaluation of transport projects or transport-related measures, whereas an application in the evaluation of traffic signal control is rare. However, they contain numerous methods to evaluate and monetise various transport-related impacts, which can also be applied for the evaluation of traffic signal control. Therefore, a brief overview of the evaluation methods for transport planning is given in the following subsections.

#### 3.3.1 Non-formalised Methods

Non-formalised methods compare various alternatives based only on qualitative descriptions or arguments, for which a quantification of the relevant impacts is not necessary (FGSV, 2010b, p. 15). Some examples for non-formalised methods are (FGSV, 2010b, p. 15; Fornauf, 2015, pp. 58-61):

- intuitive method
- SWOT analysis
- expert judgement
- public discussion

The listed methods were elaborated in Fornauf (2015, pp. 58-61) and FGSV (2010b, p. 15). A summary of these methods is provided in the following paragraph. Although more examples are available, they are not explicitly explained here due to their similarity to the methods mentioned above.

The **intuitive method** means an overall evaluation based on the experiences and personal valuations of one evaluator. The advantage of this method is the low workload and time requirement. However, the opinions of one single person can be subjective, which limits the transparency and the traceability of the decision-making process. The **SWOT analysis** means a collection of arguments concerning four aspects: Strengths, Weaknesses, Opportunities and Threats. For the evaluation, it is necessary to consider that a strategy should use the existing strengths and reduce the weaknesses, in order to increase the chances of achieving the predefined objectives and to avoid the identified risks. The **expert judgement** bases the evaluation on the opinions of experts, who have professional knowledge of the corresponding topic area. A special form of the **expert judgement** is the Delphi technique. It follows an iterative process with multiple rounds of expert interviews and subsequent statistical analyses to obtain results. Another method is the **public discussion**. In this form, all stakeholders for decision-making need to be gathered together to find out the best alternative through negotiation.
In summary, non-formalised methods can barely provide comprehensive and objective evaluation results due to the lack of quantification (Fornauf, 2015, pp. 58-61). Due to their advantages of flexibility, low cost and simple implementation, they are usually applied in the first stage of a project assessment, after which more sophisticated evaluation procedures may follow (FGSV, 2010b, p. 15). However, the design of signal timing is an engineering topic, which requires quantification of the relevant effects as well as trade-offs between different criteria and traffic modes. Non-formalised methods are not able to fulfil this requirement and therefore not appropriate for the evaluation of traffic signal control.

3.3.2 Partially Formalised Methods

Partially formalised methods require a quantified impact assessment but a qualified comparison between the evaluated alternatives. Examples for partially formalised methods include (Fornauf, 2015, pp. 61-65; FGSV, 2010b, pp. 16-21):

- multi-criteria impact analysis
- compatibility analysis
- elimination analysis
- simple ranking method

The listed methods are similar in the way that the various impacts remain to be shown in their original scales (FGSV, 2010b, pp. 16-21). However, they use different techniques to display the multi-dimensional impacts.

The first three methods all display various impacts using a strengths-weaknesses profile, based on which, evaluation decisions are made. The strengths-weaknesses profile looks similar to a wind rose graph, and shows the performance of the evaluated alternative with regards to various criteria, which are represented by axes in different directions. However, the first three methods use different techniques to derive results from the strengths-weaknesses profile, which are summarised as follows (FGSV, 2010b, pp. 16-21). During a multi-criteria impact analysis, comparisons between the strengths-weaknesses profiles are made. In a compatibility analysis, another requirement profile is defined additionally. The ability of an alternative to reach the predefined objective is assessed by comparing its strengths-weaknesses profile and the requirement profile. An elimination analysis eliminates the unsatisfactory alternatives by iterative tightening of the requirement profile.

The last method - simple ranking method - establishes a rank for the alternatives by pairwise comparison with regards to different goals using a comparison matrix (Fornauf, 2015, p. 65). The number of winning of each alternative is the basis for further ranking them.

The partially formalised methods mentioned above have the potential to be used in the evaluation of traffic signal control. However, the following limitations apply to the design of traffic signal control under consideration of various criteria and traffic modes involved.

First, it is complicated to establish and compare strengths-weaknesses profiles if there are a large number of criteria of concern. Weighting criteria is necessary in this case, but difficult to conduct, since the strengths-weaknesses profiles support only qualitative trade-offs between criteria. This limitation applies to the multi-criteria impact presentation, the compatibility analysis and the elimination analysis. For the simple ranking method, the complexity also increases dramatically, if the number of criteria increases. Second, the workload increases sharply, as the number of alternatives to be evaluated increases since most partially formalised methods use pairwise comparison to choose the most suitable alternative.

In summary, there is a sharp increase in workload and complexity due to the lack of aggregation procedure if there is a large number of criteria and alternatives. It can be considered as an advantage because the impacts are presented in their original scales, and no information gets lost (FGSV, 2010b,
However, this could also be a constraint for applying these methods in the evaluation of traffic signal control.

### 3.3.3 Formalised Methods

Formalised methods have a **stringent structure and process** as well as a **high degree of quantification** (Fornauf, 2015, p. 66). Various impacts, no matter qualitative or quantitative, are transferred and aggregated to an overall result, which serves as the basis for further decision-making. Examples of formalised methods are:

- cost-benefit analysis
- cost-effectiveness analysis
- multi-attribute utility theory

Another two formalised methods mentioned in (Fornauf, 2015, pp. 66-72) - formalised weighting and ranking method and **Analytic Hierarchy Process (AHP)** - use pairwise comparison in the evaluation and have a similar problem of complexity like non-formalised methods. Therefore, they are not explained here in details.

The **cost-benefit analysis** is widely applied for the evaluation of infrastructure projects, e.g. street facilities and vehicles. Countries all around the world have developed their frameworks for the **cost-benefit analysis** in transport planning (Mackie and Worsley, 2013). The critical concept of the **cost-benefit analysis** is to compare alternatives based on their benefits and costs, which are all expressed in monetary values (FGSV, 2010b, p. 25). Cost rates are needed to convert the benefits of the evaluated transport projects, e.g. save of time or reduction in air pollution emissions, into the corresponding monetary values. Since the planning and the implementation of such infrastructure projects usually last for several years, a discounting of the costs over a long period to the current price is necessary in some cases. A ranking of alternative projects can then be derived by comparing their total benefits and costs.

The **cost-efficiency analysis** is different from the **cost-benefit analysis** concerning the way to express the benefits of evaluated projects. In this process, they are converted with an objective function (or a utility function) into dimensionless values (utility scores) to represent the performance of alternatives on the defined objectives (FGSV, 2010b, p. 29). Multiple utility scores for different objectives can be weighted and aggregated to build the overall efficiency. FGSV (2010b, p. 29) pointed out the following advantages and disadvantages of the **cost-efficiency analysis**. It has the advantage that non-quantifiable benefits can be considered in the framework. However, the conversion of absolute values to dimensionless efficiency values shows significant flexibility. Besides, a sensitivity analysis is necessary due to the usage of subjective weights during the aggregation.

During a **multi-attribute utility theory**, all relevant aspects (including benefits and costs) are converted into the utility scores for the defined objectives (FGSV, 2010b, p. 27; Ishizaka and Nemery, 2013, pp. 81-82). The total utility includes the utility scores for not only benefits but also costs. This formalised method has similar advantages and disadvantages like the **cost-efficiency analysis**. The only difference is that the costs are also converted into the utility scores and aggregated with the benefit scores, but not compared against them. Therefore, statements about efficiency (benefits against costs) cannot be given (FGSV, 2010b, p. 27).

**Cost-benefit analysis** is widely implemented in guidelines for the evaluation of transport projects in the planning process across countries. Although these well-established guidelines cannot be directly applied to the evaluation of traffic signal control, valuable hints can still be derived from the original methodologies to be transferred in this new application area. An important aspect is the methods to **monetise transport-relevant impacts**. There are various impacts generally considered in the evaluation of transport projects, including (Bickel et al., 2006; FGSV, 2010b, p. 24):
• changes in travel time or congestions
• changes in operation costs
• changes in accident risks
• changes in emissions (air pollution, noise and global warming)
• separation effects and land-use changes

Among these impacts, separation effects and land-use changes are not relevant for the evaluation of traffic signal control, since it is operated on existing road infrastructures. Operation costs include many aspects. Some of them can be influenced by traffic signal control, such as fuel consumption, while some not. The cost rates for non-relevant aspects are not reviewed in the following paragraphs.

Since cost rates are very country-specific, only the most relevant documents in Germany are presented here in detail:

• State Level Road Infrastructure Planning and Appraisal, original German title "Empfehlungen für Wirtschaftlichkeitsuntersuchungen an Straßen (EWS)"
• Federal Transport Infrastructure Plan, original German title "Bundesverkehrswegeplan (BVWP)"
• Developing Harmonised European Approaches for Transport Costing and Project Assessment (HEATCO)

**State Level Road Infrastructure Planning and Appraisal (EWS)**

EWS is a German guideline for the economic appraisal of road investments (FGSV, 1997). FGSV originally published it in the year 1997. Five years later, another publication compiled all relevant articles about practical experiences and further development of EWS that were published in journals in the period 1997-2002 (FGSV, 2002b). Table 5 summarises part of the cost rates in EWS, which are relevant for the evaluation of traffic signal control.

As shown in Table 5, the cost rates are still expressed in the old German currency Deutsche Mark (DM) and remain at the price of the year 1995. Therefore, they could only serve as an orientation for the development of the evaluation method. However, the values are not up-to-date and should not be further used. The EWS is currently under revision (FGSV, 2017). The updated methodology and cost rates may be used in the future as a reference for the further development of the evaluation method that is proposed in this thesis.

**Federal Transport Infrastructure Plan (BVWP)**

The current version of BVWP is BVWP 2030, which was published by the German Federal Ministry of Transport and Digital Infrastructure (original German name: Bundesministerium für Verkehr und digitale Infrastruktur (BMVI)) in the year 2016. The projects included in the BVWP 2030 were evaluated using an appraisal approach documented in Dahl, Kindl, et al. (2016). One part of this appraisal approach is a cost-benefit analysis, which covers a wide range of transport-related impacts, which include not only the general aspects mentioned above but also the difference of implicit benefits due to modal shifts.

Table 6 shows the cost rates according to the appraisal approach of BVWP 2030, which are related to the possible direct impacts of traffic signal control. During the preparation of BVWP 2030, several research projects were initiated by the BMVI in order to review and improve the evaluation method. The values in BVWP 2030 represent the most updated progress in research and knowledge (at 2012 price) in comparison to other evaluation methods. Therefore, they are used as a reference for the thesis.

Different from EWS, the environmental costs are calculated here using exhaust emissions instead of ambient air quality. The toxicity of different air pollutants and their impacts on human health are considered while determining the corresponding cost rates. Five air pollutants are considered, including...
### Table 5: Cost rates according to EWS (source: own illustration based on FGSV, 1997; FGSV, 2002b)

<table>
<thead>
<tr>
<th>Main goal</th>
<th>Parameters</th>
<th>Monetary values</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mobility</td>
<td>Walking</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Cycling</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>PuT</td>
<td>125</td>
<td>DM/veh-h</td>
</tr>
<tr>
<td></td>
<td>PrT</td>
<td>11</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Heavy transport</td>
<td>42/60</td>
<td></td>
</tr>
<tr>
<td>Traffic safety</td>
<td>Number of accidents</td>
<td>11,000–290,000</td>
<td>DM/accident</td>
</tr>
<tr>
<td></td>
<td>Number of slight injuries</td>
<td>7,500</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Number of severe injuries</td>
<td>170,000</td>
<td>DM/person</td>
</tr>
<tr>
<td></td>
<td>Number of deaths</td>
<td>2,400,000</td>
<td></td>
</tr>
<tr>
<td>Emissions</td>
<td>Exhaust emissions</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Ambient air quality</td>
<td>47,000</td>
<td>DM/SEG&lt;sup&gt;a&lt;/sup&gt;-a</td>
</tr>
<tr>
<td></td>
<td>Noise emissions</td>
<td>85</td>
<td>DM/LEG&lt;sup&gt;b&lt;/sup&gt;-a</td>
</tr>
<tr>
<td></td>
<td>CO&lt;sub&gt;2&lt;/sub&gt; emission</td>
<td>180</td>
<td>DM/t-CO&lt;sub&gt;2&lt;/sub&gt;</td>
</tr>
</tbody>
</table>

<sup>a</sup> SEG (pollutant-resident-values; German: Schadstoff-Einwohner-Gleichwerte) are calculated using the toxicity factor of one air pollutant, the ambient air quality and the number of affected residents.

<sup>b</sup> LEG (noise-resident-values; German: Lärm-Einwohner-Gleichwerte) are calculated using the sound level and the number of affected residents.

NO<sub>x</sub>, CO, HC, PM and SO<sub>2</sub>. However, the proposed cost rates for PM are only applicable to particles emitted by the combustion process, not for those from resuspension and wear.

A new component in the BVWP 2030 is the **difference of implicit benefit**, which values the changes in costs due to modal shifts. It is calculated using the number of switching users as well as the ex-ante and ex-post user costs of both traffic modes (Dahl, Meunier, et al., 2016). In order to calculate the total cost, this additional component is added to other components while keeping them unchanged (Dahl, Meunier, et al., 2016).

The BVWP 2030 is applied to evaluate the federal infrastructure projects, which might lead to significant changes in **modal shifts**, at least on specific routes. In comparison to infrastructure projects, the modification of traffic signal control might cause less significant changes in modal shifts. They are only measurable on a macroscopic level, if there are any. Still, they should not be ignored.
Table 6: Cost rates according to BVWP 2030 (source: own illustration based on Axhausen et al., 2014; Dahl, Kindl, et al., 2016)

<table>
<thead>
<tr>
<th>Main goal</th>
<th>Parameters</th>
<th>BVWP 2030</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Cost rate</td>
</tr>
<tr>
<td>Mobility</td>
<td>Delay for vehicles</td>
<td>Walking</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Cycling</td>
</tr>
<tr>
<td></td>
<td>PuT</td>
<td></td>
</tr>
<tr>
<td></td>
<td>PrT</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Heavy transport</td>
<td></td>
</tr>
<tr>
<td>Traffic safety</td>
<td>Number of accidents</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Number of slight injuries</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Number of severe injuries</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Number of deaths</td>
<td></td>
</tr>
<tr>
<td>Emissions</td>
<td>NO\textsubscript{x}</td>
<td></td>
</tr>
<tr>
<td></td>
<td>CO</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Exhaust emissions</td>
<td>HC</td>
</tr>
<tr>
<td></td>
<td></td>
<td>PM</td>
</tr>
<tr>
<td></td>
<td>SO\textsubscript{2}</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Ambient air quality</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Noise emissions</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Fuel consumption</td>
<td></td>
</tr>
<tr>
<td></td>
<td>CO\textsubscript{2} emission</td>
<td></td>
</tr>
</tbody>
</table>

Developing Harmonised European Approaches for Transport Costing and Project Assessment (HEATCO)

The European project HEATCO aimed to develop a uniform tool to assess the performance of transport and energy systems on a European basis. This study not only proposed an evaluation methodology but also suggested country-specific cost rates based on the information gathered from different European countries. Table 7 shows the cost rates for Germany that were suggested in the framework of HEATCO.

As shown in Table 7, HEATCO gave only the value of time for public transport and motorised private transport. For heavy transport, the cost of transported products is considered instead of the personal value of time for the driver or passengers. The value of safety differentiated between slight injuries, serious injuries and deaths. The values are relatively higher than the values in EWS.

Different from EWS, the environmental cost rates in HEATCO do not relate to the ambient air quality, but to exhaust emissions. The following air pollutants are considered in the study: NO\textsubscript{x}, NMVOC, SO\textsubscript{2}.
and PM$_{2.5}$. The usage of emissions in the evaluation methodology reduces the complexity and the effort to measure or estimate the parameters. However, other factors, such as meteorological conditions and affected population, also influence the health impacts of emissions and the corresponding cost rates significantly. In the framework of HEATCO, these factors are considered for different countries while developing the country-specific cost rates (Bickel et al., 2006, p. 17). Due to the complete difference in related parameters, it is difficult to compare the cost rates between EWS and HEATCO directly.

Table 7: Cost rates according to HEATCO (source: own illustration based on Bickel et al., 2006)

<table>
<thead>
<tr>
<th>Main goal</th>
<th>Parameters</th>
<th>HEATCO 2006</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Cost rate</td>
</tr>
<tr>
<td>Mobility</td>
<td>PuT</td>
<td>4.85-22.35</td>
</tr>
<tr>
<td></td>
<td>PrT</td>
<td>6.74-27.86</td>
</tr>
<tr>
<td>Traffic safety</td>
<td>Number of accidents</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Number of slight injuries</td>
<td>18,600</td>
</tr>
<tr>
<td></td>
<td>Number of severe injuries</td>
<td>229,400</td>
</tr>
<tr>
<td></td>
<td>Number of deaths</td>
<td>1,661,000</td>
</tr>
<tr>
<td>Emissions</td>
<td>NO$_x$</td>
<td>3,100</td>
</tr>
<tr>
<td></td>
<td>NMVOC</td>
<td>1,100</td>
</tr>
<tr>
<td></td>
<td>SO$_2$</td>
<td>4,500</td>
</tr>
<tr>
<td></td>
<td>PM$_{2.5}$</td>
<td>430,000/80,000</td>
</tr>
<tr>
<td></td>
<td>Ambient air quality</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Noise emissions</td>
<td>0-441</td>
</tr>
<tr>
<td></td>
<td>CO$_2$ emission</td>
<td>26</td>
</tr>
</tbody>
</table>

3.4 Existing Evaluation Methods for Traffic Signal Control

Evaluation is an important component of the existing methods to plan or optimise traffic signal control. There are not only methods that can be directly applied (e.g. an assessment of LOS), but also those that are implicitly embedded in the optimisation models (e.g. a performance index). The following subsections provide a detailed description on these aspects.
The most commonly used method to evaluate traffic signal control is the **Highway Capacity Manual (HCM)**, which provides a set of methodologies and associated application procedures for evaluating the performance of street facilities in terms of operational measures and one or more quality-of-service indicators (TRB, 2010, pp. 1-2). Although highway facilities can also be evaluated using the HCM, they are not discussed here, since there are usually no traffic signal systems on highways, except the ones for ramp metering.

The first HCM was published in the United States in the year 1950, which initially focused on the quantification of capacity for transportation facilities (TRB, 2010, pp. 1-1). Since then, significant improvements have been undertaken by introducing the concept of the LOS and broadening the assessment methods to consider all roadway users and more performance measures. The **United States version of HCM (US-HCM)** is also widely implemented and quoted in other countries to assess the performance of street facilities (Ravinder, Velmurugan, and Gangopadhyay, 2014).

Inspired by the ideas of the US-HCM, other countries have also developed their own technical guidelines to assess the capacity and further the performance of street facilities, such as China, Germany, India, Netherlands and Sweden (Bergh et al., 2016; Heikoop and Henkens, 2016; Lemke, 2016; Ravinder, Velmurugan, and Gangopadhyay, 2014; Zhou et al., 2016). Since **HCMs in different countries** have many similar basic ideas and structures, the focus of the following literature review lies only on the US-HCM and the German HCM.

The German HCM, commonly abbreviated as the **HBS**, was first officially approved in the year 2001 by FGSV. Since then, it has been widely implemented at the stage of planning and preliminary engineering to assess the design of a future or rebuilt facility in Germany (Lemke, 2016).

The HBS and the US-HCM follow a similar methodology. Both methods use the **LOS**, a quantitative stratification, to describe how well a transportation facility or service operates from a traveller’s perspective (TRB, 2010, pp. 5-2). Six levels of service are defined, ranging from A (the best) to F (the worst).

Both guidelines focus mainly on the **quality of traffic flows** for evaluating the performance of signalised intersections. Fuel or energy consumption is not considered in the evaluation. For motorised vehicles, the criteria to determine the LOS are the same in both guidelines, namely, the delay and the volume-capacity ratio. A comparison of the threshold values for motorised vehicles between both guidelines are shown in Table 8.

For non-motorised traffic modes, the HBS and the US-HCM use **different criteria to assess the LOS**. In the HBS, the LOS is based on the maximum delay of pedestrians and bicycles (FGSV, 2015a, pp. 4-9). In the US-HCM, the LOS is determined by the traveller’s perception score. The delay and the availability of circulation areas are combined into a pedestrian perception score, while a bicycle score is derived only from the bicycle delay (TRB, 2010, pp. 18-7 - 18-73). Table 9 shows the comparison of the threshold values for non-motorised modes between both guidelines.

In the United States, the **Transit Capacity and Quality of Service Manual (TCQSM)** (Brinckerhoff, 2013) is an accompanied manual to the US-HCM that documents the methods for evaluating the service quality of public transport. The HBS and the TCQSM apply different methods for estimating the public transport LOS. For public transport vehicles on separated lanes, the HBS uses the average delay to determine the LOS (FGSV, 2015a, pp. 4-9). In the TCQSM, a relatively complex methodology is introduced to determine the LOS, which incorporates factors that bear on all aspects of a public transport trip up to the point that a passenger boards a vehicle at a stop along an urban street (Brinckerhoff, 2013, pp. 5-39):

- walking to the stop satisfaction
- waiting for public transport service satisfaction
- on-board satisfaction
Table 8: Comparison of the LOS threshold values for motorised private vehicles between the HBS and the US-HCM (source: own illustration based on FGSV, 2015a, pp. 4-9; TRB, 2010, pp. 18-6)

<table>
<thead>
<tr>
<th>LOS</th>
<th>HBS Average delay (s/veh)</th>
<th>US-HCM Average delay (s/veh)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Volume-capacity ratio (-)</td>
<td>Volume-capacity ratio (-)</td>
</tr>
<tr>
<td>A</td>
<td>≤ 20 AND v/c ≤ 1</td>
<td>≤ 10 AND v/c ≤ 1</td>
</tr>
<tr>
<td>B</td>
<td>≤ 35 AND v/c ≤ 1</td>
<td>≤ 20 AND v/c ≤ 1</td>
</tr>
<tr>
<td>C</td>
<td>≤ 50 AND v/c ≤ 1</td>
<td>≤ 35 AND v/c ≤ 1</td>
</tr>
<tr>
<td>D</td>
<td>≤ 70 AND v/c ≤ 1</td>
<td>≤ 55 AND v/c ≤ 1</td>
</tr>
<tr>
<td>E</td>
<td>&gt; 70 AND v/c ≤ 1</td>
<td>≤ 80 AND v/c ≤ 1</td>
</tr>
<tr>
<td>F</td>
<td>v/c &gt; 1</td>
<td>&gt; 80 OR v/c &gt; 1</td>
</tr>
</tbody>
</table>

Table 9: Comparison of the LOS threshold values for non-motorised modes between the HBS and the US-HCM (source: own illustration based on FGSV, 2015a, pp. 4-9; TRB, 2010, pp. 18-7)

<table>
<thead>
<tr>
<th>LOS</th>
<th>HBS Maximum delay (s/p)</th>
<th>US-HCM Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>≤ 30</td>
<td>≤ 2.00</td>
</tr>
<tr>
<td>B</td>
<td>≤ 40</td>
<td>≤ 2.75</td>
</tr>
<tr>
<td>C</td>
<td>≤ 55</td>
<td>≤ 3.50</td>
</tr>
<tr>
<td>D</td>
<td>≤ 70</td>
<td>≤ 4.25</td>
</tr>
<tr>
<td>E</td>
<td>≤ 85</td>
<td>≤ 5.00</td>
</tr>
<tr>
<td>F</td>
<td>&gt; 85</td>
<td>&gt; 5.00</td>
</tr>
</tbody>
</table>

Multiple parameters are transferred and combined into the public transport LOS score, which determines the corresponding LOS.

The threshold values for the LOS reflect indirectly the political goal for the design of street facilities. An average delay of 60 s/veh for motorised private vehicles means the LOS D according to the HBS and the LOS E according to the US-HCM. Since two guidelines use different methods to calculate delays, a direct comparison between the values is however difficult.

The threshold values for different LOS levels in the same guideline can also reflect the weights for different traffic modes from the political point of view indirectly. A lower threshold value indicates that a lower delay is targeted and that this traffic mode is higher weighted from the political view. Comparing the threshold values of the LOS for motorised private and public transport in the HBS, it can be found that public transport has significantly lower values and that it is higher weighted from the political point of view. However, if the evaluation criteria to determine the LOS are different for two traffic modes, it is not possible to compare the threshold values directly. That is the case for non-motorised modes and motorised modes, as the maximum delay is used to determine the LOS in the HBS for non-motorised modes while the average delay is used for motorised modes.
Table 10: Comparison of the LOS threshold values for public transport between the HBS and the TCQSM (source: own illustration based on FGSV, 2015a, pp. 4-9; Brinckerhoff, 2013, pp. 5-46)

<table>
<thead>
<tr>
<th>LOS</th>
<th>HBS Average delay (s/veh)</th>
<th>TCQSM Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>≤ 5</td>
<td>≤ 2.00</td>
</tr>
<tr>
<td>B</td>
<td>≤ 15</td>
<td>≤ 2.75</td>
</tr>
<tr>
<td>C</td>
<td>≤ 25</td>
<td>≤ 3.50</td>
</tr>
<tr>
<td>D</td>
<td>≤ 40</td>
<td>≤ 4.25</td>
</tr>
<tr>
<td>E</td>
<td>≤ 60</td>
<td>≤ 5.00</td>
</tr>
<tr>
<td>F</td>
<td>&gt; 60</td>
<td>&gt; 5.00</td>
</tr>
</tbody>
</table>

A multi-modal analysis of the performance of traffic signal control can be conducted by directly comparing the LOS for different modes. The same LOS generally indicates a similar level of traveller satisfaction with each mode (Brinckerhoff, 2013, pp. 5-39). Brinckerhoff (2013, pp. 5-39) pointed out that the individual LOS for different traffic modes should not be combined or aggregated into an overall LOS for the roadway. However, Hunter, Wolfermann, and Boltze (2011) had a different opinion and developed a method that calculates the overall LOS based on the individual LOS of each traffic mode, the number of travellers and a route importance factor. The HBS is used in Hunter, Wolfermann, and Boltze (2011) for assessing the individual LOS of each traffic mode.

Another difficulty for a multi-modal analysis with the LOS is that the comparison is relatively rough, since the LOS is a step function. Small changes in the evaluation criteria can often cause no changes in the LOS unless the criteria value is close to a threshold value. It indicates that the conditions have remained within the same performance range as before. In contrast, a change of LOS indicates that roadway performance has transitioned from one given range of traveller-perceivable conditions to another range (TRB, 2010, pp. 5-3 - 5-4). The result can, therefore, be used to support decision-making processes by estimating the necessity of the planned measure, if a significant change in service quality is targeted. However, the LOS does not fit to a fine adjustment and optimisation of traffic signal control, which is also concerned about small changes brought by an improvement of traffic signal programs.

3.4.2 Performance Index in Optimisation Models

Optimisation means, in general, the act of making something as good as possible (Cambridge dictionary 2017). For the planning and the operation of traffic signal control, there is usually the need to optimise it so that it can control the traffic flow in the best possible way. Therefore, optimisation models are usually an important component of control methods itself or their planning tools.

One basis of optimisation models is the performance index. It is a mathematical function to describe the optimisation objectives, with which an optimal alternative for solving the problem can be searched (Boltze, B. Friedrich, et al., 2006). This performance index is used to assess the generated alternatives during the optimisation procedure and thus serves a similar function as evaluation. Although the performance index lacks some steps in comparison to other comprehensive evaluation methods, it is also treated in this study as a simple evaluation method, which embeds in optimisation models.

The variables used in the performance index represent the objective criteria of decision makers (Boltze, B. Friedrich, et al., 2006), which are similar to the evaluation criteria. For the formulation of a perfor-
The performance index, the multi-dimensional criteria need to be also converted to the same scale and, if necessary, be weighted. Although the optimisation model itself doesn’t concern about the estimation of criteria values, it is usually accompanied by other models with this function.

The optimisation models for traffic signal control can be generally classified in two groups (Gartner, Tarnoff, and Andrews, 1991):

- **offline optimisation models** for fixed time control
- **online optimisation models** in adaptive traffic control

A representative example for the first group is Traffic Network Study Tool (TRANSYT), which is originally developed by Robertson (1969). It is an effective analysis tool for planning fixed time control programs, which includes two main modules: the traffic model and the signal optimiser (Wong, 1995). Besides TRANSYT, there are currently other signal-timing software programs that optimise the traffic signal setting. However, they are not included in the literature review due to the lack of available information and research on these commercial software programs.

A major disadvantage of the fixed time control is that it cannot correspond to fluctuating traffic flows and other dynamical situation changes. In order to address this issue, since 1980s, **adaptive traffic signal control** has been developed, which adjusts, in real time, signal timing plans based on the current traffic conditions, demand and system capacity (Stevanovic, 2010, p. 5). An optimisation model is also an important component of the adaptive traffic control. Representative examples for adaptive traffic control systems that utilise performance indices are:

- Balancing Adaptive Network Control Methode (BALANCE)
- Entire Priority Intersection Control System (EPICS)
- Method for the Optimisation of Traffic Signals In On-line Controlled Networks (MOTION)
- Optimisation Policies for Adaptive Control (OPAC)
- Split Cycle Offset Optimisation Technique (SCOOT)
- Urban Traffic Optimisation by Integrated Automation (UTOPIA)

Besides, there are other studies about the optimisation of traffic signal control, which proposed performance indices in other forms, e.g. Schmöcker, Ahuja, and Bell (2008) and X. Li et al. (2004). They are not explained in details since the forms of the performance index are either not easy for understanding or not appropriate for a comparable judgement of different intersections.

The following paragraphs present a comprehensive review on the performance indices of optimisation methods. The various methods mentioned above are classified into groups with similar performance indices.

**BALANCE, EPICS and OPAC**

In the first stage of BALANCE, EPICS and OPAC, **delays serve as the evaluation criterion** during the optimisation process.

**BALANCE** is a network adaptive control system which was initially developed in Munich, Germany. It has been implemented in four German cities: Ingolstadt, Remscheid, Hamm and Hamburg until 2010 (Bundesministeriums für Verkehr, Bau und Stadtentwicklung, 2010, p. 69). The performance index is used in BALANCE to optimise the network cycle time and offsets (B. Friedrich, 1999, pp. 109-114). Although B. Friedrich (1999, pp. 46-49) presented the possibilities to integrate multiple criteria in the performance index for the development of BALANCE, only delays were actually considered in the field test. The general performance index in BALANCE is shown as follows\(^1\) (B. Friedrich, 1999, p. 48):

\(^1\) The form of presentation has been adjusted.
\[ PI = \sum_{i=1}^{N_{SG}} \sum_{j=1}^{N_{AT}} (\alpha_{ij} C_{ij}) \]  

(1)

Where:
- \( N_{SG} \) the number of signal groups
- \( N_{AT} \) the number of arterials
- \( \alpha_{ij} \) the weight for the signal group \( i \) and the arterial \( j \)
- \( C_{ij} \) the total cost for the signal group \( i \) and the arterial \( j \)

Various weights can be assigned to different signal groups and arterials to reflect the priority due to planning or political reasons (B. Friedrich, 1999, pp. 46-49). The criteria are first transferred into costs and then aggregated in the performance index. B. Friedrich (1999, pp. 46-49) pointed out that the following criteria can be generally included in the performance index:

- the delays for motorised private transport (in signal groups), public transport (for lines) and walking (in signal groups)
- queue lengths for motorised private transport
- the number of stops for motorised private transport and public transport
- air pollution and noise emissions from motorised private transport
- the energy consumption of motorised private transport

However, no concrete suggestion for cost rates and weighting strategy was given in B. Friedrich (1999, pp. 46-49). In the field study, only delays were included in the performance index. Therefore, the conversion and the aggregation of multiple criteria have not been studied.

**EPICS** is an adaptive traffic control system for individual signalised intersections. It was developed in Germany by Mertz (2001) within the framework of research project TABASCO and has been tested in several empirical case studies. EPICS can be combined with the network adaptive control system BALANCE to adapt the superordinate plan defined by BALANCE locally (PTV Group, 2020).

EPICS compares and evaluates alternative signal plans with the following performance index \(^2\) (Mertz, 2001, p. 59):

\[ PI = \sum_{i=1}^{N_{SG}} (\alpha_{i} d_{i} + \beta \Delta) \]  

(2)

Where:
- \( N_{SG} \) the number of signal groups
- \( \alpha_{i} \) the weight for the signal group \( i \)
- \( d_{i} \) the sum of delays of the signal group \( i \) over the time horizon \( T \)
- \( \Delta \) the deviation of the signal plan to the reference signal plan
- \( \beta \) the weight for the deviation to the reference plan

From the equation 2, it is clear that EPICS uses the sum of weighted vehicle delays in the evaluation. The number of vehicle stops is not considered here in order to reduce the processing time for the real-time optimisation (Mertz, 2001, p. 58). Although Mertz (2001, p. 58) pointed out that the number of stops in the performance index should be included with the technical improvement of control hardware, there was no concrete suggestion given, how it is weighted in comparison to delays.

---

2 The form of presentation has been adjusted.
Another speciality of EPICS is that there is a deduction of performance if the signal plan deviates from the **reference signal plan**. It is either defined offline by traffic engineers or generated online by the network adaptive control system, e.g. BALANCE (Mertz, 2001, p. 59).

**OPAC** is an adaptive traffic control system which was first developed in the United States in the 1980s. It is an online control algorithm which can serve as a building block for demand-responsive decentralised traffic signal control (Gartner, 1983).

According to Gartner (1983), the performance index of OPAC optimises signal control strategies based on the **total delay** at the intersection. Although Gartner, Tarnoff, and Andrews (1991) also mentioned the number of stops as a possible performance measure, further details about how to combine these two parameters are missing. Besides, two other constraints of OPAC are worth mentioning. Firstly, the methodology focuses basically on motorised private transport. Public transport vehicles and non-motorised traffic modes are not taken into consideration. Secondly, there is no weighting for signal groups. The inflows from different streams are treated on the same basis.

**MOTION, SCOOT, TRANSYT and UTOPIA**

MOTION, SCOOT, TRANSYT and UTOPIA consider delays and the number of stops in the performance index.

The adaptive traffic control system **MOTION** was initially developed in Germany from 1980s to 1990s (Busch and Kruse, 1993). By the year 2010, MOTION was operated or under development in 17 cities, most of which are European cities (Bundesministeriums für Verkehr, Bau und Stadtentwicklung, 2010, pp. 75-76).

MOTION operates in total on three levels (Busch and Kruse, 1993):

- The cycle time and coordination between intersections are defined on the strategic level (every 10-15 minutes).
- The real-time signal timing is adapted on the tactical level.
- Response to each vehicle is possible on the operational level.

To realise coordination in the road network, MOTION optimises phase sequences and offsets with the following performance index\(^3\) (Kruse and Busch, 2002):

\[
P I = \sum (\alpha_D D + \alpha_S SK)
\]

Where:
- \(\alpha_D\) the weight for delays
- \(D\) total delays
- \(\alpha_S\) the weight for stops
- \(S\) the total number of stops
- \(K\) the conversion factor from stops to delays

The performance index does not differentiate between weights for signal groups or streams. The concrete conversion factor between stops and delays is also not given in Busch and Kruse (1993) and Kruse and Busch (2002).

MOTION provides the function to **prioritise public transport** both on the strategic and tactical level. The public transport signal priority can be flexibly set between "no delay for public transport" and "minimise delay for all road users". However, non-motorised traffic is not explicitly considered in the evaluation and optimisation process.

\(^3\) The form of presentation has been adjusted.
TRANSYT is one of the first optimisation models for traffic signal control. It was developed at Transport and Research Laboratory in England in the 1960s (Robertson, 1969). It is an offline optimisation method of determining optimum fixed time traffic signal settings, which has been widely implemented in many other countries (Robertson and Bretherton, 1991). Based on TRANSYT, an urban adaptive traffic control system SCOOT was developed. It also belongs to the most widely implemented adaptive control system, which has been installed in over 200 cities worldwide (Bretherton, 2007).

TRANSYT and SCOOT share some of the basic concepts, including the optimisation criteria (Robertson and Bretherton, 1991). The original performance index in TRANSYT is as follows (Robertson, 1969, p. 3):

\[
P I = \sum_{i=1}^{N_L} (d_i + Ks_i)
\]

Where:
- \(N_L\) the number of links
- \(d_i\) the average delay on the link \(i\) of the network
- \(s_i\) the average number of stops per second on the link \(i\)
- \(K\) the weighting factor between stops and delays

Robertson and Bretherton (1991) recommended that one stop should be given a weighting equivalent of 20 s of delay. Binning, Crabtree, and Burtenshaw (2013, p. 500) proposed an updated performance index to TRANSYT, which is also a weighted combination of the rate of delay and the number of stops as follows. However, both of them are first converted into cost and then aggregated.

\[
P I = \sum_{i=1}^{N_L} (C_D\alpha_{d_i}d_i + C_S\alpha_{s_i}s_i) + \sum_{i=1}^{N_P} (C_P\beta_jd_j)
\]

Where:
- \(N_L\) the number of streams or links
- \(C_D\) the total cost per unit delay
- \(\alpha_{d_i}\) the delay weighting for stream (or link) \(i\)
- \(d_i\) the average delay on the stream (or link) \(i\) of the network
- \(C_S\) the total cost per unit stop
- \(\alpha_{s_i}\) the stop weighting for link \(i\)
- \(s_i\) the average number of stops per second on the \(i\)th link
- \(N_P\) the total number of pedestrian crossing sides
- \(C_P\) the total cost per average pedestrian-hour of delay
- \(\beta_j\) the delay weighting on pedestrian crossing side \(j\)
- \(d_j\) the delay on crossing side \(j\)

The vehicle delay costs, stop costs and pedestrian delay costs can be adapted based on the UK Government’s Web-based Transport Analysis Guidance (Binning, Crabtree, and Burtenshaw, 2013, pp. 500-505). The pedestrian costs are considered separately to make it easier to adapt its value. That is due to the argument that even relatively modest delays to pedestrians could encourage red-running of pedestrian signals, discourage walking generally (which could lead to increased vehicular traffic) and also reduce the distances of journeys that pedestrians are willing to make on foot (Binning, Crabtree, and Burtenshaw, 2013, pp. 500-505). Special weightings can be assigned to different streams or links. Since

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4 The form of presentation has been adjusted.
5 The form of presentation has been adjusted.
public transport usually operates on separate links, high weightings to it support a signal priority at intersections. There is no direct estimation of emissions and energy consumption in TRANSYT and SCOOT.

UTOPIA is another adaptive traffic control system on the network basis, which was developed in Italy during the 1980s. UTOPIA is installed and operates in numerous cities throughout Europe (Stevanovic, 2010, p. 78).

UTOPIA operates on two levels: the strategic level, which is responsible for setting the overall control strategy, and the tactical level, which adapts at each intersection signal timings, such as the minimum, average, and maximum length of each stage and offsets.

The performance index of UTOPIA is a weighted combination of different cost elements, including:

- the travel time of the vehicles on the incoming links
- the number of stopped vehicles on the incoming links
- the excess queuing on the incoming links
- the travel time of the vehicles on the outgoing links
- the travel time of public transport vehicles

For the evaluation, UTOPIA allows various weights for different links and priority rules. However, non-motorised traffic modes are not taken into consideration. Actual values of cost rates and weights are missing.

3.4.3 Discussion

Table 11 shows a summary of these two groups of evaluation methods with regards to the evaluation criteria, the leading criteria, the weighting and the functions. Representative examplary methods of both groups are listed in Table 11. Deficiencies were identified for the listed evaluation methods for traffic signal control.

<table>
<thead>
<tr>
<th>Evaluation method</th>
<th>Criteria</th>
<th>Leading criteria</th>
<th>Weighting</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>Assessment of LOS</td>
<td>• HBS</td>
<td>Delays</td>
<td>LOS</td>
<td>Implicated by the threshold values of LOS</td>
</tr>
<tr>
<td></td>
<td>• US-HCM</td>
<td>Volume-capacity ratio</td>
<td></td>
<td>Defined according to the threshold values</td>
</tr>
<tr>
<td>Performance index in optimisation models</td>
<td>Delays</td>
<td>Costs</td>
<td>Weighted sum of criteria</td>
<td></td>
</tr>
<tr>
<td>• BALANCE</td>
<td>Stops</td>
<td>Delays Indices</td>
<td>Weight for links, signal groups, certain criteria</td>
<td></td>
</tr>
<tr>
<td>• EPICS</td>
<td>Queue lengths</td>
<td>Emissions</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• MOTION</td>
<td>Emissions</td>
<td>Fuel consumption</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• OPAC</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>• SCOOT/TRANSYT</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>• UTOPIA</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Schmöcker, Ahuja, and Bell, 2008</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>• X. Li et al., 2004</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
First, most methods focus mainly on the traffic flow quality. The assessment of the LOS based on the US-HCM and the HBS is mostly based on traffic parameters, such as delays and the volume-capacity ratio. For the performance index in optimisation models, although it was pointed out that parameters related to energy consumption, air pollution and noise emissions can be integrated, there is no comprehensive investigation on this issue.

Second, an evaluation of traffic signal control from the multi-modal point of view is possible but limited. An assessment of the LOS for each road user group can be conducted separately. An overall analysis is possible by directly comparing the LOS. It is controversial whether the individual LOS should be integrated into an overall LOS. In the performance index of optimisation models, the non-motorised traffic modes are not taken into consideration (at least not clearly mentioned) in most of the adaptive control systems, except for SCOOT and TRANSYT (Binning, Crabtree, and Burtenshaw, 2013, pp. 500-505; Bretherton, 2007). Non-motorised traffic modes are generally prioritised in the urban traffic management due to environmental sustainability. It is important to include them in the evaluation framework to have an overview of all traffic modes at intersections.

The third deficiency applies to the assessment of the LOS only. Small changes in the evaluation criteria cannot be adequately reflected in the LOS unless the criteria value is close to a threshold value, since it is a step function. It is, therefore, not applicable for the fine adjustment and the optimisation of traffic signal control, which usually concern about small changes brought by an improvement of traffic signal programs.

The fourth deficiency applies to the performance indices in optimisation models only. In most studies, the description of the performance index is relatively brief. Although the basic structure and the evaluation criteria are given, there is no further information on the values of cost and weighting factors. Suggestions about how to define these values and recommendations for the range of values are missing as well. Besides, the influence of changes in cost and weighting factors on the optimisation results has not been investigated comprehensively. However, a comprehensive method to evaluate the signal timings is a foundation for further optimisation. Therefore, the goal of this study is to develop a multi-criteria and multi-modal evaluation method for traffic signal control, which can be used not only to optimise signal timings during the planning or operation stage but also to assess its performance in the quality management.

Fifth, the situation responsiveness was inadequately discussed in the reviewed evaluation methods. The cost and weighting factors should not only be varying from site to site, but also responsive to real-time situations locally. It helps traffic signal control to react to the demands from road users and to fulfil the requirements under certain conditions, e.g. reduce emissions in the critical pollution condition. This aspect needs to be further explored.

These deficiencies are also important aspects to consider while developing the multi-criteria and multi-modal evaluation methods, as explained in Chapter 4.

3.5 Conclusions

This chapter describes the general issues about evaluation methods, the existing evaluation methods in transport planning and those for traffic signal control. The following conclusions can be made.

• The evaluation method should provide users with comprehensive information and results by using a practical and appropriate method that treats the involved criteria and road user groups fairly.

The evaluation is defined as a systemic investigation of the quality or the utility of an evaluation target. In order to ensure qualified results, the evaluation method that is developed in this thesis should focus on its target - traffic signal control - and serve to provide useful information about it.
It is also required to follow a practical procedure and use appropriate methods. A comprehensive and fair assessment of the considered aspects (different criteria and road user groups) is essential. Besides, the evaluation results should be accurate.

- **A formalised method is suitable for the evaluation of traffic signal control due to its stringent structure and process as well as a high degree of quantification.**

Evaluation methods in transport planning can be categorised into three groups: non-formalised, partially formalised and formalised methods. The non-formalised methods are not suitable for the evaluation of traffic signal control since they are not able to quantify the relevant effects and the trade-offs between different criteria and traffic modes. The partially formalised methods are not suitable because of the high workload and complexity if there is a large number of criteria and alternatives to evaluate. The formalised methods is appropriate due to a stringent structure and process as well as a high degree of quantification. Among different types of formalised methods, the formalised weighting and ranking method as well as Analytic Hierarchy Process have a similar problem of complexity like non-formalised methods since they use pairwise comparison in the evaluation.

- **The well-established guidelines for the evaluation of transport projects in the planning process can provide valuable hints for developing the evaluation method for traffic signal control.**

The cost-benefit analysis is widely used in guidelines to appraise transport projects in the planning phases. Although the methods defined there cannot be directly implemented for evaluating traffic signal control, they provide valuable hints on the monetisation of transport-related impacts. They can be further used to value the impacts of traffic signal control in costs.

- **The deficiencies identified in the existing evaluation methods for traffic signal control confirm the need to develop a new evaluation method.**

There are established evaluation methods for traffic signal control, including the assessment of the LOS in HCMs and the performance indices in optimisation methods. The review of the existing evaluation methods has identified several deficiencies, including the one-dimensional focus on the traffic flow quality, the limited multi-modal analysis, insensitive to the fine adjustment of traffic signal control\(^6\), a lack of detailed description\(^7\) and an inadequate discussion on the situation responsiveness. There is a need for developing a new evaluation method under consideration of the identified deficiencies.

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\(^6\) This statement applies only to the assessment of the LOS.

\(^7\) This statement applies only to the performance indices in optimisation methods.
4 Development of a Multi-criteria and Multi-modal Evaluation Method

4.1 Introduction

Chapter 4 explains in detail the development of a multi-criteria and multi-modal evaluation method for traffic signal control - Darmstadt Method of Traffic Signal Evaluation (D-MoTSE) - step by step. In the beginning, Section 4.2 gives an overview of the general issues about D-MoTSE. Later on, the upcoming Sections 4.3 to 4.11 explain in details each work step of the evaluation method and two additional essential issues. One is about the influences of various situations on the evaluation in Section 4.8 while the other deals with the superordinate effects on microscopic level in Section 4.9. An overview and discussion of the evaluation method is given in Section 4.2.

4.2 General Issues

The evaluation purpose

Based on the gaps identified in the existing evaluation methods for traffic signal control, the purpose of D-MoTSE is to investigate the overall performance of alternative traffic signal programs with regards to multiple goals and road user groups. It can be used to compare different alternative traffic signal programs for an evaluation target and find out the one with the best performance under the predefined goals.

Scope of the evaluation

The evaluation method is applicable not only for small investigation areas (e.g. single intersections and road sections) but also for large investigation areas (e.g. corridors and networks). D-MoTSE as described in this chapter can be directly applied for the case of single intersections and road sections, where only one traffic signal system is investigated. Four examples of single intersections and road sections are investigated in Chapter 5 as case studies. For the case of corridors and networks, several traffic signal systems in an investigation area may be combined and evaluated as a whole. The evaluation can be more complexed since more aspects need to be considered e.g. the superordinate effects of traffic signal control. A further development of the evaluation method may be necessary. A discussion on this issue is given in Section 6.2.1.

D-MoTSE is intended for an application both in the planning and operation phase. In the planning phase, it can serve to develop or optimise a traffic signal system. In the operation phase, it can be used for the modification and the quality management. The available data sources and the methods for measuring evaluation criteria may vary between different phases. However, the core of the evaluation remains the same.

There are different kinds of traffic signal programs depending on the changeability of the components, including the fixed-time program, the traffic-actuated program and the adaptive traffic signal program. The developed evaluation method D-MoTSE can investigate different kinds of traffic signal programs. The fixed-time program and the traffic actuation programs are investigated in the case studies (see Section 5.2.4). An investigation of the adaptive traffic signal program is possible by adapting the performance index of its optimisation model according to D-MoTSE. However, it has not yet been tested using case studies. Different kinds of traffic signal programs have different installation and maintenance
costs. They are an additional aspect to consider while comparing different kinds of traffic signal programs. However, they are not addressed here, since D-MoTSE proposed in this study focuses mainly on the impacts of traffic signal systems.

Requirements for the evaluation method

The requirements for the evaluation method D-MoTSE to be developed have been derived from the review of the existing research (compare Section 2.8 and 3.5). They are summarised as follows:

- The evaluation method should provide users with comprehensive information and results by using a practical and appropriate method that treats the evaluation criteria and road user groups fairly.
- Traffic signal control has impacts on multiple criteria that need to be considered in the evaluation method.
- Traffic signal systems serve users of different traffic modes that need to be considered in the evaluation method.
- A fair balance between multiple goals and different traffic modes is necessary while evaluating traffic signal control.
- The basic terms related to traffic signal programs will be used while designing alternative signal programs for evaluation.
- It is proposed to consider the situation responsiveness in the evaluation of traffic signal control.
- A formalised method is suitable for the evaluation of traffic signal control.
- The values used in the evaluation method should refer to the well-established guidelines for the evaluation of transport projects if relevant.

Process to develop the evaluation method

Under consideration of the purpose and the requirements mentioned above, the evaluation method D-MoTSE is developed as follows. In the beginning, a goal system for the evaluation is defined (see Section 4.4). In correspondence with the goal system, the suitable evaluation criteria need to be selected (see Section 4.4). As a basis for selecting the evaluation criteria, the appropriate measurement methods for each criterion in different phases are selected (see Section 4.3). It is explained before the definition of a goal system and selection of evaluation criteria since the selection of evaluation criteria should refer to the measurement methods. Then, it is to define how to develop alternative traffic signal programs that are going to be compared using the evaluation method (see Section 4.5). Later, it is to define how the measured evaluation criteria in original values should be processed to generate evaluation results. As discussed in Section 3.3, formalised evaluation methods are suitable for the evaluation of traffic signal control due to the rigid structure and process as well as a high degree of quantification. However, the formalised methods that use pairwise comparison in the evaluation, such as AHP, are not applicable for this case since there is a sharp increase in workload and complexity if there is a large number of criteria and alternatives. It is, therefore, proposed to convert the original criteria values into the same scale and summarise them in order to compare different alternative traffic signal programs.

The data processing is divided into three steps: the normalisation of evaluation criteria (see Section 4.6), the particular weighting of evaluation criteria (see Section 4.7) and the aggregation (see Section 4.10). Besides, two essential issues relevant to the evaluation of traffic signal control are discussed. One is the situation responsive traffic signal control and how to consider it in the evaluation method (see Section 4.8). Another one is the superordinate effects that are of higher importance on a macroscopic level. How to consider them in the evaluation method are discussed in Section 4.9.
4.3 Selection of Methods to Measure Evaluation Criteria

The aim is to develop a multi-criteria evaluation method that generally covers all significant impacts of traffic signal control. However, different impacts and their corresponding parameters require different measurement methods. Section 2.4 gives an overview of the available methods for various parameters. Among them, the most appropriate methods are selected, and their application procedures are analysed.

Some of these methods can be carried out individually while others must be combined and applied in sequence. For instance, the results of the traffic flow simulation can serve as the input for the emission modelling in order to estimate emissions of air pollutants. Afterwards, the estimated emissions are again provided as input for the dispersion modelling, which estimates the ambient air quality. These three methods need to be applied in sequence. Therefore, it is an important aspect to consider the relationship between various measurement methods and their application sequence.

First, the available data sources and the possibility to measure the evaluation criteria in reality is different between in the planning phase and the operation phase. Besides, significant differences arise between the cases with or without the traffic flow simulation. The traffic flow simulation is a powerful tool to measure traffic-related parameters. Its output can serve as a basis for measuring other evaluation criteria. There is a clear distinction of the measurement methods between the case when the traffic flow simulation is implemented and when it is not. Hence, four scenarios are defined, for which the appropriate measurement methods need to be specified:

- Scenario 1: planning phase, without the traffic flow simulation
- Scenario 2: planning phase, with the traffic flow simulation
- Scenario 3: operation phase, without the traffic flow simulation
- Scenario 4: operation phase, with the traffic flow simulation

If there are several possible measurement methods available, the most appropriate measurement methods are selected under consideration of their efforts and accuracy, as shown in Table 1. For all four scenarios, the selected methods and their application procedures are graphically demonstrated and explained in the following chapters.

4.3.1 Scenario 1: Planning Phase, without the Traffic Flow Simulation

The first scenario is suitable for the case when traffic flow simulation is not applied to design a traffic signal control system. In this case, traffic engineering calculation methods are applicable. Figure 2 shows the methods and the data flow for this scenario.

The method in HBS can be used in the planning phase to estimate traffic-related parameters, in case that a traffic flow simulation is not applied. In Germany, this method is commonly applied by traffic engineering offices and administrative authorities to design traffic signal control and to examine its performance. Results of the method in HBS are the saturation degree of green times, queue lengths and delays for vehicles/individuals. The delays determine the quality of traffic flows that is expressed in the LOS. The LOS gives hints on the traffic situation (fluent/dense/saturated/stop+go), which is used then to model emissions with the Handbook Emission Factors for Road Transport (HBEFA). The modelled emissions of air pollutants serve further as input data for the calculation of the ambient air quality. The most appropriate method in this scenario is RLuS 2012. The abbreviation bases on the original German title of this guideline in order to avoid misunderstanding.

In Germany, the method in RLS-19 is generally applied in the planning phase to estimate the noise level on roads. The abbreviation is a shortened form of the original German title of this guideline. This method can be applied individually without linking to other methods.
There are several methods available to estimate traffic safety at intersections in the planning phase. Among these, the **accident analysis with data under similar situations** is most suitable. It takes some effort to search for the comparable studies or data under similar situations. If they exist, their results can be taken over for rough estimation.

The significant **advantage** of this scenario is that the corresponding measurement methods require less effort to apply. However, it has the following **limitations**:

- Certain traffic-related parameters cannot be calculated, such as average travel speeds and the number of stops. Only the maximum delay for pedestrians can be calculated, not the average delay.
- The method in HBS 2015 is not applicable for a complex actuated traffic signal control system. However, this is often the case at intersections.
- The macroscopic emission model HBEFA is not applicable for comparison between emissions under different traffic signal programs.
- The method in RLuS 2012 is not applicable for the intersections in the urban area because of the dense buildings. An alternative method is the screening models for ambient air quality.

Under consideration of these limitations, scenario 1 is **not recommended** for measuring parameters in the planning phase.

### 4.3.2 Scenario 2: Planning Phase, with the Traffic Flow Simulation

The traffic flow simulation is an alternative method to estimate traffic-related parameters, which has a larger application area and can offer more detailed information. The models of environmental aspects change accordingly. Figure 3 shows the selected methods and the data flow for scenario 2.

The main **difference** to scenario 1 lies in the change of methods to determine traffic-related and environmental parameters. The methods for noise level and accident data, however, remain unchanged.

Therefore, scenario 2 has the following **advantages** in comparison to scenario 1.
The traffic flow simulation can estimate all kinds of traffic-related parameters in details.

The traffic flow simulation is suitable not only for analysing the fixed time control but also for simulating other kinds of traffic signal programs, such as actuated and adaptive traffic signal programs. Especially it is necessary to use it if signal programs at multiple intersections interact with each other.

The traffic flow simulation can record the vehicle movements for each simulation second. These serve as the basis for the microscopic emission modelling, which can be used to analyse the influence of changes in traffic signal control on emissions.

In the next step, dispersion or statistical models can be applied to estimate air quality. They are suitable for simulating all kinds of landscapes, including the dense urban area. However, applying them requires lots of effort.

The disadvantage of scenario 2 is that a higher effort is required for its application. Under consideration of the advantages and the disadvantages mentioned above, Scenario 2 is recommended for the measurement of parameters in the planning phase due to its productive outcomes, broad application areas and high accuracy of results. However, it should be mentioned that the modelling of ambient air quality should be only carried out in exceptional cases due to its high effort. Generally, it is enough to consider only emissions.

4.3.3 Scenario 3: Operation Phase, without the Traffic Flow Simulation

Scenario 3 suggests the suitable methods to measure parameters in case the traffic flow simulation is not carried out in the planning phase. Figure 4 shows its working procedure.

Under this context, the measurement of parameters should be based on the existing data. If there are no data available, **measurements or surveys** are necessary to collect them. As shown in Figure 4, each method can be applied individually without relying on the others.
Traffic-related parameters can be derived from the data from controllers and the operation systems of public transport. These include, e.g. the process, operation and defect data of controllers as well as data about the location and the occupancy of public transport. These data are already documented in the existing systems. The derivation requires relatively low effort. However, a limitation is that only part of the parameters can be calculated based on the existing data. As an example, it is only possible to get the maximum delays for vehicles/individuals from the process data, but not average delays.

In Germany, accident data are also well documented by police. They are summarised and analysed periodically. Therefore, it needs a low effort to collect the data and perform an analysis for those intersections where accident data are available.

There are no existing data available for parameters such as comfort, emissions of air pollutants and CO₂, energy consumption, the average travel speed as well as the noise level. It requires high effort to conduct corresponding measurements or surveys. One speciality is ambient air quality. There is an existing measurement network which is operated by the administrative authority. These measurement stations collect air quality data continuously, which can be used in the evaluation with low effort. How-
ever, the number of measurement stations are limited. At places without measurement stations, own measurements require a significant amount of effort in terms of time and cost. A significant advantage of scenario 3 is that the actual situations in reality can be well reflected by the measured or collected data. The accuracy of results is high. A disadvantage is that a high effort shall be required for conducting measurements and surveys. Therefore, the selection of scenario 3 requires a trade-off between the available funds and the expected accuracy.

4.3.4 Scenario 4: Operation Phase, with the Traffic Flow Simulation

The last scenario combines scenario 2 with scenario 3, as shown in Figure 5. Similar to scenario 2, modelling tools are implemented to estimate traffic-related parameters, emissions of air pollutants, energy consumption and CO₂ emissions. The process, operation and defect data, as well as data from the operation systems of buses and trams, can be used to validate simulation models in order to increase their accuracy. The modelling tools have similar advantages like those of scenario 2, as explained in Subsection 4.3.2. Same methods with scenario 3 are used to measure comfort, the noise level and traffic accidents.

The estimation of emissions requires relatively low effort under scenario 4. Therefore, Scenario 4 is suitable in the operation phase if emissions are considered in the evaluation method.

The reduction of environmental pollution is a critical goal of traffic signal control. In order to have an overall evaluation of its performance, environmental parameters should not be left out of consideration. For this reason, scenario 4 is recommended for the measurement of parameters in the operation phase. Similar to scenario 2, the modelling of ambient air quality is used to support the emission modelling only in exceptional cases.

Figure 5: The measurement procedure in scenario 4 - operation phase, with the traffic flow simulation (own illustration)
4.4 Definition of a Goal System and Selection of Evaluation Criteria

The four main goals for traffic signal control and their relevant parameters are summarised from the literature in Section 2.3. Based on these goals, the possible evaluation criteria and their relevance to different traffic modes are defined. A summary is shown in Appendix B. From the complete list, a **qualitative selection procedure** is conducted to pick out the evaluation criteria that are suitable for the evaluation method D-MoTSE.

The selection follows two **steps**. First, suitable parameters are chosen. Second, the most appropriate evaluation criteria are selected from the multiple criteria corresponding to every single parameter.

Three parameters are first left out of consideration. The delay for vehicles and the delay for individuals are highly related to each other. In order to avoid double consideration, only one of them is included in the evaluation method. The **delay for individuals** is chosen to make the evaluation more precise. **Comfort** is a personal perception of road users about the transport system and the transport service they experience. It is common to judge it qualitatively by using the quality level. However, it is difficult to quantify it and compare it with other quantifiable criteria. Thus, it is not considered in the evaluation method. As explained in Section 4.3, the measurement of **ambient air quality** takes a great effort. It is, therefore, left out of consideration in the evaluation method.

There are still a large number of parameters left, which makes the implementation of the evaluation method difficult. Further selection bases on the relationships between parameters as shown in Figure 6). Comfort is not shown in Figure 6 since it is indirectly related to most other parameters, except for emissions of air pollutions, ambient air quality and CO$_2$. Road users can not perceive these three impacts.

According to the review of existing evaluation methods in Section 4.3, delays are an essential component in the evaluation of transport planning projects and traffic signal control. Rich knowledge about them is already available in literature, which can serve as a reference here. Moreover, delays are closely related to other traffic-related parameters such as queue lengths, the number of stops, speeds and the saturation degree of green times. In order to avoid duplication, only the **delay for individuals** is selected as an evaluation criterion in the evaluation method. Two possible parameters correspond to the delay for individuals. One is the average delay and the other is the maximum delay. In comparison, the **average delay** can give a better overview of the overall situation and should, therefore, be selected.

The parameters that are related to **traffic safety** should also be a component of the evaluation method. They are an essential part of the evaluation method for transport planning projects. There are established cost rates available to convert the number of different kinds of traffic accidents into the corresponding accident costs (H. Baum, Kranz, and Westerkamp, 2011). All four possible evaluation criteria should be included.

The last group of selected parameters is related to environmental impacts. Although environmental parameters are also closely related to traffic parameters, they cause additional external cost to the public due to the negative impacts on human health, environment and climate. These additional losses need to be separately valued in the evaluation. Traffic signal control can barely influence the noise level. Thus, it can be left out of consideration. In the end, the evaluation method D-MoTSE includes **emissions of air pollutants (PM and NO$_x$)**, **energy consumption and CO$_2$ emissions**. Two possible evaluation criteria correspond to energy consumption: the **fuel consumption of combustion vehicles and the power consumption of electric vehicles**. Both can be applied. The selection of criterion depends on vehicle types and the existing fleet composition.

As a summary, Figure 7 shows the list of the selected evaluation criteria for D-MoTSE.
4.5 Development of Alternative Traffic Signal Programs

As mentioned in Section 4.3, the evaluation of traffic signal control can be conducted both in the planning phase and the operation phase. The procedure to develop alternatives for traffic signal control can vary between these two phases.

The planning phase

If a new traffic signal system is in planning, all the components of the traffic signal program need to be designed. Section 2.6 gives an overview of the signal program structure and signal timing parameters. FGSV (2015b, pp. 12-29) explains in detail the working steps to design these parameters for a fixed time program. They are dependent on each other. In this process, the needs of non-motorised traffic and public transport should be given special consideration.

In a traffic-actuated program, the signal design and timing parameters are changeable according to the real-time situation. For developing a traffic-actuated program, it is necessary to define what control...
parameters are used and how they are collected. The types and locations of detectors should be given. Furthermore, a control logic needs to be established, which documents how the signal design and timing parameters change according to the control parameters. Essential components of a control logic are logical conditions, time conditions, state conditions and switching commands (FGSV, 2015b, pp. 46-47). Detailed explanations of conditions and switching commands are helpful to make them understandable. There is no universally standardised working process to design a traffic-actuated signal program. Commercial software programs on the market provide their own methods and standardised commands. Examples for widely implemented software programs in Germany are LISA+, VS-PLUS and TRELAN/TRENDS.

Due to the working principles of the adaptive traffic signal control, it is usually unnecessary to develop a new adaptive signal control system for a planned intersection, corridor or network. Instead, the existing signal control systems are adapted and applied to the target traffic facility. As mentioned in Section 3.4, widely implemented adaptive signal control systems are BALANCE, EPICS, MOTION, SCOOT and UTOPIA. Therefore, the development of such an adaptive control system is not explained here in detail.

The operation phase

It is necessary to distinguish between two cases in the operation phase. The first case deals with the situation when a traffic signal program needs to be completely redesigned. It is the case when an intersection is reconstructed (with different layout) or when fundamental changes in a traffic signal program are required. Under this context, the working procedure to redesign a new traffic signal program is the same as that for the planning stage, which is explained above.

The second case concerns the examination of a traffic signal program under the condition that there are no significant changes in the layout of an intersection. It is suitable for the quality management of traffic signal control or the update of a traffic control program after a long time of operation. The
existing traffic signal program can serve as a basis for developing possible alternatives for traffic signal control.

The following parameters or functions should be taken into consideration for developing alternative traffic signal programs:

- cycle time
- stage design
- green split
- public transport priority
- pedestrian request
- coordination

The selected parameters or functions are important aspects to consider while designing a traffic signal program. Transition time and intergreen time are left out of consideration here since they remain the same if the layout and basic conditions of the intersection are unchanged.

The development of alternative traffic signal programs begins with defining the meaningful options for each parameter or function. Not all listed terms need to be considered for a specific intersection. A selection process needs to be conducted to narrow down the solution range in order to reduce the effort for further investigation. The selection considers the type and the basic conditions of an intersection that are analysed in the inventory analysis at the beginning of the evaluation. At a pedestrian crossing, the focus shall be laid on how signals correspond to pedestrian requests. If a traffic signal system coordinates with neighbouring intersections, the option coordination shall be investigated. At an intersection that serves public transport, the analysis shall consider the different forms of public transport priority. It is not possible to give a complete list, in which situations which parameters or functions shall be included. The selection process is individual for each intersection. A problem analysis can provide useful hints for the selection process.

Afterwards, combining the options for parameters or functions would generate a list of possible alternative signal programs. A small example is explained as follows. It is assumed that there are two possible options for each parameter - the cycle time and the stage design. A traffic control system can either operate with the 90 s cycle time or a variable one. The two possible stage designs are named stage design 1 and 2. In this case, four alternative traffic signal programs are theoretically possible:

- 90 s cycle time & stage design 1
- variable cycle time & stage design 1
- 90 s cycle time & stage design 2
- variable cycle time & stage design 2

In the next step, the combinations shall be carefully examined to rule out the meaningless ones. The purpose is to reduce the effort for further investigation as well.

### 4.6 Normalisation of Evaluation Criteria

#### 4.6.1 Selection of a Leading Indicator

Normalisation means adjusting multidimensional evaluation criteria on different scales to the same scale. For this purpose, a leading indicator that serves as the common scale should be defined. Four possible leading indicators are identified from the literature review: costs, delays, eco-points and the LOS.

Table 12 shows a rough assessment of these leading indicators concerning four aspects:
• Reference: are there referenced values in the literature?
• Understandability: are normalised values easy to understand?
• Simplicity: is the normalisation process simple to conduct?
• Applicability: how many parameters can be converted into the leading indicator?

Table 12: Appraisal of leading indicators (own illustration)

<table>
<thead>
<tr>
<th></th>
<th>Reference</th>
<th>Understandability</th>
<th>Simplicity</th>
<th>Applicability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Costs</td>
<td>high</td>
<td>high</td>
<td>high</td>
<td>medium</td>
</tr>
<tr>
<td>Delays</td>
<td>medium</td>
<td>medium</td>
<td>medium</td>
<td>medium</td>
</tr>
<tr>
<td>Eco-points</td>
<td>low</td>
<td>low</td>
<td>low</td>
<td>low</td>
</tr>
<tr>
<td>LOS</td>
<td>medium</td>
<td>high</td>
<td>low</td>
<td>high</td>
</tr>
</tbody>
</table>

The cost is a common comparative scale for research about multidimensional impacts (FGSV, 2010b, p. 25). The original idea to introduce money is to measure the values of different products and make them comparable. It is widely used in the cost-benefit analysis and the performance index in optimisation models, as explained in Chapter 3. There are numerous economic studies about the monetisation of transport-related aspects. Their results can serve as a reference. The monetary values are straightforward and easy to understand. The normalisation process is simple by multiplying the criteria values in original scales with their corresponding cost rates. The applicability is assessed as medium since not all the identified parameters in Section 2.3 can be converted into monetary values. However, it applies to all the selected evaluation criteria in Section 4.4.

The delay is not only one of the selected evaluation but also used in the performance index in optimisation models as a leading indicator. Other criteria (e.g. the number of stops) are multiplied with a conversion rate to transfer in the delay of the same value. FGSV (2015a, pp. 4-79) suggested a conversion rate 1 stop = 30 s delay. It is generally possible to use the delay as a leading indicator. However, some questions arise while developing conversion rates for accident risks and environmental aspects. The basic idea is to assess the loss of life due to the health impacts of accidents, air pollution and noise. Through this, these two criteria are converted in time scale. Still, two essential questions cannot be answered in the framework of this study.

The first question is how to compare the loss of life with delays at intersections. Although both parameters express the expected time lost by people, they are valued differently. People would definitely prefer to wait at intersections rather than have accidents. It still remains unclear how to compare these two kinds of time lost quantitatively. The second question is how to include other negative impacts of accidents, air pollution and noise in the evaluation. Only health impacts are taken into consideration while converting the parameters into the loss of life. Other essential negative impacts include:

- property damages due to accidents
- material damages due to air pollution
- changes of agricultural harvests due to air pollution
- damages on ecosystem due to air pollution
- climate change due to CO₂ emissions
- fuel costs

The relationships between these damages and time are unclear. There are no established methods to convert them in the time scale, which can be used as a reference.
The idea of the **eco-point** originates from Weihofen, Schebek, and Günther (2015). In that study, the **eco-point** is used to integrate the environmental impacts into the investment processes of companies. However, it is problematic to apply it as a leading indicator for the evaluation of traffic signal control. Particularly, the definition of an **eco-point** is unclear. Furthermore, it remains unclear how to convert evaluation criteria such as delays and accidents into **eco-points**.

The last possible leading indicator is the **LOS**. Despite the **LOS** for traffic flows, it is also possible to evaluate the **LOS** for traffic safety, environmental friendliness and economic efficiency. The original values shall be converted into utility values. A weighted sum of all utility values represents the total **LOS** of a traffic signal system. The main problem is to define the threshold values for each quality level and to ensure a comparability between different kinds of **LOS**. It is not only an engineering issue but more a political issue. Hunter, Wolfermann, and Boltze (2011) has developed a multi-modal evaluation methodology for traffic signal control at signalised intersections that used the **LOS** as the leading indicator. However, it only considers the transport quality for all traffic modes into consideration. Traffic safety and environmental impacts are not directly included in the methodology.

Based on the arguments, the **cost** is chosen here as the leading indicator for the normalisation of the evaluation criteria.

### 4.6.2 Delay Costs

Two cost components shall be taken into consideration while converting delays into the corresponding delay costs: the **value of time in passenger transport** and **time-dependent operation costs**. The determination of these two cost components refers to the time-related costs that are traditionally considered in the cost-benefit analysis.

A multi-modal evaluation method requires the consideration of multiple traffic modes that are possibly present at an intersection into consideration. The **classification of traffic modes** is explained in Section 2.5. Five traffic modes are identified, namely walking, cycling, public transport, motorised private transport and heavy transport. Cost rates shall be distinguished between different traffic modes.

**Value of time in passenger transport**

The first cost component to consider is the value of time in passenger transport. According to the definition of the delay in Section 2.3, the delay is part of travel time. It is attached with values, since it cannot or just partially be used for other activities (possibly productive or useful activities) (Dahl, Kindl, et al., 2016, p. 33). For society as a whole, a **reduction in travel time (the delay also)** has two positive influences: a potential increase in the gross domestic product if such reductions translate into more work and increase in social welfare as travel conditions improve (Mackie, Jara-Diaz, and Fowkes, 2001). Therefore, the related costs are a crucial part of estimating delay costs.

The value of time of a travel mode is determined by the **willingness-to-pay** of a person or a person group for a reduction of travel time with the corresponding travel mode (Axhausen et al., 2014, p. 88). The value is mainly influenced by the following factors (Mackie, Jara-Diaz, and Fowkes, 2001):

- the time at which the trip is made
- the characteristics of the trip (congested, repetitive or free-flow and novel)
- the trip purpose
- the trip length
- the travel mode
- the size of the time saving

In the previous research, the value of time differentiates mostly on the dimensions: **trip purpose**, **trip length** and **travel mode**. Different countries make different decisions on how the value of time is
differentiated (Mouter, 2016). Axhausen et al. (2014) suggests that the how detailed the value of time is should correspond to its intended purpose in order to reduce the effort for further implementation.

Here, two of the above-mentioned influencing factors are ignored. The first one is the characteristics of a trip. At an intersection, the main difference in the characteristic is the traffic condition, namely stop-and-go, congested, dense and free-flow traffic. However, this factor is related closely to the size of the delay. The more congested the traffic, the higher the delay. Therefore, the characteristics of the trip can be ignored to avoid double consideration. Second, the trip length is not explicitly considered due to the lack of data for vehicles that pass an intersection. The trip length can be considered in the evaluation of infrastructure projects, since it is fixed for a project. However, it is difficult to collect data about trip lengths in the case of traffic signal control.

The development of delay cost rates takes the rest of the influencing factors into consideration. The cost rates differentiate between various traffic modes since an important research goal is to analyse the trade-offs between traffic modes. The time of the day and the distribution of trip purposes are closely related. Both factors are summarised to derive the typical distribution of trip purposes for different traffic time (peak, off-peak or lean hour). Based on that, cost rates for each traffic time can be derived. The size of the time saving is without doubt included in estimating delay costs.

Research on the value of time has a long history. The value has been widely implemented in the cost-benefit analysis to evaluate transport infrastructure projects. Subsection 3.3.3 has given an overview of the established cost-benefit analyses in Germany. Among those, the latest study (Axhausen et al., 2014, pp. 139-148) is selected as the basis for developing D-MoTSE in this chapter. It has already been used in the evaluation method of the newest German Federal Transport Infrastructure Plan (BVWP 2030). The results represent the up-to-date knowledge for the value of time in the German context. The values suggested by BVWP 2030 (Axhausen et al., 2014, pp. 139-148) are shown in Table 13. They represent the price state of the year 2012. They differ according to travel modes and trip purposes.

<table>
<thead>
<tr>
<th>Trip purpose</th>
<th>Public transport (Passengers)</th>
<th>Motorised private transport (Persons in cars)</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Education</td>
<td>4.28</td>
<td>3.8</td>
<td>BVWP 2030 (Axhausen et al., 2014, pp. 139-148)</td>
</tr>
<tr>
<td>Commuting</td>
<td>4.35</td>
<td>4.75</td>
<td></td>
</tr>
<tr>
<td>Shopping</td>
<td>5.15</td>
<td>4.31</td>
<td></td>
</tr>
<tr>
<td>Leisure</td>
<td>4.33</td>
<td>4.00</td>
<td></td>
</tr>
<tr>
<td>Business</td>
<td>24.21</td>
<td>24.21</td>
<td>BVWP 2030 (Dahl, Kindl, et al., 2016, p. 98)</td>
</tr>
</tbody>
</table>

For business trips, the value of time proposed by Axhausen et al. (2014, pp. 139-148) is not adopted since it is significantly below the average wage rate. Instead, Dahl, Kindl, et al. (2016, p. 98) used a value of 24.21 €/p-h for trips within the distance of 50 km and 75.00 €/p-h for trips beyond 500 km. For trips between 50 to 100 km, the calculation follows a linear interpolation. Due to the lack of data on trip lengths, the value of time for business purpose is set at 24.21 €/p-h, since trips at a traffic control system are mostly local or regional.
Other countries have their country-specific value of time as well. Table 14 shows a comparison between Germany and other European countries concerning the cost rates for valuing time. There are distinct variations between values in different countries. The German values are comparatively lower.

Table 14: Overview of the considered value of time in European countries (own illustration)

<table>
<thead>
<tr>
<th>Country</th>
<th>Unit</th>
<th>Public transport (Passengers)</th>
<th>Motorised private transport (Persons in cars)</th>
<th>All</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Germany</td>
<td>[€/p-h]</td>
<td>4.80</td>
<td>4.63</td>
<td>4.80</td>
<td>Axhausen et al., 2014, p. 140</td>
</tr>
<tr>
<td>Switzerland</td>
<td>[CHF/p-h]</td>
<td>in 2003</td>
<td>14.9</td>
<td></td>
<td>König, Axhausen, and Abay, 2004</td>
</tr>
<tr>
<td>France</td>
<td>[€/p-h]</td>
<td>in 2010</td>
<td>10&lt;sup&gt;a, b&lt;/sup&gt;</td>
<td></td>
<td>Meunier and Quinet, 2015</td>
</tr>
<tr>
<td></td>
<td></td>
<td>17.5&lt;sup&gt;c&lt;/sup&gt;</td>
<td>17.5&lt;sup&gt;c&lt;/sup&gt;</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>6.8&lt;sup&gt;d&lt;/sup&gt;</td>
<td>6.8&lt;sup&gt;d&lt;/sup&gt;</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Great Britain</td>
<td>[£/p-h]</td>
<td>in 2010</td>
<td>22.08&lt;sup&gt;c&lt;/sup&gt;</td>
<td></td>
<td>Department for Transport, 2014</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5.08&lt;sup&gt;b&lt;/sup&gt;</td>
<td>5.08&lt;sup&gt;b&lt;/sup&gt;</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>5.72&lt;sup&gt;a, d&lt;/sup&gt;</td>
<td>5.72&lt;sup&gt;a, d&lt;/sup&gt;</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Netherlands</td>
<td>[€/p-h]</td>
<td>in 2010</td>
<td>6.75</td>
<td></td>
<td>Kouwenhoven et al., 2014</td>
</tr>
<tr>
<td>Norway</td>
<td>[NOK/p-h]</td>
<td>in 2009</td>
<td>60</td>
<td></td>
<td>Ramjerdi et al., 2010</td>
</tr>
<tr>
<td>Sweden</td>
<td>[€/h]</td>
<td>5.3&lt;sup&gt;b&lt;/sup&gt;</td>
<td>9.8&lt;sup&gt;b&lt;/sup&gt;</td>
<td></td>
<td>Börjesson and Eliasson, 2014</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2.8&lt;sup&gt;a, c, d&lt;/sup&gt;</td>
<td>6.1&lt;sup&gt;a, c, d&lt;/sup&gt;</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Trip purpose:  
<sup>a</sup> Education  
<sup>b</sup> Commuting  
<sup>c</sup> Business  
<sup>d</sup> Shopping, leisure and others

The literature review indicates that walking and cycling are generally ignored in the established cost-benefit-analyses. The main reason is that the evaluation of transport infrastructure projects concerns mainly about supra-regional projects that cover long distances. In this case, walking and cycling play a minor role in the evaluation. However, for the evaluation of traffic signal systems, they are an essential part that requires separate consideration. Due to the lack of data, the same cost rates as those for persons in cars are assumed. Further research on this field is desired to improve the accuracy of the evaluation.

Furthermore, the development of cost rates takes the distribution of trip purposes into consideration. As explained before, this aspect varies significantly according to the week of day and the time of day. The daily temporal fluctuation of transport demands has a certain pattern, which supports the classification of time into three groups: peak hour, off-peak hour and lean hour. Mobilität in Deutschland (MiD) (Follmer, 2010) documented the typical distribution of trip purposes in different periods, which was collected through a nationwide survey about transport behaviours by BMVI. Besides, the study demonstrated the modal split for trips of each trip purpose. Based on that, the distribution of trip purposes for each traffic mode is derived by combining two parameter values, as shown in Table 15, 16 and 17. These distributions are combined with the value of time (see Table 13) to calculate the cost rates (the average value of travel time saving for each travel mode) in each period. The results are shown in Table 15, 16 and 17. The values are lowest in the lean hour since leisure trips dominate in this period. They increase with an increased share of commuting, shopping, education and business trips, as in the case of peak and off-peak hour.
Table 15: The value of time in the peak hour (source: own calculation based on Dahl, Kindl, et al., 2016 and Follmer, 2010)

<table>
<thead>
<tr>
<th>Peak hour</th>
<th>Walking</th>
<th>Cycling</th>
<th>Public transport</th>
<th>Motorised private transport</th>
<th>Heavy transport</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Bus, tram</td>
<td>Car</td>
<td>LCV</td>
</tr>
<tr>
<td>Share of the trip purpose [%]</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Education</td>
<td>36.5</td>
<td>32.9</td>
<td>52.9</td>
<td>11.5</td>
<td></td>
</tr>
<tr>
<td>Commuting</td>
<td>22.8</td>
<td>46.1</td>
<td>37.9</td>
<td>59.4</td>
<td></td>
</tr>
<tr>
<td>Shopping</td>
<td>9.3</td>
<td>5.2</td>
<td>1.6</td>
<td>5.4</td>
<td></td>
</tr>
<tr>
<td>Leisure</td>
<td>14.6</td>
<td>7.2</td>
<td>3.4</td>
<td>6.2</td>
<td></td>
</tr>
<tr>
<td>Business</td>
<td>0.4</td>
<td>0.5</td>
<td>0.5</td>
<td>2.4</td>
<td></td>
</tr>
<tr>
<td>Others</td>
<td>16.5</td>
<td>8.1</td>
<td>3.8</td>
<td>15.1</td>
<td></td>
</tr>
<tr>
<td>Average occupancy rate [p/veh]</td>
<td>-</td>
<td>-</td>
<td>40 (bus)</td>
<td>80 (tram)</td>
<td>1.3</td>
</tr>
<tr>
<td>Average value of travel time saving [€/p-h]</td>
<td>4.21</td>
<td>4.4</td>
<td>4.42</td>
<td>4.93</td>
<td></td>
</tr>
<tr>
<td>Time-dependent operation costs</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Personnel cost [€/p-h]</td>
<td></td>
<td></td>
<td>20.14</td>
<td>17.64</td>
<td>20.14</td>
</tr>
</tbody>
</table>

In traffic accounts, existing detector techniques can only count the number of vehicles that pass an intersection. However, the number of persons that sit or stand in the vehicles cannot be accounted for. Therefore, it is necessary to estimate the number of persons based on the number of vehicles in order to consider delays for individuals in the evaluation. The occupancy rates of vehicles can serve this purpose. For passenger cars, Dahl, Kindl, et al. (2016) and Follmer (2010) give recommendations for the average occupancy rates, as shown in Table 18. The average occupancy rates in different periods are then derived by combining the occupancy rates in Table 18 with the distributions of trip purposes in Table 15, 16 and 17.

To verify the occupancy rates calculated based on the literature, traffic counts were conducted to collect empirical data at four test sites in Darmstadt. All of them are located in the urban area. Detailed information to them is given in Chapter 5. The total time counted is eight hours, two hours at each test site. They cover up the morning peak hour, the midday off-peak hour and the evening peak hour. In total, 12,699 vehicles have been counted.

The distributions of car occupancy rates are shown in Figure 8. It can be observed that cars with only the driver are dominant in all periods. They take up about 88% in the morning peak hour, 74% in the midday off-peak hour and 77% in the evening peak hour. Cars with more than two persons are very few.

The following average occupancy rates are measured for each traffic time:

- 1.1 p/veh in the morning peak hour
- 1.3 p/veh in the midday off-peak hour
- 1.3 p/veh in the evening peak hour
Table 16: The value of time in the off-peak hour (source: own calculation based on Dahl, Kindl, et al., 2016 and Follmer, 2010)

<table>
<thead>
<tr>
<th>Off-peak hour</th>
<th>Walking</th>
<th>Cycling</th>
<th>Public transport</th>
<th>Motorised private transport</th>
<th>Heavy transport</th>
</tr>
</thead>
<tbody>
<tr>
<td>Share of the trip purpose [%]</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Education</td>
<td>4.6</td>
<td>7.3</td>
<td>22.2</td>
<td>2.4</td>
<td></td>
</tr>
<tr>
<td>Commuting</td>
<td>2</td>
<td>7</td>
<td>11</td>
<td>8.6</td>
<td></td>
</tr>
<tr>
<td>Shopping</td>
<td>37.1</td>
<td>36.2</td>
<td>20.7</td>
<td>35.8</td>
<td></td>
</tr>
<tr>
<td>Leisure</td>
<td>34.3</td>
<td>29.6</td>
<td>26.3</td>
<td>24.2</td>
<td></td>
</tr>
<tr>
<td>Business</td>
<td>0.2</td>
<td>0.5</td>
<td>0.9</td>
<td>2.2</td>
<td></td>
</tr>
<tr>
<td>Others</td>
<td>21.8</td>
<td>19.4</td>
<td>19</td>
<td>26.8</td>
<td></td>
</tr>
<tr>
<td>Average occupancy rate [p/veh]</td>
<td>-</td>
<td>-</td>
<td>25 (bus)</td>
<td>1.5</td>
<td></td>
</tr>
<tr>
<td>Average value of travel time saving [€/p-h]</td>
<td>4.17</td>
<td>4.24</td>
<td>4.66</td>
<td>4.61</td>
<td></td>
</tr>
</tbody>
</table>

Time-dependent operation costs

| Personnel cost [€/p-h] | 20.14 | 17.64 | 20.14 |

Figure 8: Distributions of car occupancy rates based on traffic counts (own illustration)

Having a look at the peak hours, a distinction between morning and evening peak hour is possible based on traffic counting data. However, the value calculated based on previous studies, as shown in Table 15, is related only to the morning peak hour, since no data for the evening peak hour are available. Given
Table 17: The value of time in the lean hour (source: own calculation based on Dahl, Kindl, et al., 2016 and Follmer, 2010)

<table>
<thead>
<tr>
<th>Lean hour</th>
<th>Walking</th>
<th>Cycling</th>
<th>Public transport</th>
<th>Motorised private transport</th>
<th>Heavy transport</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Bus, tram</td>
<td>Car</td>
<td>LCV</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Value of time in passenger transport</th>
<th>Share of the trip purpose [%]</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Education</td>
<td>0.5</td>
<td>0.9</td>
<td>2.8</td>
<td>0.3</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Commuting</td>
<td>2.3</td>
<td>8.7</td>
<td>14.4</td>
<td>11</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Shopping</td>
<td>10.6</td>
<td>11</td>
<td>6.6</td>
<td>11.1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Leisure</td>
<td>70.8</td>
<td>64.6</td>
<td>60.9</td>
<td>54</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Business</td>
<td>0.2</td>
<td>0.3</td>
<td>0.7</td>
<td>1.6</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Others</td>
<td>10.8</td>
<td>10.5</td>
<td>11.6</td>
<td>11.5</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Average occupancy rate [p/veh]</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>-</td>
<td></td>
<td></td>
<td>15 (bus)</td>
<td>1.5</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>30 (tram)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Average value of travel time saving [€/p-h]</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3.89</td>
<td>4</td>
<td>4.39</td>
<td>4.02</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Time-dependent operation costs</th>
<th>Personnel cost [€/p-h]</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>20.14</td>
<td>17.64</td>
<td>20.14</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

This information, the occupancy rates for the morning peak hour are 1.1 p/veh based on traffic counts and 1.3 p/veh according to own calculation based on previous studies. For the midday off-peak hour, the occupancy rate counted is 1.3 p/veh while that calculated based on previous studies is 1.5 p/veh as shown in Table 16. The comparisons above show that the average occupancy rates collected from test sites are generally slightly lower than those calculated based on existing statistical data from the literature.

The occupancy rates of public transport vehicles are needed in the evaluation as well. Verband Deutscher Verkehrsunternehmen (2016) uses an average occupancy of 19 % for trams (33 passengers if the capacity of a tram is 170 passengers) and 21 % for buses (21 passengers if the capacity is 100 passengers). However, these two values are averaged over the whole time. The temporal, site-specific and line-specific fluctuations are still unknown. No established statistical values regarding these can be found. Therefore, presumed average occupancy rates in different time periods are defined after discussion with the authorities of the City of Darmstadt, as shown in Table 15, 16 and 17. These are only estimations based on expert experiences without reliable statistics as the reference. If possible, the occupancy rate of public vehicles should be gathered specifically for different intersections, lines and periods in order to increase the accuracy of the evaluation. For dynamic traffic signal control, the real-time occupancy rate could also be included in the online optimisation of signal timing.

**Time-dependent operation costs**

**Overall operation costs** cover all costs that arise from the operation of vehicles. The following cost items belong to the operation costs:
Table 18: Average occupancy rate (source: own illustration based on Dahl, Kindl, et al., 2016, p. 117 and Follmer, 2010, p. 91)

<table>
<thead>
<tr>
<th>Trip purpose</th>
<th>Occupancy rate [p/veh]</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Education</td>
<td>1.7</td>
<td>BVWP 2030 (Dahl, Kindl, et al., 2016, p. 117)</td>
</tr>
<tr>
<td>Commuting</td>
<td>1.1</td>
<td></td>
</tr>
<tr>
<td>Shopping</td>
<td>1.3</td>
<td></td>
</tr>
<tr>
<td>Leisure</td>
<td>1.9</td>
<td>MiD 2008 (Follmer, 2010, p. 91)</td>
</tr>
<tr>
<td>Business</td>
<td>1.0</td>
<td>BVWP 2030 (Dahl, Kindl, et al., 2016, p. 117)</td>
</tr>
</tbody>
</table>

- time-dependent operation costs (personnel costs)
- the costs that depend on the number of public transport vehicles (the capital costs of vehicles and insurance costs)
- the costs that depend on the kilometres of operation (fuel costs and maintenance costs)
- other costs

Among these, only the **time-dependent operation costs (personnel costs)** are related and shall be considered in calculating delay costs. The fuel costs are explained together with the environmental costs in Subsection 4.6.4. The costs that depend on the number of public transport vehicles are only relevant for the evaluation if long delays at intersections lead to an extra demand for public transport vehicles. However, they are more relevant for the evaluation at the corridor or network level and are explained in detail in Section 4.9.

Personnel costs of drivers arise not only for public transport but also for light commercial and heavy duty vehicles. Dahl, Kindl, et al. (2016, p. 134) recommended the wage rates for light commercial and heavy duty vehicle drivers. Due to the lack of data for bus or tram drivers, the same wage rate with heavy duty vehicle drivers is assumed. This assumption is made, since both drivers should have the driving licence of category C. The **cost rates for the time-dependent operation costs** are shown in Table 15, 16 and 17.

**Calculation of delay costs**

The recommended calculation procedure for delay costs is as follows:

*Step 1: quantification of traffic volumes*

The number of road users that use (or pass) a traffic signal system in the investigated period serves as the basis for calculating traffic volumes. They can be either estimated in the planning phase or collected through traffic counting in the operation phase.

A distinction is made between non-motorised and motorised traffic modes. For non-motorised traffic modes (walking and cycling), the number of road users is estimated or counted directly. However, for motorised vehicles (cars and public transport vehicles), the number of persons in vehicles should be calculated based on the number of vehicles and the occupancy rate using Equation 6. The average occupancy rates used can be found in Table 18.

\[ N_{p,m} = N_{v,m} \cdot O_m \] (6)
Where:
- \( m \) traffic mode or vehicle type m (here only cars or public transport relevant)
- \( N_{p,m} \) the number of persons or passengers in traffic mode (or vehicle type) m
- \( N_{v,m} \) the number of vehicles in traffic mode (or vehicle type) m
- \( O_m \) the average occupancy rate for traffic mode (or vehicle type) m

**Step 2: quantification of the average delay for different traffic modes**

The recommended measurement methods to assess delays are explained in Section 4.3. The measured average delay for different traffic modes serves as a basis for calculating delay costs in further steps.

**Step 3: calculation of the value of time in passenger transport**

The value of time in passenger transport is calculated using the number of persons, the average delay and the cost rates that are shown in Table 15, 16 and 17. This cost component is relevant for the walking and cycling mode as well as public transport vehicles and cars. The equation is shown belown.

\[
C_{D,P,m} = N_{p,m} \cdot d_m \cdot F_{D,P,m}
\]

Where:
- \( C_{D,P,m} \) the delay costs in passenger transport for traffic mode (or vehicle type) m
- \( N_{p,m} \) the number of persons that use a traffic signal system in traffic mode (or vehicle type) m
- \( d_m \) the average delay for traffic mode (or vehicle type) m
- \( F_{D,P,m} \) the delay cost rates in passenger transport for traffic mode (or vehicle type) m

**Step 4: calculation of time-dependent operation costs**

The calculation of the time-dependent operation costs uses the number of drivers, the average delay and the cost rates that are shown in Table 15, 16 and 17. Only the personnel costs for drivers are considered here because of the lack of data about additional workers inside a vehicle. Since there is usually only one driver in each vehicle, the number of drivers is the same as the number of vehicles. This cost component is relevant for public transport, light commercial and heavy duty vehicles.

\[
C_{D,Op,m} = N_{v,m} \cdot d_m \cdot F_{D,Op,m}
\]

Where:
- \( C_{D,Op,m} \) the time-dependent operation costs for traffic mode (or vehicle type) m
- \( N_{v,m} \) the number of vehicles in traffic mode (or vehicle type) m
- \( d_m \) the average delay for traffic mode (or vehicle type) m
- \( F_{D,Op,m} \) the cost rates of the time-dependent operation costs for traffic mode (or vehicle type) m

**Step 5: summarisation**

The delay costs for each traffic mode are the sum of delay costs in passenger transport and the time-dependent operation costs. Since the time-dependent operation costs are not relevant for walking and cycling mode, the delay costs are the same as those passenger transport. For heavy transport, delay costs are the same as the time-dependent operation costs, since the delay costs in passenger transport are not relevant. Equation 9 is used to summarise the delay costs for each traffic modes to calculate the total delay cost.

\[
C_{D,m} = C_{D,P,m} + C_{D,Op,m}
\]

\[
C_D = \sum_m C_{D,m}
\]
Where:
\[ C_{D,m} \] the delay costs for traffic mode m
\[ C_{D,pm} \] the delay costs in passenger transport for traffic mode (or vehicle type) m
\[ C_{D,op,m} \] the time-dependent operation costs for a certain traffic mode (or vehicle type) m
\[ C_D \] the total delay cost

**Comments**

Cost can also be attached to the delays of transported goods in freight transport. Dahl, Kindl, et al. (2016, p. 33) gave the following two reasons for valuing the transport time of goods. First, goods cannot be used productively during transport, which results in a waste of value during this period. Second, shorter transport time accelerates the involvement of goods in the production and sales process. The reorder time is accordingly lower, which reduces the warehousing amount and fees. However, valuing the transport time of goods requires detailed knowledge about the types of goods and truckloads. A definition of this information in advance is difficult since they are site- and time-specific. Traffic counts cannot collect this information as well. Therefore, the transport time costs of goods in freight transport are not considered in the evaluation, unless a quantification is possible and highly important for the corresponding evaluation target.

A controversial point of defining delay cost rates is how to treat the small time saving. For the evaluation of traffic signal control, most changes in travel time saving are only several seconds, which can possibly not be noticed by road users. According to Obermeyer, Wieland, and Evangelinos (2014), each travel time saving should be treated equally by planners regardless of its size. Tiny travel time saving still has benefits, although road users cannot perceive it (Axhausen et al., 2014, pp. 124-127). The study summarised that large and small travel timing savings are given the same cost rate in international practice.

In the above paragraphs, a set of delay cost rates are derived from the established value of time used in BVWP 2030 and applied on the evaluation of traffic signal control. However, the following **critical comments** are given to the developed delay cost rates. They shall be considered while conducting the evaluation.

- Due to the lack of information, **morning peak hours** and **evening peak hours** are not distinguished in the definition of traffic periods, although the corresponding distributions of trip purposes are different. According to Follmer (2010, pp. 135-138), traffic in morning peak hours on weekdays is mainly dominated by commuting and education traffic, whereas the commuting traffic overlaps with the leisure and shopping traffic in evening peak hours. A speciality of Follmer (2010) is that it analyses distributions of trip purposes based on the starting time of trips. The commuting traffic starts mostly in the morning and ends in the evening. It is only counted once in the analysis (mostly in morning peak hours). In this case, the distribution of trip purposes in evening peak hours given by Follmer (2010) does not reflect the real situation on roads, since the commuting traffic is not counted here. Table 15 shows the corresponding occupancy rate and value of travel time saving that correspond to the morning peak hour. It is suggested to apply them also for evening peak hours due to the lack of further information.

- The **distribution of trip lengths** is not investigated in detail. Instead, the weighted values of time over all distances given by Axhausen et al. (2014) are used here.

- The **distribution of trip purposes** can vary according to the location of intersections. If there are local information available, the cost rates can be modified accordingly.

- The **cost rate for heavy transport** only includes the personnel costs for the driver, since no further information about the occupancy rate of trucks has been found.
• Surcharges to wages for Sunday, holiday and night works are not considered in the personnel cost rate.

• The proposed calculation process of delay costs is valid not only for a single intersection or a road section but also a larger investigation area. For the case of a larger investigation area, the delays that a road user experiences in the whole investigation area should be quantified and used further for calculating delay costs. In the meanwhile, there may be effects on traffic shifts that need to be considered in the calculation. A discussion on this issue is given in details in Section 4.9.

• Generally, the suggested cost rates in Table 15, 16 and 17 can be modified accordingly, if there is more specific local information available.

4.6.3 Accident Costs

Accident costs may be estimated through an established method of evaluating traffic safety, which combines the number of accidents with their severity (Baier et al., 2012, p. 18). The following cost components belong to the calculation of accident costs (H. Baum, Esser, and Höhnscheid, 1998, p. 60; H. Baum, Kranz, and Westerkamp, 2011, pp. 7-8; Wijnen and Stipdonk, 2016):

• Reproduction costs concern the cost for measures that are implemented to recover the status before a traffic accident. Reproduction costs are distinguished between direct costs and indirect costs. Direct costs include medical costs resulting from the treatment of casualties and the costs of recruitment and training of new employees. Indirect reproduction costs include the costs of police services, law courts and insurance).

• Production loss concerns the loss of production due to human damages and property damages.

• Unpaid production loss includes the loss of production that is not part of the social product, such as shadow economy and household work.

• Human costs concern the immaterial costs through suffering, pain, sorrow, loss of life and quality of life.

• Congestion costs value the delays due to congestions that result from accidents.

• Avoidance costs are the amount of money that road users are ready to pay in order to avoid accidents.

Accident cost rates

In Germany, the Federal Highway Research Institute (original German name: Bundesanstalt für Straßenwesen (BASt)) calculates and publishes yearly the accident cost rates and the economic costs of traffic accidents in Germany (H. Baum, Kranz, and Westerkamp, 2011, p. 7). The cost rates in Euro per person (€/person) or Euro per accident (€/accident) vary according to the severity of accidents (death, serious injured and slight injured) and the category of property damages. The calculation model has been updated several times since the first introduction of a concept in the year 1984 by Krupp and Hundhausen (1984). A computer model was developed in the year 1998 (H. Baum, Esser, and Höhnscheid, 1998). Based on previous studies, H. Baum, Kranz, and Westerkamp (2011) published the most up-to-date model, whose value is further used in this section. It considers the following cost components as mentioned above: reproduction costs, production loss, unpaid production loss, human costs and congestion costs. The avoidance costs are left out of consideration.

As illustrated above, the accident cost rates based on the computer models from BASt are updated yearly. Figure 9 shows the development of cost rates for person injuries and property damages from the year 2005 to 2014. A slightly increasing trend can be observed in the past years, especially for the cost rate for deaths.
The accident cost rates in the year 2012 are used here for the evaluation of traffic signal control. Table 19 shows the cost rates according to Bundesanstalt für Straßenwesen (2016), which are calculated based on the model of H. Baum, Kranz, and Westerkamp (2011). The price level in 2012 is chosen in order to be consistent with the price level of delay cost rates.

An evaluation of traffic signal control can be conducted in both the planning and the operation phase. In the operation phase, the cost rates can be multiplied with empirical accident data to calculate the accident costs in the current state. They are valid for the current traffic signal program under operation. In contrary to that, the accident data or costs can only be estimated in the planning phase or for the evaluation of alternative signal programs in the operation phase. As explained in Section 4.3, the results from relevant research projects can be used as a reference if situations are similar. Generally, the
Table 19: Accident cost rates (source: own illustration based on H. Baum, Kranz, and Westerkamp, 2011)

<table>
<thead>
<tr>
<th></th>
<th>Cost rate (at 2012 price)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Personal injury</strong></td>
<td></td>
</tr>
<tr>
<td>Death</td>
<td>1,161,892 €/person</td>
</tr>
<tr>
<td>Serious injury</td>
<td>116,151 €/person</td>
</tr>
<tr>
<td>Slight injury</td>
<td>4829 €/person</td>
</tr>
<tr>
<td><strong>Property damage</strong></td>
<td></td>
</tr>
<tr>
<td>Accident with personal injury</td>
<td>15,606 €/accident</td>
</tr>
<tr>
<td>Accident with death</td>
<td>43,096 €/accident</td>
</tr>
<tr>
<td>Accident with serious injury</td>
<td>20,782 €/accident</td>
</tr>
<tr>
<td>Accident with slight injury</td>
<td>13,959 €/accident</td>
</tr>
<tr>
<td>Serious accident just with property damage</td>
<td>20,808 €/accident</td>
</tr>
<tr>
<td>Other accident (including alcohol accident)</td>
<td>5951 €/accident</td>
</tr>
</tbody>
</table>

Accident rates (at 2005 price) suggested in HVS (Bark et al., 2008) can be used as an estimation for intersections that are compliant to the rules defined in that study. An update of the values on the current price level might be necessary. Besides, if the design of an intersection or a traffic signal system differs, the influences on the safety level need to be further analysed. A substantial influencing factor on traffic safety at intersections is the form of signals for left-turning streams. It can be distinguished between the unsafe left-turning in all approaches, the partially safe left-turning with lead (or overrun) time and the safe left-turning. Baier et al. (2012) have investigated the safety level of different left-turning forms based on a relatively large sample (230 intersections in different regions in Germany). Baier et al. (2012) estimated the average accident rates that relate to the form of signals for left-turning streams and their shares among the total accident rates. It is shown that the share of accident rates that relate to the left-turning streams decreases with increasing protection for them. Based on the results of Baier et al. (2012), the accident costs of traffic signal programs with various left-turning forms can be roughly estimated.

Calculation of accident costs

When calculating accident costs, a distinction is made between the accidents with personal injuries and those with property damages only. Different from delays which can be measured in a short investigated time, accident data are only available in the long term. It is not possible to estimate the possibility of accidents in a short period. Therefore, it is recommended to first calculate the accident costs in the long term and then estimate those for an investigated period. Assumptions are necessary in this process. The recommended calculation procedure for accident costs are as follows:

**Step 1: quantification of accidents number in the long term**

The number of accidents for different types of accidents should be estimated or collected using the measurement methods suggested in Section 4.3. The types of accidents are shown in Table 19. The accident data should relate to a long period (such as one year, three years or five years).

**Step 2: calculation of accident costs in the long term**

The accident costs include two cost components: the cost of personal injuries and the cost of property damages. Equation 10 is used to calculate the total accident cost.
\[ C_{A,I,P_i} = \sum_{T_p} N_{A,I,P_i,T_p} \cdot F_{A,P_i,T_p} \]
\[ C_{A,I,P_d} = \sum_{T_p} N_{A,I,P_d,T_p} \cdot F_{A,P_d,T_p} \]
\[ C_{A,I} = C_{A,I,P_i} + C_{A,I,P_d} \] (10)

Where:
- \( C_{A,I,P_i} \) the accident costs for personal injuries in a long term
- \( N_{A,I,P_i,T_p} \) the number of deaths or injured persons (type \( T_p \)) in a long term
- \( F_{A,P_i,T_p} \) the cost rates for injury type \( T_p \)
- \( C_{A,I,P_d} \) the accident costs for property damages in a long term
- \( N_{A,I,P_d,T_p} \) the number of accidents for type \( T_p \) in a long term
- \( F_{A,P_d,T_p} \) the cost rates for accident type \( T_p \)
- \( C_{A,I} \) the total accident cost in a long term

Step 3: derivation of accident costs for the investigated periods

The accident costs for an investigated period are estimated using the accident costs per 1000 vehicles in €/1000veh. The Average Annual Daily Traffic (AADT) is needed for calculating the accident costs per 1000 vehicles. If there are no data available, it can be extrapolated based on the results from short-term traffic counts. A possible extrapolation method is given in HBS 2009 (FGSV, 2009, pp. 2-15-2-20). The accident costs per 1000 vehicles is calculated using Equation 11.

\[ CR_A = \frac{C_{A,I} \cdot 1000}{N_y \cdot 365 \cdot AADT} \] (11)

Where:
- \( CR_A \) the accident costs per 1000 vehicles
- \( C_{A,I} \) the total accident cost in a long term
- \( N_y \) the number of years of the accident data
- \( AADT \) the average annual daily traffic

A simplified method to calculate the accident costs for an investigation period is to multiply the accident costs per 1000 vehicles and the number of vehicles that pass an intersection within this period (see Equation 12). Two assumptions made for this simple calculation method are:

- The occurrence of traffic accidents is closely related to traffic volumes.
- The probability for traffic accidents remain constant in different periods.

\[ C_A = CR_A \cdot \sum_{m} N_{v,m} \] (12)

Where:
- \( C_A \) the total accident cost for the investigated time period
- \( CR_A \) the accident costs per 1000 vehicles
- \( N_{v,m} \) the number of vehicles in traffic mode \( m \)
Comments

The following critical comments are given to the calculation of accident costs using cost rates:

- The delay for pedestrians has a significant influence on traffic safety. FGSV (2002a) stated that the share of pedestrians that cross a street on red would increase significantly if their delay exceeds 40 s. However, the violation behaviour of pedestrians is still very situation-responsive. It is influenced by many factors, as explained in Subsection 2.5.3. Besides, pedestrians are usually cautious about the surrounding traffic situation. It is not possible to estimate generally the influence of the delay for pedestrians on accident costs in the framework of this study. Further research in this particular aspect is a promising topic for the future. Therefore, this aspect is not considered here while calculating traffic costs.

- Avoidance costs are not part of the cost rates developed using H. Baum, Kranz, and Westerkamp (2011). The cost rates and their resulting accident costs will rise if this additional cost component is included.

- Simple assumptions are made while deriving the accident costs of a short time period (for example hourly value) from the long-term accident costs (annual, three years or five years value). It is one source of inaccuracy.

- Similar to delay costs, the proposed calculation process of accident costs is both valid for the small and large investigation areas. The input accident data should correspond to the size of the investigation area. Since the empirical accident data are normally documented by the police, a quantification of the current accident costs for a large investigation is not that big challenge. However, the impacts of different traffic signal programs on accidents can be complicated to quantify for a large investigation area.

4.6.4 Energy Consumption and Environmental Costs

Environmental cost rates

Motorised vehicles can emit various kinds of air pollutants, which further influence the natural ecosystem and human health negatively. The calculation of environmental costs shall, therefore, cover costs that arise from these negative impacts. According to Schwermer (2012b, pp. 40-42), it can be distinguished between two cost components for environmental costs. The first cost component is damage costs, which consist of not only the cost to reduce the environmental and health damages from air pollution but also that to describe the unavoidable damages. The second cost component is avoidance costs, which are the willingness-to-pay to avoid certain environmental impacts (such as the reduction of air pollution).

Environmental costs are an important component of the cost-benefit-analysis for transport-related projects. For calculating environmental costs, this study uses the established cost rates according to BVWP 2030 from BMVI (Dahl, Kindl, et al., 2016, p. 111) and a study from the German Environment Agency (original German name: Umweltbundesamt (UBA)) to calculate environmental costs (Schwermer, 2012a). The suggested cost rates are based on the up-to-date research results from various studies, including the EU project New Energy Externalities for Sustainability, Torras Ortiz (2011), R. Friedrich et al. (2011) and many others. And they have already been used in practice to monetise the environmental impacts of transport infrastructures. Therefore, they are used as reference values here. Table 20 shows a summary of the cost rates used to monetise air pollutant emissions.

For the emissions of particles and NO\textsubscript{x}, the cost rates reflect only damage costs. The following negative environmental damages are considered for calculating the cost rates (Preiss, 2012, p. 6):
• harm on health
• material damages
• changes in the agricultural harvests
• damages on natural ecosystems

For the emissions of CO$_2$, the calculation of cost rates covers not only the damage costs as explained above but also the avoidance costs according to Schwermer (2012a, pp. 5-6).

Table 20: Environmental cost rates (source: own illustration based on Dahl, Kindl, et al., 2016, p. 111 and Schwermer, 2012a)

<table>
<thead>
<tr>
<th>Air pollutant</th>
<th>Cost rate [€/t] at 2010 price</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>urban</td>
</tr>
<tr>
<td>PM exhaust</td>
<td>364,100$^a$</td>
</tr>
<tr>
<td>PM$_{10}$ resuspension and wear</td>
<td>33,700$^b$</td>
</tr>
<tr>
<td>NO$_x$</td>
<td>15,400$^a$</td>
</tr>
<tr>
<td>CO$_2$</td>
<td>80$^b$,$^c$</td>
</tr>
</tbody>
</table>

$^a$ Dahl, Kindl, et al., 2016, p. 111
$^b$ Schwermer, 2012a, p. 5
$^c$ The value corresponds to the medium value that is given in the literature.

The cost rates for particles differ according to the emission sources and the location of traffic signal systems. For exhaust particle emissions in the urban area, the environmental cost rate is 364,000 €/t. This is much higher than that for PM$_{10}$ emissions from the resuspension and abrasion processes, which is 33,700 €/t in the urban area. The cost rates for particles in the rural area are generally lower than those in the urban area. The reason is that there are fewer residents exposed to the particle pollution that is emitted by motorised vehicles.

For the emissions of particles and NO$_x$, Schwermer (2012a) suggested a concrete value for each kind of emission in an area. However, for CO$_2$ emissions, Schwermer (2012a) suggested a range for the cost rate, which is 40 to 120 €/t. The median value of 80 €/t is used here. This value can be adapted according to the actual political goal of administrative authorities.

Cost rates for energy consumption

The cost rates for energy consumption are derived from the BVWP (Dahl, Kindl, et al., 2016, pp. 103-105) as well. The cost rate for fuel consumption is 0.71 €/l for vehicles with traditional combustion motors and 17.84 cent/kWh for electric vehicles (electricity costs for private households). Taxes and fees are not inclusive in the economic costs.

Calculation of energy consumption and environmental costs

The calculation of environmental costs is straightforward. The basis is the amount of emitted air pollutants in the investigation area during the investigation period that is estimated using measurement methods in Section 4.3. Equation 13 is recommended.
\[ C_{Em,Ap} = EM_{Ap} \cdot F_{Em,Ap} \]
\[ C_{Em} = \sum_{Ap} Em_{Ap} \]

(13)

Where:
- \( C_{Em,Ap} \) the emission costs for air pollution \( Ap \)
- \( EM_{Ap} \) the amount of emissions of air pollution \( Ap \)
- \( F_{Em,Ap} \) the emission factors for air pollution \( Ap \)
- \( Ap \) the type of air pollution
- \( C_{Em} \) the total emission cost

The calculation of energy consumption costs is similar (as shown in Equation 14).

\[ C_{Ec} = EC \cdot F_{Ec} \]

(14)

Where:
- \( C_{Ec} \) energy consumption costs
- \( EC \) the amount of energy consumption
- \( F_{Ec} \) the cost rates for energy consumption

Comments

The following critical comments are given to the calculation of energy consumption and environmental costs using cost rates:

- When calculating the environmental cost rates, it is not taken into consideration that, there are higher impacts on the health of pedestrians and cyclists who are much more exposed to air pollution at an intersection.

- The emissions of other air pollutants are not considered in the framework of this study, such as \( \text{CO}, \text{SO}_2 \) and \( \text{NMVOC} \). It is because their related problems are not as critical as those of particles and \( \text{NO}_x \) in the current situation of Germany. However, they can also be included if this evaluation methodology is applied in other countries where their problems are still critical.

- Dahl, Kindl, et al. (2016) suggested environmental cost rates for the emissions of air pollutants during the generation process of electricity that is used in the operation of electric vehicles. The electric vehicles mentioned here include all the vehicles that operate with an electric engine, such as trams and electric cars. Other than particles from resuspension and abrasion, electric vehicles do not emit emissions locally. The environmental costs for the emissions that are not emitted locally in the investigation area are not taken into consideration in the evaluation method. Therefore, the fuel consumption costs are used instead of the energy consumption costs in Chapter 5.

- The calculation process of energy consumption and environmental costs is both valid for small and large investigation areas. The input data for calculation need to correspond to the range of the investigation area.
4.7 Particular Weighting of Evaluation Criteria

As explained in Section 4.6, established cost rates are used to convert the multidimensional criteria into their corresponding costs for comparison and evaluation. The cost reflects the performance of a target signal program regarding each evaluation criterion and its corresponding goal. Additionally, administrative authorities or engineers can have preferences for specific traffic modes or evaluation criteria due to political or planning reasons. In order to realise these preferences, the particular weight is assigned to calculate the corresponding weighted cost. The sum of all weighted costs serves as the basis for evaluating a targeted traffic signal program.

The advantage to separate cost and its particular weight in the evaluation is to make the trade-off and decision-making process for designing and evaluating traffic signal programs more transparent and comprehensive. It is distinguished between the case when only costs are considered and the case when particular weights are included additionally. If only costs are considered (or all particular weights equal to one), the evaluation results are less biased with minimal influences from political preferences. Still, preferences for certain goals are necessary and desired from authorities in many situations due to political and planning reasons. Examples for such reasons are shown in Table 21. It must be emphasised that the introduction of such particular weighting should always be carefully justified since it causes bias to evaluation results and the decisions based thereon.

By varying the values of particular weights, it is possible to analyse their influences on the evaluation results. It gives further hints on how preferences for specific traffic modes can influence settings of traffic signal programs. It also supports the decision-makers on selecting the appropriate particular weightings for their traffic signal systems.

<table>
<thead>
<tr>
<th>Corresponding cost rates</th>
<th>Examples for planning or political reasons</th>
</tr>
</thead>
<tbody>
<tr>
<td>Delay costs for pedestrians and cyclists</td>
<td>• To promote non-motorised traffic</td>
</tr>
<tr>
<td></td>
<td>• Along cycle superhighways</td>
</tr>
<tr>
<td></td>
<td>• Near schools or bus stops etc.</td>
</tr>
<tr>
<td>Delay costs for public transport</td>
<td>• To promote public transport</td>
</tr>
<tr>
<td></td>
<td>• To avoid increase in costs due to extra vehicle demand</td>
</tr>
<tr>
<td>Delay costs for motorised private transport</td>
<td>• To harmonize traffic flow</td>
</tr>
<tr>
<td>Accident costs</td>
<td>• To promote traffic safety</td>
</tr>
<tr>
<td>Environmental costs</td>
<td>• To strengthen environmental and climate protection</td>
</tr>
<tr>
<td></td>
<td>• Impending exceedance of threshold values</td>
</tr>
</tbody>
</table>

The non-motorised traffic modes (walking and cycling) are generally promoted in traffic management due to the environmental friendliness (Boltze and Jiang, 2017; Magistrat der Stadt Darmstadt, 2015). Another case is for intersections along a cycle superhighway. As explained in Subsection 2.5.4, priority is usually given to cyclists at those intersections to reduce the delay for cyclists and increase the attractiveness of cycle superhighways. Pedestrians and cyclists also need more protection near schools or bus stops so that they can safely cross the streets. In order to reflect the goals mentioned above in the evaluation, a high weight can be given to the delay costs for pedestrians and cyclists.

Public transport is another travel mode that is generally prioritised in the urban planning procedure. The importance of public transport priority is already explained in Subsection 2.5.5. Under this context, a particular weight is assigned to the delay costs for public transport. Such kind of particular weighting
can also be introduced to avoid increased investment costs due to an extra demand for vehicles. An alternative to consider these extra costs is via superordinate effects that are explained in Section 4.9. Double consideration should be avoided.

Many regions or cities propose to **strengthen environmental protection** and to **protect residents’ health**. In order to achieve and emphasise this goal, environmental costs can be assigned with a high weight while evaluating traffic signal program. The problem of air pollution becomes urgent when the legal threshold value of a air pollutant is or will be exceeded. Under such circumstances, the traffic signal program shall be adapted to reduce traffic-related emissions especially. A particular weighting is necessary to consider this aspect in the selection of an appropriate traffic signal program.

### 4.8 Situation-responsive Influences on the Evaluation

For the **situation-responsive traffic signal control**, the traffic signal program varies dynamically, so that it can respond to the real-time changes in traffic, environmental or other situation. To realise such a situation-responsive control, cost rates and particular weights need to be adjusted according to the real-time situation as well.

Table 22 gives an overview of the **possible features that define different situations**. They are first distinguished between those that influence cost rates or particular weights. Besides, the background colour indicates whether a feature remains unchanged or varies temporally.

<table>
<thead>
<tr>
<th>Features that influence traffic signal control (own illustration)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Cost rates</strong></td>
</tr>
<tr>
<td>Location of a traffic signal system</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Situations and traffic situation</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Environmental situation</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
</tbody>
</table>

As explained in Section 4.6, the development of delay and environmental cost rates already takes the **traffic time** (peak, off-peak and lean hour) and the **location** of a traffic signal system into consideration. These are also shown in Table 22 and explained further in next paragraphs.
Despite the ones in Table 22, some other features are situation-responsive but have no influences on cost rates or particular weights, e.g. variations in the traffic volumes and the occupancy rates of public transport vehicles. Instead, they are already considered when the number of road users and person-related delays are included in the evaluation. Therefore, they are not listed here.

First, the **location** of a traffic signal system influences cost rates. A distinction is made between the urban and suburban area. In the urban area, the number of residents that are exposed to high air pollution from traffic is significantly higher that in the suburban area. And so is its impact on human health. As a result, the environmental cost rates for particles are higher in the urban area than in the suburban area. A comparison is shown in Table 23 as example (column 3 and 4).

### Table 23: Examples for some cost rates in defined situations (own illustration)

<table>
<thead>
<tr>
<th>Definition of situations</th>
<th>Cost rates</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Location of a traffic signal system</strong></td>
<td>4.21</td>
</tr>
<tr>
<td><strong>Transport demand and traffic situation</strong></td>
<td>4.4</td>
</tr>
<tr>
<td><strong>Traffic time</strong></td>
<td>20.14</td>
</tr>
<tr>
<td><strong>Delay costs</strong></td>
<td>4.42</td>
</tr>
<tr>
<td><strong>PuT</strong></td>
<td>4.93</td>
</tr>
<tr>
<td><strong>PrT</strong></td>
<td>17.64</td>
</tr>
<tr>
<td><strong>Accident costs</strong></td>
<td>1,161,892</td>
</tr>
<tr>
<td><strong>Energy consumption and environmental costs</strong></td>
<td>364,100</td>
</tr>
<tr>
<td><strong>PM exhaust</strong></td>
<td>33,700</td>
</tr>
<tr>
<td><strong>PM$_{10}$ resuspension and abrasion</strong></td>
<td>15,400</td>
</tr>
<tr>
<td><strong>CO$_2$</strong></td>
<td>0.71</td>
</tr>
<tr>
<td><strong>Fuel consumption</strong></td>
<td>17.84</td>
</tr>
<tr>
<td><strong>Electricity consumption</strong></td>
<td>cent/kWh</td>
</tr>
</tbody>
</table>

Second, a high weight can be assigned if a traffic signal system is located near a **public institution**. Examples for such public institutions that need special consideration are hospitals, schools or childcare facilities. Near a hospital, the requirement for noise reduction is stricter than in other areas. Noise is not explicitly considered in D-MoTSE. Still, the traffic signal control can be designed in a way to ensure a better traffic flow of motorised traffic in order to reduce the noise emission. The requirement to reduce the noise emission near a hospital is permanent and independent from its opening hour. Near a school or childcare facility, it is generally recommended to prioritise pedestrians at traffic signal systems in order to protect children while crossing streets. In order to achieve that, a high weight for pedestrian delays can be applied. However, the appearance of children near schools or childcare facilities depends closely
on the opening hour. Therefore, the adjustment of particular weighting is applied only in certain periods, in others not.

The third feature that relates to the location is the **special function** of a traffic signal system. An example is gating signals that are usually located at city borders. In peak hours, these signals are designed to limit the traffic volume that enters cities so that the traffic network in the city centre is not overloaded. Another goal to implement gating signals is to avoid high traffic in the city centre by improving traffic quality. This unique function can be considered in selecting particular weights for the corresponding gating signal system as well. The concrete implementation is individual and varies from case to case.

As explained in Section 4.6, the delay cost rates in passenger transport vary depending on the **weekday** and **traffic time**. Since surcharges to wages for Sunday, holiday and night works are ignored for simplification, the time-dependent operation costs (here the personnel costs for drivers) remain unchanged over time. A comparison of cost rates in different traffic time is shown in Table 23 (column 3 and 5).

The **real-time schedule situation** needs to be considered in traffic signal control as well. If a public transport vehicle is behind its schedule, higher priority can be given to this vehicle so that it can keep up with its schedule and maintain the service quality of public transport. In order to realise this, a higher particular weight can be assigned to the delay costs for traffic signal control. However, it is not necessary to accelerate an early public transport vehicle in the same way.

**Events** are exceptional cases. The selection of particular weights needs to consider the individual demands of each event. There is no general pattern.

At last, the **real environmental situation** has a significant influence on particular weights for the environmental costs. The environmental costs are calculated only based on the emissions from motorised vehicles. However, the ambient air quality and its related human health impact are influenced strongly not only by emissions but also by the weather condition, such as the temperature, the precipitation, the wind speed, the wind direction and the vertical air exchange condition. It is, therefore, necessary to adjust particular weights on a real-time basis, so that the effects of weather conditions can be taken into consideration.

There are numerous studies about the influences of various **weather factors** on the ambient air quality (e.g. A. Baum, 2008; Düring and Lohmeyer, 2008). The correlations are complex and interdependent. Therefore it is difficult to define a situation "unfavourable condition for air pollution" based only on weather factors. A more straightforward approach is to rely upon the urban background air pollution that is measured by monitor stations. Based on that, it is basically to judge the condition of air exchange and to decide whether stronger environmental protection is necessary to be implemented or not. In order to realise such stronger environmental protection under unfavourable situations, a higher particular weight can be assigned to the environmental costs so that traffic signal programs with lower emissions get a better performance score and are more likely to be chosen. Environmental protection is also given priority if the threshold values for air pollution are about to be exceeded. In contrast, it is assigned lower priority under really favourable weather condition.

Generally, the suggested cost rates and particular weights here can be adjusted if there is **site-specific knowledge** available while implementing the evaluation method in practice (e.g. in other countries or cities). It is recommended to determine cost rates for all situations universally. The **universality** here does not mean that all authorities should follow the same cost rates. Rather one authority should determine a set of cost rates that are suitable for its case and apply to all traffic signal systems that it takes responsibility on. This process should be kept away from the influence of political preferences and values as much as possible. However, the determination of particular weights is on a case-to-case basis. The value depends flexibly on the concrete situation. The purpose is to guarantee a clear and comprehensive trade-off process.
4.9 Consideration of Superordinate Effects

4.9.1 Traffic Shifts

For evaluating the traffic signal control on a larger scale (e.g. corridors and networks), it is not only necessary to consider the changes in the delays for road users, traffic safety and environmental impacts as suggested in Section 4.6, but also important to take into consideration the superordinate effects on transport networks that can be significant on a macroscopic level. The first important aspect to consider is traffic shifts.

Traffic shifts are defined as the shift of travel demands in travel modes, locations and time (FGSV, 2012a, p. 30). The settings of traffic signal control would influence mainly the delays, the travel time and the comfort for the trips made by different road users and, therefore, result in traffic shifts. There are different kinds of traffic shifts to consider:

- changes in modal splits
- changes in route decisions
- changes in the destination of trips
- time-of-day shifts

Besides, there can be an avoidance of trips, which can be barely caused by traffic signal control measures. All these changes can be reflected by the travel demand of a traffic mode in a predefined investigation period and time. The travel demands and the corresponding traffic volumes are input data for measuring the evaluation criteria considered in D-MoTSE and for assessing their corresponding cost components as illustrated in Section 4.6. Therefore, traffic shifts can be considered in the evaluation by applying elastic travel demands (or traffic volumes) while assessing and comparing different alternatives.

Traffic shifts can be directly measured using traffic counts if the alternative signal programs can be tested in reality. However, the high effort and the long period needed for the appearance of these effects should be considered before applying. More commonly, modelling tools are used to estimate the effects of a traffic control measure on traffic shifts.

Transport demand models can be used to assess the shift of travel demands between traffic modes, routes and departure time. The modal split model and the route choice model (also known as the assignment model) are two classic stages of transport demand models. There are additionally models available to model the time of day choice. The output of the transport demand modelling is traffic volumes that are expected on the road networks. It serves as the input for the evaluation of traffic signal control in the investigation area. Transport demand modelling is a very complex research topic. A good overview is given in e.g. Lohse and Schnabel (2011) and Ortúzar and Willumsen (2011). According to Ortúzar and Willumsen (2011), several problems may arise while attempting to combine route choice and traffic signal control in one model. Besides, there is still a lack of consensus, and much work is to be carried out to bring the departure time model into the mainstream of transport modelling. Therefore, the focus of the following paragraphs is laid only on the interaction of traffic signal control and the modal split.

Modal split models should be sensitive to those attributes of travel that influence individual choices of mode (Ortúzar and Willumsen, 2011, p. 207). Among those, the travel time and the monetary cost are two critical factors that can be influenced by traffic signal control in the urban area. No general conclusions can be made about what impacts these two factors have on the modal split since they vary dramatically from situation to situation. In the following, a simple example is illustrated to give a rough orientation on how small changes in travel time would possibly influence the modal shift.

The example is based on a sample calculation in Lohse and Schnabel (2011, pp. 336-343). The sketch for the example is shown in Figure 11. From an origin to a destination, there are available traffic routes
for different traffic modes: walking, cycling, public transport and motorised private transport. The travel time is mainly considered in calculating the modal split for trips from the origin to the destination. Based on the given input data, the total travel time and the modal split for trips of 2 km are shown in Table 24. It should be especially pointed out that the values shown below only correspond to the assumptions of this specific example. They cannot give statements that apply to the modal split in other case studies.

![Figure 11: Sketch for one example of the modal split model (source: Lohse and Schnabel, 2011, p. 340)](image)

Table 24: Input for an example of the modal split model (source: own illustration based on Lohse and Schnabel, 2011, p. 340)

<table>
<thead>
<tr>
<th>Travel mode</th>
<th>Total travel time [min]</th>
<th>Mode share [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Walking</td>
<td>34.5</td>
<td>3.1</td>
</tr>
<tr>
<td>Cycling</td>
<td>15.5</td>
<td>13.7</td>
</tr>
<tr>
<td>Public transport</td>
<td>25.3</td>
<td>38.1</td>
</tr>
<tr>
<td>Motorised private transport</td>
<td>10.8</td>
<td>45.1</td>
</tr>
</tbody>
</table>

Based on this example, it is calculated how changes in the travel time of public transport or motorised private transport influence their mode shares accordingly, as shown in Figure 12. It can generally be observed that the changes are within the range of 2%, if changes in travel time are not more than ±2 min.

![Figure 12: Impacts of the changes in travel time on the modal split (own illustration)](image)
The results of case studies in Chapter 5 show that the maximum differences of the averages delays for public transport and motorised private transport between alternative signal programs are around 20 s and 18 s. At signalised pedestrian crossings, the values are much lower. Under consideration of this, there would be a change of 2 min in the average travel time only if adjustments happen at multiple intersections along a corridor. Still, changes in the modal split are negligible in most cases according to the calculations above.

Another important issue is also worth mentioning. Although there can be negative and indirect impacts of traffic signal control on the middle-term or long-term modal split, there are a variety of other transport measures that can compensate these impacts, such as mobility management or regulatory and financial measures (Boltze and Jiang, 2017). An advantage of these measures can be that the impacts are more significant on a large scale. Besides, the intended deterioration of traffic flows and negative influences on air pollutant emissions can better be avoided.

For evaluating multiple traffic signal programs at only one single intersection, the corresponding traffic shift effect is negligible. For simplification, it can be assumed that travel demands and traffic volumes remain inelastic and do not change under different traffic signal programs. In this case, the same traffic volumes serve as the input for evaluation.

### 4.9.2 Operation of Public Transport

Changes in travel time due to adjustment in traffic signal control would influence not only the modal split on the macroscopic level but also the operation of public transport, especially the reliability of public transport service. For passengers, reliability means the punctuality and the assurance of connections (Schnieder, 2015, p. 3). Punctuality represents the adherence of the actual service to the planned schedule while the assurance of connections means that passengers can successfully make transfers to other lines or traffic modes.

The proposed evaluation method D-MoTSE quantifies various impacts of traffic signal control in costs. It is, however, difficult to value the reliability costs and include them in the evaluation scheme like other cost components. One possible way is to value the changes in capital costs if there is extra demand for vehicles or staffs in critical situations. That is the case, e.g. when the delays at traffic signal systems are so long that the planned time and crew schedule cannot be kept. The resulting extra capital costs of vehicles can be a potential cost component and be included in the total cost. The capital cost of buses is roughly between 210,000 € for midibuses and 330,000 € for articulated buses (Leuthardt, 2005). However, another problem occurs during this process since the increase in capital costs are a long-term investment. It is difficult to distribute such long-term costs to each single operation hour and make them comparable with other cost components that are site- and time-specific. Given this difficulty, it is recommended to apply a special weight to the delay costs for public transport, under the situation that an extra demand for vehicles is foreseen when the planned time and crew schedule cannot be kept.

Whether the above mentioned critical situation happens depends strongly on the robustness of planned time and crew schedules. In the planning process, the buffer time is necessary to compensate interruptions and the resulting deviations to schedules. In practice, disruptions can come from both traffic conditions and other aspects besides (Brinckerhoff, 2013, pp. 4-33). As summarised by that manual, the traffic-related aspects include traffic congestions, traffic signal delays, parking manoeuvres and incidents. In peak hours, traffic volumes and the frequency of disruptions are very high. There is almost no additional reserve in the schedule to compensate the additional delays that may occur due to a weaker public transport signal priority. In off-peak and lean hours, that is however possible.

Borndörfer, Grötschel, and Jaeger (2009) introduced briefly the concept of the robust and stochastic planning. The goal is to design a plan, which is not only appropriate on paper but also applicable in practice. Buffer time is planned in an optimal way so that plans are resistant against small disruptions.
during trips. Such robust planning for public transport is meaningful and helps to realise a situation-
responsive traffic signal control. It provides a buffer for adjustment of traffic signal control, especially in
off-peak and lean hours.

Besides reliability, other factors are also important indicators to value the service quality of public trans-
port so that its social function can be guaranteed, such as the travel speed, the service frequency, ac-
cessibility and comfort. The travel speed is used in HBS 2015 to evaluate the service quality of public
transport facilities. However, when the distance remains unchanged, the travel speed and travel time
have an inverse relationship. As mentioned in Subsection 4.9.1, changes in travel time are already
considered by applying variable traffic volumes to reflect possible traffic shift. Because of its direct re-
lationship to travel time, the travel speed is not directly considered in D-MoTSE. The travel speed and
the determined level of service accordingly can be used as a reference for interpreting the situation. The
other factors, including the service frequency, accessibility and comfort, can barely be influenced by
the setting of traffic signal control. Thus, they are not relevant to the evaluation of traffic signal control.

4.10 Aggregation

An aggregation of the calculated cost components in Section 4.6 serves as the basis for ranking the
alternative signal programs. There are two possible ways of aggregation. The first one is a simple
addition of all cost components using Equation 15, which delivers the total cost. The other one is a
weighted addition of all cost components and their corresponding particular weights (see Section 4.7)
using Equation 16, which delivers the total weighted cost.

\[
C = C_D + C_A + C_{Em} + C_{Ec}
\]  

(15)

Where:

- \( C \) = the total cost
- \( C_D \) = the total delay cost
- \( C_A \) = the total accident cost for the investigated time period
- \( C_{Em} \) = the total emission cost
- \( C_{Ec} \) = energy (fuel) consumption costs

\[
C_W = \sum_m W_m \cdot C_{D,m} + W_A \cdot C_A + W_{Em} \cdot C_{Em} + W_{Ec} \cdot C_{Ec}
\]  

(16)

Where:

- \( C_W \) = the total weighted cost
- \( W_m \) = the special weight for delay costs of traffic mode m
- \( C_{D,m} \) = the delay costs for traffic mode m
- \( W_A \) = the special weight for accident costs
- \( C_A \) = the total accident cost for the investigated time period
- \( W_{Em} \) = the special weight for emission costs
- \( C_{Em} \) = the total emission cost
- \( W_{Ec} \) = the special weight for energy (fuel) consumption
- \( C_{Ec} \) = energy (fuel) consumption costs

The total cost reflects the actual overall performance of a traffic signal program without bias for any goal.
On the contrary, the total weighted cost can reflect the priority of planners or administrative authorities
for a specific goal additionally. The default weight for each cost component is equal to one. In this
case, different cost components are equally weighted. The value of the total cost and that of the total
weighted cost are the same. A deviation from the equal weighting should be avoided as far as possible
since it brings bias to the evaluation results. A higher particular weight for an evaluation criteria (higher
than one) can only be introduced when there is a justified reason for doing that. Examples for possible planning or political reasons are given in Section 4.7. If a higher special weight is introduced, the total weighted cost is not equal to the total cost. The total weighted cost should further be used to rank the alternative signal programs. Then, recommendations for designing traffic signal control are given based on the ranking of alternative signal programs. However, the value of the total weighted cost does not reflect the real cost and should not be used for further analysis.

The aggregation process serves to summarise the calculated cost components in order to have an overall view of the alternative signal programs. However, the information about each cost component gets partially lost after the aggregation. Therefore, it is suggested to additionally conduct an comprehensive analysis based on the total cost and each cost component. They can reflect the real performance of each alternative traffic signal programs.

The above-mentioned aggregation process and calculation equation are both valid for a small (a single intersection or a road section) and a large (a corridor or a network) investigation area. For a large investigation area, there are other aspects to consider, such as the possibility to divide the whole investigation area in several subareas and the consideration of superordinate effects. The former should be decided for each case. The latter is discussed in Section 4.9. However, the core way to aggregate the cost components remains the same.

### 4.11 Ranking of Alternative Traffic Signal Programs and Sensitivity Analysis

The alternative traffic signal programs are ranked based on the total weighted cost. Under an equal weighting of all evaluation criteria (all equal to one), the traffic signal program with the lowest cost is the optimum and most cost-effective solution. As explained in Section 4.7 and 4.10, a particular weight can possibly be assigned to a certain evaluation criteria if it is sufficiently justified. In this case, the cost-effective solution can be but must not be different from that under the equal weighting. It can be analysed how the particular weighting could influence the rank order of alternative traffic signal programs. Whether a particular weight is reasonable and acceptable depends on the investigation site and the goals for the evaluation. A sufficient justification and discussion are always necessary.

A sensitivity analysis aims to investigate how sensitive the evaluation results are against changes in the input attributes, which are cost rates, weights and the occupancy rates of vehicles in D-MoTSE. The main reason is that there are uncertainties in these attributes that may influence evaluation results. Different attributes may lead to a change in the rank order. Therefore, the sensitivity analysis is a crucial step to test the robustness of the evaluation results. In D-MoTSE, the main concern is laid on the ranking of alternative signal programs and the recommendations for traffic signal control that are drawn based on the ranking scheme.

The One-at-a-time is one of the simplest and most common approaches for the sensitivity analysis (Hamby, 1994). It investigates how the calculated costs of signal programs change by adjusting one attribute at a time while keeping other attributes constant. The results are shown graphically. The ranking of signal programs can, therefore, be read from graphics.

As mentioned above, the attributes of the evaluation method are mainly cost rates, occupancy rates and particular weights. For the cost rates and the particular weights, it is suggested to adjust the attribute values by a percentage of their baseline values. It is because the baseline values vary between different attributes and periods. Showing changes in the percentage value instead of the absolute value can make the interpretation of results easier. Due to the function for calculating the weighted cost, the sensitivity analyses of cost rates and special weights yield the same results. The occupancy rates of different types of vehicles have a relatively fixed range of values. The attribute values are adjusted by changing their absolute values to make the interpretation easier.
The **One-at-a-time** is recommended for the sensitivity analysis in the framework of this evaluation method. First, it has good comparability since only one attribute is changed at a time. The resulting change in the output can be unambiguously linked to the change in the input. Another advantage of this approach is that it is relatively simple to implement. Despite its advantages, this approach cannot explore the simultaneous variation of input attributes since only one is changed at a time. However, it is still suitable for D-MoTSE developed in this study as the cost rates, the particular weights and the occupancy rates of vehicles are independent of each other.

### 4.12 Overview and Discussion

#### 4.12.1 Overview of the Process to Apply the Developed Evaluation Method

Summarising all the information in the previous sections, Figure 13 shows a complete overview of the process to apply the developed evaluation method D-MoTSE. The process is described step by step in the following paragraphs.

**Step 1. Description of the investigation area**

As the preparation for conducting an evaluation, the **framework conditions** of the investigation area where the targeted traffic signal system is located should first be analysed. It serves as the basis for further steps. The relevant aspects that need to be considered are summarised from Section 4.3 to Section 4.9 in this chapter. They can be categorised into six groups: the location, the geometric design, functions, the involved traffic modes and the environmental condition.

First, the **location** of the investigation area is an essential condition to consider, which determines partially other framework conditions. The facilities in or near the investigation area that need a special consideration should be identified. Examples for such facilities are given in Section 4.8. Second, it is to observe the **geometric design** of the investigation area. A layout plan can show the geometric design in detail. Still, it is necessary to observe the investigation area on site. Third, it is to analyse and decide whether one or multiple traffic signal systems serve a **particular function**, such as the coordination, the access metering for a corridor or network, the reduction of delays for certain traffic modes and the reduction of traffic emissions. Despite the listed functions, there are more individual cases to consider, which need to be determined based on the framework conditions analysed before. Fourth, it is to observe which **traffic modes** are present on-site and whether the traffic signal system regulates them. The classification of traffic modes is explained in Section 2.5. Fifth, the **environmental condition** in the investigation area can be considered using monitoring data.

**Step 2. Data collection**

In the second step, data required for conducting an evaluation should be collected. They are further used to measure the evaluation criteria in the subsequent steps. According to the selected measurement methods in Section 4.3, the required data are **traffic volumes**, the **geometric design** of the investigation area, data about the **traffic signal control**, data about the **vehicle fleet composition** and **accident data**.

The first three kinds of data are mainly used for building a **traffic flow simulation model**. While determining traffic volumes, it is necessary to distinguish between different traffic modes and traffic streams. The traffic flow simulation generates the trajectory data of vehicles, which can be used together with data about the vehicle fleet composition for the **emission modelling**. Accident data are further used for the **measurement of accident costs**.
# Specification

Preparation

1. Description of the investigation area → compare Section 4.3 – 4.9
2. Data collection → compare Section 4.3

Specification

3. Examination of the goal system and evaluation criteria → compare Section 4.4
4. Development of alternative traffic signal programs → compare Section 4.5

Measurement

7. Measurement of evaluation criteria → compare Section 4.3

Data processing

8. Normalisation of evaluation criteria using cost rates → compare Section 4.6 & 4.8
9. Particular weighting of evaluation criteria → compare Section 4.7 & 4.8
10. Aggregation → compare Section 4.10

Interpretation

11. Ranking of traffic signal programs → compare Section 4.11
12. Sensitivity analysis → compare Section 4.11

<table>
<thead>
<tr>
<th>Process</th>
<th>Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Description of the investigation area → compare Section 4.3 – 4.9</td>
<td>• Traffic volumes • The geometric design of the intersection • Data about traffic signal control</td>
</tr>
<tr>
<td>2. Data collection → compare Section 4.3</td>
<td></td>
</tr>
<tr>
<td>3. Examination of the goal system and evaluation criteria → compare Section 4.4</td>
<td>• Alternative traffic signal programs</td>
</tr>
<tr>
<td>4. Development of alternative traffic signal programs → compare Section 4.5</td>
<td></td>
</tr>
<tr>
<td>7. Measurement of evaluation criteria → compare Section 4.3</td>
<td>• The average delay for individuals in various traffic modes • The number of traffic accidents, slight injuries, serious injuries and deaths • PM, NOₓ, CO₂ emissions and the fuel consumption • Changes in traffic volumes • Impacts on the reliability of the public transport service</td>
</tr>
<tr>
<td>5. Quantification of traffic shifts → compare Subsection 4.9.1</td>
<td></td>
</tr>
<tr>
<td>6. Quantification of the effects on public transport operation → compare Subsection 4.9.2</td>
<td></td>
</tr>
<tr>
<td>8. Normalisation of evaluation criteria using cost rates → compare Section 4.6 &amp; 4.8</td>
<td>• Delay costs • Accident costs • Energy consumption and environmental costs • The total cost • The total weighted cost</td>
</tr>
<tr>
<td>10. Aggregation → compare Section 4.10</td>
<td></td>
</tr>
<tr>
<td>11. Ranking of traffic signal programs → compare Section 4.11</td>
<td>• Recommendations for the design of traffic signal control</td>
</tr>
</tbody>
</table>

# Should superordinate effects be considered?

**Figure 13:** The application process of the developed evaluation method D-MoTSE (own illustration)
Step 3. Examination of the goal system and evaluation criteria

For D-MoTSE, a goal system and its corresponding evaluation criteria have already been defined. It can serve as a basis while applying the evaluation method. Not only traffic flow quality but also traffic safety and environmental impacts are considered in D-MoTSE. The selected evaluation criteria include:

- the average delay for individuals
- PM, NOx, CO2 emissions and the fuel consumption
- the number of traffic accidents, slight injuries, serious injuries and deaths

However, an examination of the predefined goal system and evaluation criteria is still necessary to check the relevance to the evaluation target and the availability of the required data. A specific goal and its corresponding evaluation criteria can (or have to) be disregarded if it is irrelevant (or unavailable). Besides, the priority between different goals and traffic modes can be defined qualitatively. The priority level is used later as a reference for determining the weight for evaluation criteria in the evaluation process.

Step 4. Development of alternative traffic signal programs

As mentioned in Section 4.5, alternative traffic signal programs for evaluation can be developed by varying the following features related to the traffic signal timing:

- cycle time
- stage design
- green split
- public transport priority
- pedestrian request
- coordination

Several options are designed for each feature under consideration of the local framework conditions that are analysed in the first step. Afterwards, combining the options generates a list of possible alternative signal programs.

The development and investigation of multiple signal programs require time and efforts. Hence, the number of alternative programs should be limited in order to save high temporal and physical costs. It can be achieved in several ways. First, the constrains of intersections can be considered to rule out meaningless alternatives. Second, the focus of the investigation should be laid on the main problems or advantages of the target signal system.

Step 5. Quantification of traffic shifts

Changes in traffic signal control on a large scale may cause traffic shifts that need to be further considered in the evaluation. It can be achieved by applying elastic transport demands and the corresponding traffic volumes for each alternative. However, when the effect on traffic shifts is negligible, this issue can be ignored by keeping the same transport demands and traffic volumes under different alternatives.

Most commonly, transport demand models are used to estimate traffic shifts and the corresponding changes in transport demands. In order to conduct the transport demand modelling, it is first necessary to quantify the estimated impacts of alternative signal programs on the travel time and other influencing factors on transport demands. The output of transport demand modelling is traffic volumes that are expected on road networks. They serve further as the input for measuring delays using the traffic flow simulation. Since transport demands and travel time (delays also) have relationships between each other, both modelling tools should be combined. Multiple iterations may be needed to increase the accuracy of modelling.
Step 6. Quantification of the effects on public transport operation

Quantification of the effects on public transport operation focuses on two aspects: whether the current timetable of public transport can be kept and whether there is an extra demand of public transport vehicles and staffs due to the changes in operation. As explained in Section 4.9.2, it is difficult to directly integrate the resulting changes in capital and operation costs into the evaluation scheme. It is, therefore, recommended to apply a particular weight to the delay costs for public transport when the planned time and crew schedule cannot be kept.

Step 7. Measurement of evaluation criteria

In this step, the evaluation criteria need to be measured using appropriate measurement methods. After reviewing all possible methods (as explained in Section 2.4, Section 4.3 and Appendix A, it is recommended to use:

- the traffic flow simulation for traffic-related parameters
- the emission modelling for air pollution emissions
- the empirical traffic accident data for traffic safety

A traffic flow simulation model can be built based on the data about the geometric design, traffic volumes and traffic control rules. The required output of the model are delays for different road user groups in the investigation area, which are evaluation criteria that are used in the evaluation method. Other output of the traffic flow simulation can be the detailed speed-time profile of vehicles in the investigation area, which serves as the input data for the microscopic emission modelling. There are well-established software packages for the traffic flow simulation in the scientific and commercial context, which can be implemented in this step. Vissim developed by PTV AG is a widely implemented software in Germany. Other well-known examples are Crosim, Transms, Matsim, Integration, Hutsim and Sumo (Dallmeyer, 2014).

The emission modelling can be conducted to measure the traffic-related emissions in the investigation area. Air pollutants PM, NO\textsubscript{x} and greenhouse gas CO\textsubscript{2} are considered in D-MoTSE. Besides, the fuel consumption is considered as well. The microscopic emission modelling is more applicable for evaluating traffic signal control since it is detailed enough to reflect the corresponding changes. The input for the microscopic emission modelling is the detailed speed-time profile of vehicles and the vehicle fleet composition. Important parameters to describe the fleet composition include vehicle types, the share of fuel types, vehicle ages and emission standards. There are different kinds of PM emissions in road transport, including emissions from the combustion process, resuspension and wear (brake and tyre). If the emission model can not estimate certain kinds of PM emissions, other data sources may be used instead. Due to the close relationship between the fuel consumption and CO\textsubscript{2} emissions, an estimation of fuel consumption based on the amount of CO\textsubscript{2} is possible.

In the operation stage, empirical traffic accident data can be used for calculating the accident costs in the current status. In the planning stage or for alternative signal programs in the operation stage, established data under a similar situation can be used for a rough orientation of accident costs.

Step 8. Normalisation of evaluation criteria using cost rates

In this step, the multi-dimensional evaluation criteria are normalised in order to bring them on the same scale for comparison. The cost is selected as the leading indicator that serves as the basis for comparison. Cost rates are needed to convert the evaluation criteria in original scales into the corresponding costs. The cost rates proposed in this study (see Section 4.6) are derived based on the established values from the existing literature for the German context.
For each alternative traffic signal program, three groups of cost components are calculated based on the collected traffic data and the measured evaluation criteria: delay costs, accident costs as well as energy consumption and environmental costs.

**Delay costs** are calculated for different traffic modes, including walking, cycling, public transport, motorised private transport and heavy transport. The following data are required:

- the traffic volumes (in the number of vehicles or pedestrians or cyclists) that are collected from traffic counting
- the average delays that are modelled using the traffic flow simulation
- the average occupancy rates of vehicles as shown in Table 15, 16 and 17
- the cost rates as shown in Table 15, 16 and 17

The calculation steps and equations used are explained in details in Subsection 4.6.2.

**Accident costs** are calculated using empirical accident data and their corresponding cost rates. The calculation steps and equations used are explained in details in Subsection 4.6.3.

**Energy consumption and environmental costs** are calculated based on the output of emission modelling and the estimated fuel consumption. It is noted that the environmental costs for PM emissions consist of those for exhaust emissions as well as for resuspension and various kinds of wear. The calculation steps and equations used are explained in details in Subsection 4.6.4.

The cost rates can vary in various situations. Section 4.8 lists several typical situations and gives guidance on how cost rates change under different situations.

**Step 9. Particular weighting of evaluation criteria**

Each cost component calculated in the previous step is further weighted with a factor, which is defined as the particular weight in this study. Administrative authorities or other institutes who use the evaluation method may prioritise specific traffic modes or goals due to political or planning reasons. Particular weights are, therefore, introduced to reflect these potential priorities in the evaluation. The main benefit of considering the cost components and their weights separately is to make the trade-off process comprehensive and transport.

An equal weighting of all cost components (all equal to one) is recommended generally. A deviation from that should always be carefully justified since it causes bias to evaluation results and the decisions made thereon. Examples for planning or political reasons to introduce particular weighting are explained in details in Section 4.7. The determination of particular weights can refer to the framework conditions of the investigation area and the predefined evaluation goals. They can also change situation-responsively so that traffic signal control can adjust to different situations.

**Step 10. Aggregation**

All cost components and particular weights are aggregated to calculate the total cost and the total weighted cost, which are used further to rank alternative signal programs. The calculation steps and equations used are explained in details in Section 4.10. It must be emphasised that the total weighted cost can not reflect the real cost.

**Step 11. Ranking of alternative traffic signal programs**

The alternative traffic signal programs are ranked according to the calculated total weighted cost in the last step, as explained in Section 4.11. Recommendations for the traffic signal control can be derived accordingly. Under equal weighting of all cost components, the evaluation shows minimal bias. The alternative with the lowest cost is theoretically the system optimum and the cost-effective solution.
However, if a higher particular weight for a specific cost component is introduced, the best alternative can differ from the system optimum. By comparing both situations, it is possible to analyse the extra losses that should be accepted, if priority is given to a specific aspect.

**Step 12. Sensitivity analysis**

In the last step, a sensitivity analysis should be conducted to investigate the robustness of evaluation results. The approach **One-at-a-time** is used due to its good comparability and simplicity. Changes in the rank order of alternative traffic signal programs are observed while adjusting one attribute at a time and keeping the others constant. The attributes to vary in the developed evaluation method are cost rates, occupancy rates and particular weights. The results of the sensitivity analysis can be shown graphically.

### 4.12.2 Discussion about the Developed Evaluation Method

In comparison to the existing evaluation methods for traffic signal control (as explained in Section 3.4), the **main benefits** of the developed methods are listed as follows:

- a comprehensive consideration of not only traffic flow quality but also traffic safety and environmental impacts
- a multi-modal analysis that takes all road user groups into account
- the possibility to evaluate actuated traffic signal control that has a complex structure and many intervention possibilities
- the possibility to include superordinate effects in the evaluation
- the possibility to vary cost rates and particular weights under different situations as that different requirements for traffic signal control can be fulfilled

However, the following critical comments can be given to D-MoTSE. First, it can not give an absolute statement about the performance of a traffic signal system. HCMs judges the performance of a road facility based on the LOS (six levels from A to F). However, there are no reference values for judging the performance of a traffic signal system based on the calculated costs and weighted costs using D-MoTSE. Second, the implementation of D-MoTSE requires a higher working effort than that of HCMs and the performance indices in optimisation models. The main reasons are a more complex structure, more aspects to consider and more complicated measurement methods of evaluation criteria. Third, the accuracy of the evaluation methods depends highly on the accuracy of measurement methods and cost rates. The developed evaluation method derives cost rates based on the established and widely implemented studies in order to increase the accuracy of evaluation results. Besides, errors should be avoided while conducting measurements. Fourth, the introduction of particular weights should always be carefully justified since it causes bias to evaluation results and the decisions based thereon.

### 4.13 Conclusions

The literature review in Chapter 2 and 3 identifies several principles for the evaluation of traffic signal control and the deficiencies of the existing evaluation methods (see Section 2.8 and 3.5). This chapter describes step by step the development of an evaluation method D-MoTSE that addresses these issues. The following conclusions can be made accordingly:

- By considering multiple evaluation criteria and traffic modes in a uniform framework, D-MoTSE can provide a comprehensive judgement on the overall performance of traffic signal programs.

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8 This statement is given while comparing D-MoTSE with HCMs.
Traffic signal control has impacts on not only multiple aspects but also different traffic modes, which need to be considered in its design. Most existing evaluation methods have the deficiency that they make judgements from only one dimension\(^9\). However, D-MoTSE can provide a more comprehensive judgement on the overall performance by integrating multiple evaluation criteria and traffic modes into a uniform framework. The considered aspects include not only traffic flow quality but also traffic safety and environmental impacts. The involved traffic modes are walking, cycling, public transport, motorised private transport and public transport.

- **Monetisation enables a simple aggregation and a good comparison of the multi-dimensional evaluation criteria.**

Using the cost as the leading indicator to normalise multi-dimensional evaluation criteria has the advantage of rich established values for reference, easy understandability, simplicity and broad applicability. It is, therefore, proposed to convert all original evaluation criteria into corresponding costs in order to aggregate and compare them. While developing D-MoTSE, cost rates that are suitable for the German context are derived based on the established values from the existing literature.

- **A separate consideration of cost components and their corresponding particular weights makes the trade-off process transparent and comprehensive.**

Priority may be given to specific traffic modes or aspects due to political or planning reasons. It can be reflected in the evaluation by weighting the evaluation criteria and their corresponding cost components separately. It is possible to vary the particular weights and analyse the subsequent effects on evaluation results. The trade-off process is kept comprehensive and transparent by doing so. It must be emphasised that the introduction of such particular weights should be avoided as much as possible and always carefully justified.

- **Applying dynamic cost rates and particular weights under different situations is meaningful so that the selected traffic signal program can respond to the real-time changes in the traffic, environmental or other situation.**

A situation-responsive traffic signal control is meaningful so that the signal timing can respond to the real-time situation. This concept can be realised in D-MoTSE by adjusting the cost rates and the particular weights dynamically. Relevant features for defining the situations can be the location of a traffic signal system, transport demands and the traffic situation as well as the environmental situation.

- **Although it is possible to consider the potential superordinate effects in D-MoTSE, there are other measures for influencing transport demands on a larger scale that are more suitable than traffic signal control.**

Two essential superordinate effects to consider are traffic shifts and the impacts on public transport operation (e.g. non-compliance with the timetable and the resulting extra capital or staff costs. Suggestions are given on the consideration of these two aspects in D-MoTSE. However, it must be emphasised that some other measures can influence traffic shifts and, at the same time, do not have negative environmental impacts, such as pricing, regulatory policies and information (Boltze and Jiang, 2017). They are more suitable than traffic signal control in affecting people’s mode choices.

- **It is necessary to investigate the robustness of the evaluation results through a sensitivity analysis.**

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\(^9\) As explained in Section 3.4.3, most methods focus mainly on the traffic flow quality.
At the end of the evaluation, a sensitivity analysis is necessary to test the robustness of the evaluation results and the derived recommendations for designing traffic signal control. The technique One-at-a-time is recommended in the framework of D-MoTSE.

- **An improvement and further development of the evaluation method D-MoTSE is meaningful.**
  
  D-MoTSE can be further improved and developed in several directions, including the evaluation of safety issues, more data about the occupancy of public transport, further exploration of the superordinate effects with case studies, more practical case studies on the application of the evaluation method.
5 Case Studies on the Application of the Evaluation Method

5.1 Introduction
The developed evaluation method for traffic signal control D-MoTSE is applied on four test sites to assess its applicability and to analyse how the cost rates and particular weights influence traffic signal timing. The methodology is first introduced in Section 5.2. Then, the description and results of each test site are described in Section 5.3 to Section 5.6. Besides, Section 5.7 shows the analysis of the correlations between evaluation criteria based on the results of all test sites. In the end, the interim conclusions are summarised in Section 5.8.

5.2 Methodology
This section aims to explain the methodology for applying D-MoTSE on case studies. Generally, it follows the process described in Section 4.12 (see Figure 13), which is not repeated at this point. However, some specific details still need to be additionally explained since they are only valid for the four case studies in the framework of the study. The common issues for all four case studies are explained in this section. The individual settings for each case study can be found in the corresponding section.

The methodology is divided into the following subsections.

- description of the investigation area (step 1)
- data collection (step 2)
- examination of the goal system and evaluation criteria (step 3)
- development of alternative traffic signal programs (step 4)
- measurement of evaluation criteria (step 7)
- data processing and ranking of alternative traffic signal programs (step 8, 9, 10 and 11)
- sensitivity analysis (step 12)

All four case studies are single intersections or road sections. The superordinate effects are negligible on such a small scale. Therefore, step 5 and 6 about the quantification of the superordinate effects are not conducted for the four case studies. The data processing (step 8, 9 and 10) serve as the basis for ranking alternative traffic signal programs (step 11). A combined analysis of all four steps is meaningful. Therefore, the corresponding subsection explains not only the rank order but also the performance of alternative traffic signal programs in details.

5.2.1 Description of the Investigation Area

Four traffic signal systems in the City of Darmstadt, Germany are selected as test sites:

- Hindenburgstraße/ Elisabethenstraße (A 99)
- Rheinstraße/ Haltestelle Berliner Allee (A 7)
- Dieburger Straße/ Pützerstraße/ Heinheimer Straße (A 33)
- Hügelstraße/ Karlstraße (A 81)

The names of the test sites correspond to their locations. The authorities officially assign the numbers in brackets behind the names. The locations of the intersections are shown in Figure 14.
The City of Darmstadt is located in the middle of Germany. It is one regional centre of the metropolitan region Rhein-Main-Area where the city Frankfurt am Main is also located. It has a total population of 162,428 inhabitants (status year 2019) on a total area of 12,201 ha (Wissenschaftsstadt Darmstadt, 2020). As shown in Figure 14, the four case studies are located in different regions in the city.

The four test sites are representative of the typical traffic signal systems in a middle-sized city. They are of different complexities and have their own features. Traffic signal systems Hindenburgstraße/Elisabethenstraße (A 99) and Rheinstraße/Haltestelle Berliner Allee (A 7) are located at mid-block pedestrian crossings. At A 99, there is no public transport line that passes by. However, A 7 is located at a public transport station to assist pedestrians in heading to or leaving from the station. It is more complicated with four separate parts to signalise four separate crossings. Traffic signal systems Dieburger Straße/Pützerstraße/Heinheimer Straße (A 33) and Hügelstraße/Karlstraße (A 81) are located at intersections. The intersection at A 33 is a typical four-leg intersection while that at A 81 is a complicated intersection with an irregular form and complex traffic flows. A comparison of the four test sites is shown in Table 25.

5.2.2 Data Collection

The city planning office of Darmstadt provided existing traffic counting data for some test sites. Besides, the detector data from controllers were provided by the civil construction office of Darmstadt. Additionally, manual traffic counts for short periods were conducted to collect the still missing data. It is usually the case for the traffic volumes of pedestrians and cyclists. The timetables of public transport vehicles are downloaded from the internet site of the local public transport organisation, Rhein-Main-Verkehrsverbund. Detailed information is collected from the timetables, such as the number of public transport vehicles that pass an intersection and when they plan to pass. However, there is no information about the real-time deviation to the timetables.

The geometric design of an intersection is documented in details in the layout plan of the traffic signal system. The locations of signal heads and detectors can be found here as well. Other data about traffic signal control are documented in the technical documents, including signal groups, the stage design, the number of stages, the stage sequence, the stage change, the control logic for the traffic-actuated program as well as the back-up fixed time programs. These existing information about the current traffic
**Table 25:** Overview of the test sites (own illustration)

<table>
<thead>
<tr>
<th>Category</th>
<th>Hindenburgstraße/ Elisabethenstraße (A 99)</th>
<th>Rheinstraße/ Haltestelle Berliner Allee (A 7)</th>
<th>Dieburger Straße/ Pützerstraße/ Heinheimer Straße (A 33)</th>
<th>Hügelstraße/ Karlstraße (A 81)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Category</td>
<td>Mid-block pedestrian crossing</td>
<td>Mid-block pedestrian crossing</td>
<td>Intersection</td>
<td>Intersection</td>
</tr>
<tr>
<td>Location</td>
<td>Urban</td>
<td>Urban, near a public transport stop</td>
<td>Urban</td>
<td>Urban, junction of the city ring and a main public transport axis</td>
</tr>
<tr>
<td>Geometric design</td>
<td>Single crossing on a street with two lanes in each direction</td>
<td>Four separate crossings with the median public transport stop</td>
<td>Four-legged intersection</td>
<td>A irregular form</td>
</tr>
<tr>
<td>Particular function</td>
<td>To protect pedestrians and cyclists while crossing the street, the potential to coordinate with the neighbouring intersections</td>
<td>The potential to coordinate with the neighbouring intersections</td>
<td>Public transport priority</td>
<td>Public transport priority</td>
</tr>
<tr>
<td>Traffic modes</td>
<td>No public transport</td>
<td>Public transport not controlled by A 7</td>
<td>Public transport in mixed traffic</td>
<td>Public transport on separated lanes</td>
</tr>
</tbody>
</table>

Signal programs is an important reference for developing other alternatives in the next step. The civil construction office of Darmstadt provided both the layout plans and the technical documents of test sites.

The empirical accident data for accident analysis. The accident data for years 2013-2015 were used in this thesis. The following data are extracted from the primary database:

- the number of deaths
- the number of serious injuries
- the number of slight injuries
- the number of the accidents with deaths
- the number of the accidents with serious injuries
- the number of the accidents with slight injuries
- the number of the accidents with property damages

The detailed data obtained for each test site are further explained in each section.

### 5.2.3 Examination of the Goal System and Evaluation Criteria

This step checks the transferability of the predefined goal system and evaluation criteria (see Section 4.4 on case studies. The framework conditions and collected data serve a basis for this step. The settings for each test site are explained individually in Sections 5.3 to 5.6.
5.2.4 Development of Alternative Traffic Signal Programs

The goal of the case studies is not to optimise traffic signal control, but to test the evaluation method. There is no iteration performed to search for the best traffic signal program. Instead, several meaningful alternatives with different features are designed and investigated further.

How to develop alternative traffic signal programs is generally described in Section 4.5. At all test sites, the traffic signal systems are currently under operation. They are all using traffic-actuated control programs. Besides, there are fixed time control programs documented in the technical documents as a back-up. Both the existing traffic signal programs and those documented in the technical documents can serve as a basis for developing other alternatives for traffic signal control.

As mentioned in Section 4.5, the following features can be considered for developing alternatives:

- the cycle time
- the stage design
- the green split
- the public transport priority
- the pedestrian request
- the coordination

Under consideration of the local framework conditions in the city of Darmstadt, the concrete options of features are described in the following paragraphs.

The options for cycle time refer partially to the standard cycle time for traffic signal control in Darmstadt. It is 90 s in peak hours, 70 s in off-peak hours and 56 s in lean hours. This standard is valid for most of the traffic signal systems in the city. Those at signalised pedestrian crossings can also have a variable cycle time. It is usually the case when there are no relatively fixed periodical changes of phases.

In each case study, the current stage design is usually kept the same for investigation. A new option for the stage design shall only be proposed and investigated if there is a significant improvement in the performance of a traffic signal system.

Similar to stage design, options for the green split are also developed under consideration of the current green split of each traffic signal system. They can vary within a reasonable range.

According to the intensity, the public transport priority can be roughly categorised into three groups: no, conditional and absolute priority. The meaning of no priority is straightforward. Public transport vehicles are treated similar to other vehicles. No additional measures are implemented to shorten their delays. Absolute priority means that public transport vehicles almost have no delays or stops that are caused by traffic signal control. If the priority is weakened, it is defined as a conditional priority in this thesis.

The form of pedestrian request is roughly categorised into three groups: no pedestrian request, the conditional pedestrian request, and the immediate green. No pedestrian request means that pedestrians who cross the street or intersection do not need to push the touch button. That is usually the case for a fixed time signal control or a preset permanent pedestrian request. The conditional pedestrian request means that pedestrian requests for green time need to be registered actively. After that, green time will be first guaranteed if certain conditions are fulfilled. In this case, pedestrians may have to wait a while before crossing. The immediate green means that pedestrians are immediately shown green if the minimum green time of other streams is reached. The delay for pedestrians is kept as low as possible.

There are two possible options for the feature coordination: coordinated or uncoordinated.

The design of traffic signal programs for each test site should consider its location and features. The details for each test site are further explained in each section.
5.2.5 Measurement of Evaluation Criteria

The microscopic traffic flow simulation software **PTV Vissim** and its additional emission modelling module, **EnViVer**, are used for measuring the evaluation criteria delays and amount of emissions in the framework of this study. The accident data collected can be directly used for calculating accident costs. There is no need for an additional measurement process. Therefore, only the traffic flow simulation and the emission modelling are described in details in the following paragraphs.

**Traffic flow simulation**

**PTV Vissim** is a microscopic, behaviour-based multi-purpose traffic simulation software, produced by the German company PTV Planung Transport Verkehr AG, to analyse and optimise traffic flows. It is widely used in projects involving the road traffic simulation across different countries. Some suitable application areas are (Fellendorf and Vortisch, 2010, pp. 63-64):

- analysis of alternative actuated and adaptive signal control strategies in subarea networks
- signal priority schemes for public transport within multi-modal studies
- corridor studies on arterials with signalised and non-signalised intersections

The behaviour of various road user groups can be modelled in the software, including pedestrians, cyclists, cars, heavy duty vehicles, buses and trams (Fellendorf and Vortisch, 2010, pp. 63-64). Besides, various road facilities with different layouts can be modelled. A traffic model in Vissim consists of four building blocks, including the infrastructure modelling, the traffic modelling, the control modelling and the data output (Fellendorf and Vortisch, 2010, pp. 66-67).

First, all the relevant network elements of each test site are replicated to scale according to its layout plan, including roadways, signal control facilities (signal heads, stop lines, detectors) and the stop locations for public transport vehicles. The neighbouring intersections are also replicated in a simplified form, if they are relevant to the traffic flows at the target test site.

Second, the collected traffic volumes for different traffic modes are provided as the input into the models. They are classified into six categories: pedestrians, cyclists, buses, trams, cars and heavy duty vehicles. Light commercial vehicles are assumed to have similar size and behaviour with cars. Therefore, no separate vehicle class for light commercial vehicles is modelled. The following comments should be pointed out for modelling traffic volumes:

- While modelling the traffic volumes of pedestrians, routes with multiple crossings are modelled only partially. It is because a full tracking of pedestrians is difficult based on the manual traffic counts on-site.
- Cyclists can ride on roadways, road facilities and pedestrian crossings. Their routes are relatively free in comparison to other road users. All three possibilities are represented in models to the best of the available knowledge and information. However, there are still uncertainties relating to this aspect.
- The entering time of public transport vehicles in the network and their offsets are based on the timetables of public transport lines. However, the arrival time of a public transport vehicle at a bus stop is fluctuating in reality. In order to model this fluctuation in the model, a fictive stop station is incorporated upstream of the real stop station in the investigation area. The dwell time at each fictive stop station is programmed to follow an assumed normal distribution. With this method, the arrival time of public transport vehicles at stop stations can be replicated in the models to fluctuate around the scheduled time in timetables.

Third, the traffic control rules are modelled in the traffic simulation model. In this study, not only the traffic signal program that is currently under operation is included, but also alternative traffic signal
programs for evaluation are incorporated. The original traffic signal programs in the technical documents are usually developed with other signal timing software. They are translated in another format in VisVap which is compatible with the PTV Vissim software. The control logic is kept the same to the best of knowledge.

Fourth, settings for generating outputs (delays) need to be defined. For motorised vehicles, the measurement area is in most cases the area between 100 m before the stop line and 100 m after the stop line of the opposite direction. This area can be adapted if long queues often occur at an approach. For public transport, the definition of measurement area shall consider locations of stop stations. The delays due to approaching or leaving stop station shall not be counted in delays that are relevant to traffic signal control. For pedestrians, the begin and end of the measurement area are located near roadside.

The developed traffic flow simulation models use the standard parameters of car following models and lane changing behaviours at signalised intersections in Vissim because they are applicable for the German context and suitable for the test sites. The validation of the developed models is conducted through a visual comparison of the traffic flows at traffic signal systems in simulations models and those in reality. The developed models are shown to the staffs from the civil construction office of Darmstadt and approved by them. A quantified validation of the developed studies is desirable and can increase the accuracy of the evaluation results, which rely upon the output of simulation models. However, it cannot be conducted in the framework of this study due to the lack of data. The main goal of this chapter is to investigate the applicability of D-MoTSE using test sites. This primary goal can still be achieved, although the developed simulation models are not validated quantitatively.

The individual settings for each test site are further explained in each section.

Emission modelling

The emission module EnViVer Vissim is used for modelling emissions of air pollution. This module is based on the emission model VERSIT+ which is developed by Netherlands Organisation for Applied Scientific Research (TNO). The VERSIT+ model estimates the emissions based on the speed-time profile of vehicles and vehicle-related variables. It consists of a set of statistical models for detailed vehicle categories that were constructed using multiple linear regression analysis (Smit, Smokers, and Rabé, 2007).

As an additional module of PTV Vissim, the input data of EnViVer are the trajectory data generated by the traffic flow simulation. In these data, the location and the speed of each vehicle are documented on a second basis. Besides the usage of trajectory data, the vehicle fleet composition needs to be defined for modelling emissions. Important parameters of the fleet composition that can be defined by users include vehicle types, the share of fuel types, vehicle ages and emission standards (European standards 0 to 6). The measurement area of the emission modelling is the same as that of delay measurement. Output results of EnViVer are the amount of PM$_{10}$, NO$_x$ and CO$_2$ emissions for different vehicle types include cars, buses as well as medium or large HDV. The NO$_x$ and CO$_2$ emissions are directly taken from EnViVer. However, more calculation steps are still needed to estimate PM$_{10}$ emissions.

As explained in Subsection 4.6.4, exhaust emissions and emissions that result from resuspension and wear need to be treated differently. They are assigned significantly different cost rates. However, the results of EnViVer are the sum of exhaust emissions and emissions that result from brake and tyre wear (Ligterink et al., 2008). It is, therefore, necessary to estimate the exhaust emissions by subtracting the brake and tyre wear emissions from the sum. It can be achieved using the emission factors, as shown in Equation 17.

\[
EF_{PM}^{exh} = EF_{PM}^{EnViVer} - EF_{PM}^{brk+tyr} \\
EM_{PM}^{exh} = EF_{PM}^{exh} \cdot L_{veh} \tag{17}
\]
Where:

- \( EF_{\text{exh}} \) the emission factors for exhaust PM emissions from combustion process
- \( EF_{\text{PM}^{\text{EnV}}\text{Ver}} \) the output emission factors of EnViVer
- \( EF_{\text{PM}^{\text{brk+tyr}}} \) the emission factors for brake and tyre wear
- \( EM_{PM}^{\text{exh}} \) the amount of exhaust emissions
- \( L_{\text{veh}} \) the vehicle distances travelled in the investigation area

The exact emissions factors for brake and tyre wear in EnViVer are unknown. Instead, the reference values from Klein et al. (2016) that was also developed by TNO are used for subtracting, as shown in Table 26. EnViVer and Klein et al. (2016) are both from the same institute. The inaccuracy of the resulting exhaust emission factors is, thus, kept as small as possible. The amount of PM exhaust emissions is calculated by multiplying the corresponding emission factors and the total vehicle distances travelled in the investigation area.

**Table 26: PM\(_{10}\) emission factors for brake and tyre wear (source: own illustration based on Klein et al., 2016, table 3.20A)**

<table>
<thead>
<tr>
<th>Area</th>
<th>EF for brake and tyre wear [mg/km]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>PrT</td>
</tr>
<tr>
<td>Urban</td>
<td>16.85</td>
</tr>
<tr>
<td>Rural</td>
<td>7.32</td>
</tr>
</tbody>
</table>

Other than the PM\(_{10}\) emissions from brake and tyre wear, there are also PM\(_{10}\) emissions from resuspension and wear of road surface (Thorpe and Harrison, 2008). For estimating the total amount of emissions from resuspension and wear, the PM\(_{10}\) emission factors according to Schmidt, Düring, and Lohmeyer (2011, p. 63) are used. The suggested values from this research study are distinguished first between light and heavy transport. Cars and LCV belong to light transport while buses and HDV belong to heavy transport. Second, the values vary under different traffic situations. A traffic situation is defined by the location, the street type, the speed limit and the traffic flow condition. The emission factors and detailed explanations of traffic situations are shown in Appendix C.

EnViVer cannot directly model the fuel consumption. Under consideration of its close relationship to CO\(_2\) emissions, the fuel consumption is estimated based on the amount of CO\(_2\) emissions using a conversion rate of 2398 g CO\(_2\) per litre. This conversion rate is determined based on the emission and fuel consumption data in Table 27 that are based on the established values in the literature.

**Table 27: Average emission data for different fuel types (source: Kraftfahrt-Bundesamt, 2016 and Kraftfahrt-Bundesamt, 2011)**

<table>
<thead>
<tr>
<th>Fuel type</th>
<th>Average CO(_2) emission factor [g/km]</th>
<th>Average fuel consumption on 100 km</th>
<th>Share of vehicles [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diesel</td>
<td>130</td>
<td>4.91</td>
<td>32.4</td>
</tr>
<tr>
<td>Petrol</td>
<td>130</td>
<td>5.61</td>
<td>66.4</td>
</tr>
<tr>
<td>Liquid gas</td>
<td>130</td>
<td>7.21</td>
<td>1.1</td>
</tr>
<tr>
<td>Natural gas</td>
<td>130</td>
<td>7.9 kg</td>
<td>0.1</td>
</tr>
</tbody>
</table>
5.2.6 Data Processing and Ranking of Alternative Traffic Signal Programs

Subsequently, the evaluation criteria are normalised, weighted and aggregated to calculate the total cost and the total weighted cost, which serve to rank the alternative traffic signal programs. The working steps generally follow the steps described in Section 4.12. They are not repeated here.

It is proposed to calculate three cost components in the framework of D-MoTSE. That can be achieved for two test sites - A 33 and A 81. They are both intersections. At both test sites, the form to signalise left-turning vehicles is kept the same while developing alternative traffic signal programs. Therefore, there are no significant changes in accident costs compared to the current situation. It is assumed that the accident costs for the developed alternative traffic signal programs are the same as those for the current traffic signal programs under operation.

However, at traffic systems at midblock pedestrian crossings (A 99 and A 7), accident costs are left out of consideration due to the lack of accident data and the fact that there are no reference values about the potential influence of pedestrian delay on accident costs. Therefore, only two cost components are calculated for these two test sites, namely, delay costs; fuel and environmental costs.

5.2.7 Sensitivity Analysis

As explained in Section 4.12, the approach One-at-a-time is used in conducting the case studies. Only one input attribute is adjusted at a time while keeping the others constant. The attribute values are adjusted within the following ranges. They are defined based on the values of input attributes as described in Section 4.6.

- cost rates and particular weights within the range of ±50% of their baseline values
- the average occupancy rate of cars within in the range of 1.0 to 2.0 p/veh
- the average occupancy rate of buses within in the range of 20 to 70 p/veh in evening peak hours and 5 to 55 p/veh in midday off-peak hours
- the average occupancy rate of trams within in the range of 40 to 140 p/veh in evening peak hours and 10 to 110 p/veh in midday off-peak hours

5.3 Test Site 1: Hindenburgstraße/ Elisabethenstraße (A 99)

5.3.1 Description of the Investigation Area

The traffic signal system A 99 is located at a signalised pedestrian crossing near the intersection of streets Hindenburgstraße and Elisabethenstraße in the City of Darmstadt. The A 99 serves to protect pedestrians and cyclists while crossing the Hindenburgstraße which is a street with two lanes in each direction. The signal heads for motorised traffic are placed on the two approaches of the Hindenburgstraße. The inflow from the Elisabethenstraße is not signalised but has to follow a give way sign and yield the right of way to the vehicles on the Hindenburgstraße. A layout plan of the A 99 is shown in Figure 15.

It is observed from the on-site inspection that some of the cyclists cross the Hindenburgstraße in the intersection area instead of using signalised pedestrian crossings. The violating behaviour of pedestrians and cyclists are not specifically considered in the modelling. Public transport is also left out of consideration because no bus or tram line passes this test field.

The A 99 is located on a corridor Dolivostraße-Hindenburgstraße, where dynamic coordination between traffic signal systems is currently activated in peak hours. The two neighbouring traffic systems of the A 99, namely the Hindenburgstraße/Hügelstraße/havelstraße (A 98) and the Rheinstraße/Hindenburgerstraße (A 3) are part of the coordination, which means that the begin and the end of their green
times react with each other. However, the A 99 was not integrated into the coordination as the data collection of this study was conducted (November 2016). An interruption into the green band is possible, depending on the waiting time of a crossing pedestrian (or cyclist) and the time point when he or she registers the request. As a result, vehicle platoons may have to stop before the pedestrian crossing. The observation on-site showed that long queues occasionally occurred at the A 99 due to the interruption of pedestrians into the green band, especially in the morning peak hours.

The A 99 was operated with a fully traffic-actuated control program at the time when the data collection of this study was conducted (November 2016). The signals for the main street Hindenburgstraße remain green until there is a request from pedestrians or cyclists to cross the street and the criteria for breaking off the green signal are fulfilled (Schulze-Clewing, 2014). In June 2017, the civil engineering office of Darmstadt informed that the signal program of A 99 was changed to a coordinated program based on the recommendation from another research project other than this study.

5.3.2 Data Collection

A traffic count is conducted at the intersection Hindenburgstraße/Elisabethenstraße on 24 November 2016 in the morning and the midday to collect the traffic volumes of vehicles, pedestrians and cyclists. The weather was cloudy and dry with the temperature from 7 to 14°C. Two time periods are selected for further investigation. One is the morning peak hour 7:30 - 8:30 while the other is 12:45 - 13:45, which is a typical off-peak hour. The directional flow volume diagrams of the A 99 in both periods are shown in Figure 16. It is recommended from FGSV (2012b, p. 27) that a traffic count for non-motorised traffic
should be conducted in the summer half year (March to October). However, this requirement is not fulfilled due to the time constraint of the project, in which part of this thesis is conducted. In November, the number of pedestrians and cyclists is assumed to be relatively low because of the low temperature.

![Traffic Volume Diagrams](image)

**Figure 16:** Directional traffic volume diagrams of the A 99 (own illustration)

Another traffic count was conducted on 27 April 2017 by the city planning office of Darmstadt at the same intersection to verify the collected traffic volumes. A total number of 146 pedestrians and cyclists was counted in the same morning peak hour. It is 36% higher than the number counted in November 2016. Still, there are no dramatic differences in results between both traffic counts. The result of the second traffic counting is incomplete, due to the fact that motorised vehicles were not counted and no data for off-peak hours were available. Therefore, the result of the counting in November 2016 is used for further investigation. The counting data of the neighbouring intersection A 98 were also provided by the city planning office and used to verify the data about motorised vehicles at the A 99. The traffic volume data used in the study is proven to be reasonable.

The high traffic volumes counted on the Hindenburgstraße confirm that it is a main axis for motorised private transport. The Elisabethenstraße is a minor street with few vehicles. The number of pedestrians and cyclists crossing the Hindenburgstraße is comparably low as well. In the morning peak hour, the number of vehicles heading towards the city centre (from south to north) is significantly higher than vice versa. In the midday off-peak hour, they are relatively comparable.
The current signal program of the A 99 under operation is obtained from its technical document. In order to build up the coordination along the corridor Dolivostraße-Hindenburgstraße, the signal programs of the neighbouring traffic signal systems were collected as well.

There is no knowledge about how to quantify the influence of the delay for pedestrians on the accident costs at signalised pedestrian crossings. Accident data are also not available at this test site. Hence, traffic safety is not considered at A 99.

### 5.3.3 Examination of the Goal System and Evaluation Criteria

Three constraints are identified while transferring the predefined goal system and evaluation criteria to the A 99. First, the crossing pedestrians and cyclists are not differentiated in the traffic counting. Therefore, delays for pedestrians and cyclists are considered together. Second, no buses and trams pass through this test site. Thus, delays for public transport are left out of consideration here. Third, the traffic safety issue is left out of consideration at this test site due to the lack of accident data and the difficulty to quantify the impacts of the delay for pedestrians on the accident costs at signalised pedestrian crossings.

Thus, only two goals are considered in the evaluation of A 99, namely the satisfaction of mobility needs and the reduction of environmental pollution. A consideration of traffic safety is desirable, but can not be achieved in the framework of this study. An exploration of this issue is a future research topic. Other than the evaluation criteria mentioned above, the rest is included in the evaluation scheme.

The signalised pedestrian crossing serves to support and protect pedestrians and cyclists while crossing the street. A 99 lies on a street where there is a coordination between several neighbouring traffic signal systems. these two aspects require a special consideration in the evaluation.

### 5.3.4 Development of Alternative Traffic Signal Programs

Three features are mainly considered for designing alternative traffic signal programs for the A 99, as shown in Table 28. Two to four options are assigned to each feature. A meaningful solution space can be covered by combining the options of different features.

An important feature to consider is the cycle time. Currently (Status: November 2016), the traffic signal system operates with a variable cycle time both in morning peak hours and midday off-peak hours. The signals for the main streams on the Hindenburgstraße remain green until requests from crossing pedestrians or cyclists are registered. There is no periodical change of the signal program. It is possible to change the traffic signal program in periodical signal programs with fixed cycle time. The standard cycle time in the City of Darmstadt are 90 s for morning peak hours and 70 s for midday off-peak hours. Other than that, a cycle time of 60 s can be tested, since delays for pedestrians would decrease as cycle time shortens.

At such a signalised pedestrian crossing, there are different ways of reacting to pedestrians requests. For the option no pedestrian request, the traffic signal system operates with a fixed time signal program so that there is a fixed green time for crossing streams in each cycle. The current signal program for the A 99 falls under the second option - the conditional pedestrian request. For this option, crossing streams are first released if their requests are registered, and at the same time, certain criteria for stopping main streams are fulfilled. The last option is most friendly for the crossing streams. They would have a green signal immediately if the minimum green time of main streams is guaranteed.

Another feature to vary is whether the traffic signal system is integrated into the coordination along Hindenburgstraße or not. It is not coordinated with neighbouring traffic signal systems currently (status: November 2016). Alternatively, a coordinated signal program can be set up in a way that the main period of the green band for coordination cannot be interrupted by crossing pedestrians or cyclists.
Table 28: Features considered for designing alternative traffic signal programs for the A 99 (own illustration)

<table>
<thead>
<tr>
<th>Feature</th>
<th>Options</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cycle time</td>
<td>60 s</td>
</tr>
<tr>
<td></td>
<td>70 s</td>
</tr>
<tr>
<td></td>
<td>90 s</td>
</tr>
<tr>
<td></td>
<td>Variable</td>
</tr>
<tr>
<td>Pedestrian request</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>Conditional</td>
</tr>
<tr>
<td></td>
<td>Immediate green</td>
</tr>
<tr>
<td>Coordination</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>Yes</td>
</tr>
</tbody>
</table>

All the alternative traffic signal programs are shown in Table 29. The number of signal programs for the midday off-peak hour is less than that for the morning peak hour, as some alternatives are found to be ineffective according to the evaluation results of the morning peak hour. As an example, a fixed time program without coordination (e.g. A99_M111 and A99_M211) is neither especially beneficial for crossing pedestrians and cyclists nor for the vehicles on the main streams.

The different traffic programs are further evaluated using D-MoTSE. The current signal program (status: November 2016) is highlighted in red colour while the cost-effective signal program according to the evaluation results in blue colour. The current signal program remains the same both in the morning peak hour and midday off-peak hour.

Table 29: List of the alternative traffic signal programs for the A 99 (own illustration)

<table>
<thead>
<tr>
<th>Alternative ID</th>
<th>Features</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cycle time</td>
</tr>
<tr>
<td>Morning peak hour</td>
<td></td>
</tr>
<tr>
<td>A99_M111</td>
<td>60 s</td>
</tr>
<tr>
<td>A99_M121</td>
<td>60 s</td>
</tr>
<tr>
<td>A99_M211</td>
<td>90 s</td>
</tr>
<tr>
<td>A99_M212</td>
<td>90 s</td>
</tr>
<tr>
<td>A99_M221</td>
<td>90 s</td>
</tr>
<tr>
<td>A99_M222</td>
<td>90 s</td>
</tr>
<tr>
<td>A99_M321</td>
<td>Variable</td>
</tr>
<tr>
<td>A99_M331</td>
<td>Variable</td>
</tr>
<tr>
<td>Midday off-peak hour</td>
<td></td>
</tr>
<tr>
<td>A99_O321</td>
<td>Variable</td>
</tr>
<tr>
<td>A99_O331</td>
<td>Variable</td>
</tr>
<tr>
<td>A99_O412</td>
<td>70 s</td>
</tr>
<tr>
<td>A99_O422</td>
<td>70 s</td>
</tr>
</tbody>
</table>

Current traffic signal program
Cost-effective signal program

5.3.5 Measurement of Evaluation Criteria

A traffic flow simulation model is developed based on the collected data that are described in Subsection 5.3.2. The following points should be noted:

- The traffic conditions in the two investigated hours 07:30 - 08:30 and 12:45 - 13:45 are simulated.
- Due to the limitations in traffic counting, the crossing pedestrians and cyclists are not differentiated and simply modelled as all pedestrians.
• The traffic responsiveness of neighbouring signal systems is not simulated. As a simplification, they are operated under fixed time signal programs according to their technical documents. The traffic flows at neighbouring signal systems are simulated partially.

All the listed alternative signal programs in Table 29 are modelled using the developed simulation model. The evaluation criteria are extracted from the traffic simulation model and the emission model.

5.3.6 Data Processing and Ranking of Alternative Traffic Signal Programs

The evaluation method is applied to calculate the costs for each alternative signal program so that suggestions can be given to traffic signal control at the A 99. As explained in Subsection 5.3.3, the accident costs are not taken into consideration at this test site.

First, an overview of traffic volumes helps to explain the evaluation results better. At the A 99, the total number of road users that use this traffic signal system is 1852 p/h in the morning peak hour and 1689 p/h in the midday off-peak hour. The total amount of road users are only slightly higher in the morning peak hour than the midday off-peak hour, although the number of vehicles is around 30% higher. It should be noted that the estimated traffic volumes in the number of persons are calculated using the predefined occupancy rates in both periods. This value is higher in the midday off-peak hour according to own calculations based on literature.

The shares of different road user groups are as follows:

• 6% pedestrians and cyclists + 94% persons in motorised private transport and heavy transport in the morning peak hour
• 8% pedestrians and cyclists + 92% persons in motorised private transport and heavy transport in the midday off-peak hour

There is no person in public transport since no line passes this test site. The distributions in both periods are similar. Persons in motorised private transport and heavy transport are dominant here. It is because the corridor Doliostraβe-Hindenburgstraβe is a main axis for motorised transport. The neighbouring intersections are around 150 m and 260 m away, where pedestrians can also cross the main street.

Results for the morning peak hour

The evaluation method is then applied on the alternative signal programs in the morning peak hour. For the current signal program under operation (A99_M321), the sum of delay, fuel and environmental costs are 62 €/h based on the cost rates that are defined in Section 4.6. This signal program has a variable cycle time and maintains no coordination of the green time with the neighbouring traffic signal systems. The distribution of different cost components for this signal program is shown on the left side in Figure 17.

Based on the evaluation results, the alternative signal program A99_M212 is cost-effective among all the investigated signal programs if the particular weights for all cost components are kept the same (equal to one). The total cost can be reduced to 36 €/h if coordination with the neighbouring traffic signal systems is enabled. The cycle time is 90 s, the same with the standard cycle time of Darmstadt in peak hours. It is the fixed-time control so that there is a fixed green time for crossing pedestrians and cyclists in every cycle. They do not need to register their requests actively. Figure 17 shows the distribution of different cost components. The sizes of the pie charts in Figure 17 are true to scale.

The amount of fuel and environmental costs are higher in the current signal program than the cost-effective signal program due to the worse traffic flow quality under the current condition (November 10). These values are based on the traffic volumes returned by the traffic flow simulation models as output.

11 The scale is on the right down corner.
2016), as crossing pedestrians and cyclists can interrupt the platoons along the main street in this case. For both signal programs, the fuel and environmental costs take a large part of the total cost from 65 to 78%. Furthermore, they consist of about 70% fuel costs and about 30% environmental costs.

The rest are delay costs, which take up 22 to 35% of the total cost. Both the total amount and its distribution among the traffic modes vary significantly between different signal programs. In the current signal program A99_M321, the delay costs for motorised private transport are dominant due to the relatively high average delays because of the interruption in coordination. However, crossing pedestrians and cyclists have lower delays in this case. Therefore, their delay costs take just a small part. Different results are observed for the cost-effective signal program A99_M212, the delay costs for motorised private transport can be significantly reduced by 16 €/h while the delay costs for pedestrians and cyclists are more than double the amount of those in A99_M321.

As mentioned above, a traffic signal program with coordination A99_M212 would be preferred in case of an equal weighting of all cost components. The current signal program would first be selected as a preferred solution, if a high particular weight (here: at least factor 11) is assigned to delay costs for pedestrians and cyclists. Therefore, an exceptionally high particular weight is necessary in order to reduce the delays for pedestrians and cyclists significantly.

Another alternative signal program that is worth mentioning is a traffic-actuated signal program (A99_M222) which is coordinated with the neighbouring traffic signal programs. According to the calculation, the total cost is only about 2.4 €/h higher than those of the fixed time signal program (A99_M212). The difference is mainly in the delay costs for motorised private transport. In the modelling, the coordination along the corridor works a bit worse in the A99_M222 than A99_M212. However, that is mainly due to the lack of traffic responsiveness at the neighbouring traffic signal systems in the modelling, as only fixed time signal programs are simulated there. In reality, they are operated with traffic-actuated signal programs. It could, therefore, be beneficial to run such a signal program at the test site as well, so that it can react dynamically to the variance in the outflows from the neighbouring traffic systems.
Results for the midday off-peak hour

The evaluation method is also applied to compare the traffic signal programs in the midday off-peak hour. The results are generally similar like those in the morning peak hour.

For the current signal program A99_O321 (November 2016), the total cost is 57 €/h. Among all the investigated signal programs, A99_O412 is the most cost-effective in the case of equal weighting for all cost components. Here, the total cost can be reduced to 37 €/h. The settings of this cost-effective signal program in the midday off-peak hour are similar like those in the morning peak hour, except the change in the cycle time. The cycle time is 70 s, same as the standard cycle time in the off-peak hour.

Similar distributions of cost components with morning peak hour can be observed in the midday off-peak hour, as shown in Figure 18. The fuel and environmental costs take a large part of the total cost. The distributions of the delay costs across different traffic modes are similar to the results in the morning peak hour as well.

![Figure 18: Distribution of the costs for the alternative signal programs A99_O321 and A99_O412 (own illustration)](image)

Similar to the morning peak hour, a high particular weight for pedestrians and cyclists is necessary in order to favour the current signal program A99_O321 against the A99_O412 under consideration of the weighted sum of costs. In this case, a factor 10 is needed at least.

In conclusion, similar recommendations can be made to the design of traffic signal control both in the morning peak hour and the midday off-peak hour.

### 5.3.7 Sensitivity Analysis

Sensitivity analyses are conducted for each parameter. Figure 19 shows the results of sensitivity analyses for four attributes in the morning peak hour as examples. They include the following attributes:

- the delay cost rates and the particular weight of walking and cycling
- the delay cost rates and the particular weight of motorised private transport
- the environmental cost rate and the particular weight of CO₂ emissions
- the average occupancy rate of vehicles
A complete set for all attributes and both periods can be found in Appendix D.

Figure 19: Sensitivity of the total cost to changes in the exemplary attributes for the A 99 (own illustration)

The results show that the ranking of alternative signal programs remains stable against changes in the cost rates and their corresponding weights within a range of ±50%. When the average occupancy rate of cars is adjusted within a range of 1.0 to 2.0 p/veh, the rank order stays also the same. Therefore, the ranking of signal programs and the preferred alternative according to it are generally robust, even though uncertainties may exist in the attribute values.

5.4 Test Site 2: Rheinstrasse/ Haltestelle Berliner Allee (A 7)

5.4.1 Description of the Investigation Area

The second test site is named Rheinstraße/ Haltestelle Berliner Allee and assigned the number A 7. It is located on a main street Rheinstrasse near a public transport stop named Berliner Allee. It serves to protect pedestrians while reaching and leaving the public transport stop. As shown in Figure 20, it consists of four separate crossings, two on each side. The two parallel signal heads on each side are controlled progressively. Once the signal head in the front first changes its signal, the one at behind follows it after an offset.

This traffic signal system is characterised by a high traffic volume on the Rheinstrasse and a large number of crossing pedestrians at the same time. The Rheinstrasse is a main axis for not only motorised private transport but also public transport. It links the west part of Darmstadt and the city centre. All the vehicles that enter Darmstadt from the west direction usually drive along this street. Separate public transport lanes exist with one lane in each direction and the stops are located in the middle of the street. In total, five tram lines and two bus lines use the median public transport stop. A large number of passengers need to cross the Rheinstraße in order to reach and leave the stop.
There is a coordination between traffic signal systems on the Rheinstraße. The A 7 is also integrated into the coordination. The system cycle time is 90 s in peak hours and 70 s in off-peak hours. It is observed from the on-site inspection that the average waiting time for pedestrians at the traffic signal system is relatively long. Due to the long waiting time and insufficient green time, around 20 - 30 % of pedestrians cross against red. This behaviour is not specifically modelled in the simulation.

5.4.2 Data Collection

The detector data recorded by induction loops are used to measure the traffic volumes for motorised vehicles at this test site. Among the available data for two weeks in November 2016, two time periods are selected, each as a representative for the peak hour and off-peak hour:

- 8:00 - 9:00 on 8 November 2016 for the peak hour
- 13:00 - 14:00 on 8 November 2016 for the off-peak hour

Further evaluation is conducted based on vehicle data in these two selected periods. The detector data about the number of requests registered by the touch sensors for pedestrians were also provided by the civil construction office of Darmstadt. However, according to the observation on-site, the percentage of registered requests to the total number of pedestrians is relatively low at such a heavily loaded signalised pedestrian crossing. There are usually several pedestrians waiting to cross the street at the same time. The pedestrians who arrive early in one cycle would possibly register their requests for crossing while those who come later would not have to, as the touch sensor already shows that the green signal is
coming soon. Therefore, the pedestrian volume cannot be correctly estimated using detector data. A separate traffic count for pedestrians was conducted on 29 November 2016. The weather was sunny and dry with the temperature from $-6$ to $3\, ^\circ C$. The traffic count lasted for two hours in the morning and two hours in the midday. The data of two time periods are used for further investigation:

- 08:00 - 09:00 on 29 November 2016 for the peak hour
- 13:00 - 14:00 on 29 November 2016 for the off-peak hour

Although the data for motorised vehicles and pedestrians are based on two different days, the weekday is both Thursday. These data are used in combination for the traffic flow simulation. The combined directional flow volume diagrams for A 7 are shown in Figure 21.

![Directional traffic volume diagrams](image)

**Figure 21:** Directional traffic volume diagrams of the A 7 (own illustration)

The traffic count at the A 7 was conducted in November, similar to the one at the A 99. However, most of the pedestrians here are passengers of public transport that go to or leave the public transport stop. It is unknown whether the number of pedestrians between March and October could be lower or higher than the counting data in November. Still, more than 1000 pedestrians were counted both in the morning peak hour and off-peak hour. These are much higher than the ones counted at the A 99. The traffic volume of motorised vehicles is higher at this test site as well.

For this test site, the timetable of public transport lines was useful to simulate the patterns how pedestrians arrive at the public transport stop and walk further to cross the street. Therefore, this information was downloaded from the homepage of the local public transport organisation Rhein_Main_Verkehrsverbund (www.rmv.de). There were no concrete data about the deviation of the real arrival time of the public transport lines to the planned timetable.

Traffic signal programs of the A 7 and the two neighbouring traffic signal systems were obtained from the technical documents provided by the civil engineering office and used further for the traffic flow simulation. Similar to the A 99, there were no traffic accidents available.

### 5.4.3 Examination of the Goal System and Evaluation Criteria

There are two constraints while transferring the predefined goal system and evaluation criteria. First, although public transport vehicles pass this test site, they are not regulated by the traffic signal system. Delays for public transport are, therefore, not considered in the evaluation. Second, traffic safety issue is left out of consideration at this test site. Similar to the test site A 99, the two reasons are the lack of accident data and the difficulty to quantify the impacts of the delay for pedestrians on the accident costs at signalised pedestrian crossings. The rest evaluation criteria are considered in the evaluation.
The goal system of A 7 is similar to that of A 99. Besides, delays for the crossing pedestrians and the coordination of vehicles on the road require a special consideration in the evaluation.

### 5.4.4 Development of Alternative Traffic Signal Programs

Similar to the other signalised pedestrian crossing A 99, three features are considered at the A 7 for designing alternative traffic signal programs, as shown in Table 30.

The current cycle time of the A 7 complies with the standard cycle time in Darmstadt. Based on the knowledge gained at the A 99, a shorter cycle time of 60 s is not tested. A shorter cycle time does help to reduce pedestrian delays. However, it is not as effective as another option of variable cycle time with conditional pedestrian request. At the same time, the delays for motorised private transport are relatively high in both options due to the lack of coordination with neighbouring traffic signal systems. Under consideration of these two aspects, the shorter cycle time does not have strengths in comparison to other options.

The three forms of pedestrian request (see Subsection 5.2.4) are tested. It is special at the A 7 that within a current cycle time of 90 s there are two possible green periods for crossing pedestrians. It means that pedestrians can be released maximum twice outside the core period of the green band for vehicles (Mönnich, 2002). This special form is kept for all alternative signal programs with the fixed cycle time.

The A 7 is currently integrated into the green wave on the Rheinstraße (Mönnich, 2002). Besides, it is tested what would happen if the traffic signal system operates independently from the coordination.

<table>
<thead>
<tr>
<th>Feature</th>
<th>Options</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cycle time</td>
<td>70 s</td>
</tr>
<tr>
<td></td>
<td>90 s</td>
</tr>
<tr>
<td></td>
<td>Variable</td>
</tr>
<tr>
<td>Pedestrian request</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>Conditional</td>
</tr>
<tr>
<td></td>
<td>Immediate green</td>
</tr>
<tr>
<td>Coordination</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>Yes</td>
</tr>
</tbody>
</table>

In total, four alternative traffic signal programs are each developed for the peak hour and off-peak hour, as shown in Table 31. The current traffic signal programs in the peak and the off-peak hour (A7_M122 and A7_O322) share the same control logic. They are only different in the cycle time and the time conditions. The fixed time signal programs (A7_M112 and A7_O312) are also provided in the technical documents of the A 7. The other traffic signal programs with the variable cycle time are developed based on the signal programs of the A 99. Adjustments according to the geometric design of the A 7 have been undertaken.

### 5.4.5 Measurement of Evaluation Criteria

The following comments are given with regards to the traffic flow models for the A 7.

- The traffic conditions in the two investigated hours 08:00 - 09:00 and 13:00 - 14:00 are simulated.
- The violation of traffic signals is not simulated.
- Fixed signal programs are simulated in a simplified form at neighbouring signal systems. The time conditions are based on the backup fixed time signal programs that are documented in the corresponding technical documents. In this way, the green wave along the Rheinstraße is simulated in the models.

---

12 Pedestrians cross the road against the red signal.
Table 31: List of the alternative traffic signal programs for the A 7 (own illustration)

<table>
<thead>
<tr>
<th>Alternative ID</th>
<th>Features</th>
<th>Cycle time</th>
<th>Pedestrian request</th>
<th>Coordination</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Morning peak hour</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A7_M112</td>
<td></td>
<td>90 s</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>A7_M122</td>
<td></td>
<td>90 s</td>
<td>Conditional</td>
<td>Yes</td>
</tr>
<tr>
<td>A7_M221</td>
<td></td>
<td>Variable</td>
<td>Conditional</td>
<td>No</td>
</tr>
<tr>
<td>A7_M231</td>
<td></td>
<td>Variable</td>
<td>Immediate green</td>
<td>No</td>
</tr>
<tr>
<td><strong>Midday off-peak hour</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A7_O221</td>
<td></td>
<td>Variable</td>
<td>Conditional</td>
<td>No</td>
</tr>
<tr>
<td>A7_O231</td>
<td></td>
<td>Variable</td>
<td>Immediate green</td>
<td>No</td>
</tr>
<tr>
<td>A7_O312</td>
<td></td>
<td>70 s</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>A7_O322</td>
<td></td>
<td>70 s</td>
<td>Conditional</td>
<td>Yes</td>
</tr>
</tbody>
</table>

Current traffic signal program
Cost-effective signal program

- Since the **pedestrians** who are present at this test site are mostly passengers of public transport, the appearance in the models follows a certain pattern. The pedestrians who leave the public transport stop would only appear after the arrival of a public transport vehicle at this stop. This phenomenon is simulated by installing fictive signals at the pedestrian waiting zones in the area of public transport stop. These signals react to the arrival of public transport vehicles. Once a vehicle arrives, signals become green, and a group of pedestrians would leave the public transport stop and cross the street. In the other direction, the pedestrians who head toward the public transport stop arrive at the roadside stochastically.

- The **cyclists** are not simulated and not considered in the evaluation, as they ride on separate cycle lanes either at the roadside or on pedestrian pathways. The traffic signal system does not regulate them.

- The **passengers** who remain sitting or standing in public transport vehicles and pass this signal system without leaving them are not simulated in the models. As they do not use this signal system, they are not considered in the evaluation.

Based on the output of traffic flow models, emission models are applied to model emissions of air pollutants at the test site. Similar to the case of A 99, accidents costs are not considered in the evaluation.

5.4.6 Data Processing and Ranking of Alternative Traffic Signal Programs

The **traffic volumes** at a traffic signal system depend strongly on its location. As mentioned in Subsection 5.4.1, the A 7 is located not only along a heavily loaded main street but also near a frequently used public transport stop. Therefore, the total number of road users\(^{13}\) that pass this traffic signal system are 4360 p/h in the morning peak hour and 4666 p/h in the midday off-peak hour\(^ {14}\). The **composition of road users** are as follows:

- 29% pedestrians + 71% persons in motorised private transport and heavy transport in the morning peak hour
- 31% pedestrians + 69% persons in motorised private transport and heavy transport in the midday off-peak hour

\(^{13}\) Cyclists and passengers that sit in the public transport vehicles are excluded as explained in Subsection 5.4.5.

\(^{14}\) The values are based on the traffic volumes returned by traffic flow simulation as output.
The total traffic volumes are quite high at the A 7, more than double the amount in the other signalised pedestrian crossings A 99. There are both much more pedestrians and persons in motorised vehicles.

Unlike at other test sites, the traffic volumes expressed in the number of persons are even higher in the midday off-peak hour than in the morning peak hour. That is mainly due to the higher number of pedestrians in the midday off-peak hour. In comparison to that in the morning peak hour, the number increases by about 16%. This result is not in contrast with the traditional understanding of morning peak hours and midday off-peak hours since traffic volumes are traditionally expressed in the number of vehicles per hour. At this test site, the number of vehicles is indeed higher in the morning peak hour than in the midday off-peak hour. It complies with the typical daily variance of traffic volumes. However, if other road users are also taken into consideration, that may lead to a different understanding of peak and off-peak hours.

Another speciality of this test site is the large share of pedestrians among all road users. It is four to five times that at the A 99.

**Results for the morning peak hour**

Figure 22 shows a comparison of the cost distributions of two signal programs in the morning peak hour at the A 7 as an example: the current program A7_M122 and the cost-effective program under the equal weighting A7_M112.

There are both differences and similarities between the results at the A 7 and the other signalised pedestrian crossing A 99. Because of the high traffic volumes, the total cost calculated at the A 7 is much higher than those at the A 99. The total cost of A7_M122 and A7_M112 is respectively 84 €/h and 83 €/h. The differences between them are negligible. Since the traffic responsiveness of neighbouring traffic systems is simulated in the model, a traffic-actuated signal program could be more beneficial in reality. Unlike the A 99, the current traffic signal program under operation (A7_M122) is already coordinated with neighbouring traffic signals. So is the cost-effective program A7_M112 as well.

Despite the difference in the total cost, some similar results can be withdrawn with regards to traffic signal control with the A 99. First, the distribution of cost components is similar. More than one-third of the total cost arises from fuel and environmental costs, as shown in Figure 22. Among them, fuel costs take up about 70% while the rest are costs of air pollutant and CO₂ emissions. However, the component of delay costs at the A 7 differs from that at the A 99. A large share comes from the delay costs for pedestrians. It is mainly due to the high number of pedestrians and the relatively long delays for pedestrians because of the coordination.

Second, the cost-effective signal program under the equal weighting also has two features. It is coordinated with the neighbouring traffic signal systems. It is a fixed time program, under which pedestrians do not have to register their demands. These settings are similar to the cost-effective signal program at the A 99.

Third, the distribution of costs among traffic modes varies strongly depending on the selected traffic signal program. The alternative signal program A7_M221 is a good example to show that. The settings are similar with that of the A99_M321, under which pedestrians may possibly interrupt the green wave if the termination criteria are fulfilled. The frequency of interventions in the coordination at this test site is especially high due to the high number of crossing pedestrians. The total cost of the A7_M221 increases to 126 €/h in comparison to the other two coordinated signal programs. The distribution of cost components are shown in Figure 22. The delay costs for motorised private transport increase significantly to 28 €/h and dominate the delay costs. At the same time, the delay costs for pedestrians decrease only slightly. Higher delays for motorised vehicles result in a further increase in the fuel consumption and emissions as well as their relevant costs. This kind of signal program would only be preferred, if a

---

15 The termination criteria are based on the headway of vehicles and the maximum delays for pedestrians.
high particular weight is assigned to the delay costs for pedestrians (at least factor 14). A similar result is also observed in the A 99 as well.

**Results for the midday off-peak hour**

After applying the evaluation method on the midday off-peak hour, similar results to traffic signal control are observed. Figure 23 shows the distribution of cost components for two signal programs A7_O322 and A7_O312 that are explained in details.

Despite a higher number of road users than in the morning peak hour, the calculated costs of the investigated midday off-peak hour are generally slightly lower. It is partially due to the shorter cycle time and the resulting reduction in pedestrian delays. The average delay for motorised private transport and heavy transport decreases slightly as well.

The distribution of cost components is similar to that in the morning peak hour. The fuel and environmental costs take up more than two-thirds of the total cost, as shown in Figure 23.

---

16 The cycle time is 70 s in the midday off-peak hour.
In general, similar recommendations can be given to traffic signal control in the midday off-peak hour and the morning peak hour:

- A coordinated signal program is cost-effective.
- Due to the high number of pedestrians and the two green windows available for pedestrians, a signal program that interrupts in the coordination cannot efficiently reduce the delay for pedestrians.

5.4.7 Sensitivity Analysis

Sensitivity analyses are conducted for all input attribute attributes that are relevant for the A 7. Part of the results in the morning peak hour is shown in Figure 24. The complete set of figures can be found in Appendix D.

The results show that the differences between the signal programs A7_M122 and A7_M112 are negligible. Under consideration of the uncertainties in traffic simulation models\(^\text{17}\), they should be both rated as the preferred signal programs. Ranking between them does not make much sense. Other than that, the ranking between all signal programs remains stable with changes in the cost rates, the weighting factors and the occupancy rates. As mentioned in Subsection 5.4.6, the first turning point for the A7_M221 as the preferred alternative would be a factor 14. It is far beyond the range shown in the diagrams. In the midday off-peak hour, the ranking of signal programs is also not sensitive to changes in the cost rates and the occupancy rate of cars.

\(^{17}\) For example, the traffic responsiveness is not simulated at neighbouring traffic systems.
5.5 Test Site 3: Dieburger Straße/ Pützerstraße/ Heinheimer Straße (A 33)

5.5.1 Description of the Investigation Area

The third test site A 33 is located at a typical four-legged intersection in the city centre. Three roads are meeting each other, namely Dieburger Straße, Pützerstraße and Heinheimer Straße. As shown in Figure 25, there are two approaching lanes in each direction. A separate cycle lane is located beside the right vehicle lane on all approaches. There are in total four pedestrian crossings, one for each approach. Three bus lines pass this intersection in the mixed flow with motorised vehicles. All three bus lines coming from the city centre enter the intersection from the same direction (west of Dieburger Straße), but head for three different directions. The share of heavy transport is between 2 - 4% depending on the approach.

The A 33 operates currently under a traffic-actuated signal program without coordination with neighbouring traffic signal systems. The cycle time is 90 s in peak hours and 70 s in off-peak hours. A conditional bus priority is functioning.

5.5.2 Data Collection

A traffic count was conducted at the A 33 on 16 March 2016 using a video recorder. The weather was dry with temperatures ranging from 3 to 10°C. A peak hour from 16:30 - 17:30 and an off-peak hour from 12:30 - 13:30 are selected for further investigation. The traffic volumes in these periods are shown in Figure 26. The cyclists ride partially on separate cycle lanes and partially on pedestrian crossings. Their volumes are shown together with those for motorised vehicles and pedestrians.
Since this traffic signal system operates independently with the neighbouring traffic signal systems, only signal programs of this single traffic signal system were obtained from its technical documents while those of the neighbouring traffic signal systems were not collected.

The timetable of bus lines that pass this intersection was obtained from the website of the local public transport organisation. Although the bus line KU does not run in March, it is still considered in the modelling and evaluation so that the normal and more critical case at this test site can be studied.

Traffic accident data at this intersection were collected and used further in the evaluation. The data refer to three years from 2013 to 2015.

5.5.3 Examination of the Goal System and Evaluation Criteria

The predefined goal system and evaluation criteria can be fully applied on the test site A 33. All three main goals are considered: satisfaction of mobility needs, increase of traffic safety and reduction of environmental pollution. The corresponding evaluation criteria are also included. Since three bus lines pass through this test site, public transport priority can be applied to reduce the delays for buses. A fair balance between the benefits for public transport and the resulting burdens for other road user groups is necessary. This issue requires a special consideration in the evaluation.
5.5.4 Development of Alternative Traffic Signal Programs

Under consideration of the traffic condition at the A 33, three features are varied to develop alternative signal programs, as shown in Table 32. These are namely the **cycle time**, the **stage design** and the **form of public transport priority**.

**Table 32**: Features considered for designing alternative traffic signal programs for the A 33 (own illustration)

<table>
<thead>
<tr>
<th>Feature</th>
<th>Options</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cycle time</td>
<td>70 s</td>
</tr>
<tr>
<td>Stage design</td>
<td>Option 1</td>
</tr>
<tr>
<td>Public transport priority</td>
<td>No</td>
</tr>
</tbody>
</table>

90 s and 70 s are tested. They refer to the standard **cycle time** for evening peak hours and midday off-peak hours in the City of Darmstadt. The goal is to find out whether the selection of cycle time is appropriate for the traffic volumes at this intersection.

It is observed at the test site that another **stage design** may increase the total capacity of this intersection without significant deterioration in traffic safety. Therefore, two options of stage design are investigated. Figure 27 shows the framework stage design of both options. The intermediate stages and stages on demand are not shown in the framework to make the comparison clearer. Option 1 corresponds to the current signal program under operation, while option 2 is an alternative stage design. In option 1, the traffic streams from west and east directions have their own stages. There is an additional stage between them, in which the through and right-turning streams from both directions share the same stage. In option 2, the straightforward and right-turning traffic streams from the west and east directions are
released in a stage, while the left-turning streams in another stage. The number of total stages is lower in option 2 than in option 1. That results in a lower sum of intergreen times and accordingly, an increase in capacity. The traffic signal system used to be operated using option 2 before the introduction of a new bus line (KU) in the year 2014. Since then, the stage design at the A 33 has been changed to option 1.

There are different forms of public transport signal priority. According to FGSV (1999, p. 20), an absolute public transport priority means that there should be no delays and stops related to traffic signal control for one trip (zero delay). If zero-delay cannot be realised due to traffic conditions or other reasons, a conditional public transport priority can bring benefits to public transport (FGSV, 1999, p. 20). Only a conditional public transport priority can be realised at this intersection since the public transport vehicles run together with other motorised vehicles in mixed flow. Still, there are various possibilities to configure the rules for public transport priority. Its configuration may have a significant influence on the traffic flow of other vehicles. For this test site, the current rules to prioritise public transport is named as the option "conditional". Another option "conditional(weak)" is designed in the way that the requests from public transport vehicles can be denied, if the queues in the conflicting approaches reach a limit. In order to realise this function, the queue lengths in different approaches should be included in the logical conditions for handling requests from public transport vehicles. The third option to test is no public transport priority. In this option, public transport vehicles are treated the same as other motorised vehicles. No special rules are set to process the requests from public transport vehicles so that they can pass the intersection with lower delays.

By combining different options of the three features, twelve alternative signal programs are developed in total. These alternatives signal programs are investigated not only in the midday off-peak hour, but also the evening peak hour. The complete list of alternative signal programs is shown in Table 33.

---

**Figure 27**: Options for the stage design of the A 33 (own illustration)
Table 33: List of the alternative traffic signal programs for the A 33 (own illustration)

<table>
<thead>
<tr>
<th>Alternative ID</th>
<th>Cycle time</th>
<th>Stage design</th>
<th>Public transport priority</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Evening peak hour</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A33_A111</td>
<td>70 s</td>
<td>Option 1</td>
<td>No</td>
</tr>
<tr>
<td>A33_A112</td>
<td>70 s</td>
<td>Option 1</td>
<td>Conditional (weak)</td>
</tr>
<tr>
<td>A33_A113</td>
<td>70 s</td>
<td>Option 1</td>
<td>Conditional</td>
</tr>
<tr>
<td>A33_A211</td>
<td>90 s</td>
<td>Option 1</td>
<td>No</td>
</tr>
<tr>
<td>A33_A212</td>
<td>90 s</td>
<td>Option 1</td>
<td>Conditional (weak)</td>
</tr>
<tr>
<td><strong>A33_A213</strong></td>
<td><strong>90 s</strong></td>
<td><strong>Option 1</strong></td>
<td><strong>Conditional</strong></td>
</tr>
<tr>
<td>A33_A121</td>
<td>70 s</td>
<td>Option 2</td>
<td>No</td>
</tr>
<tr>
<td>A33_A122</td>
<td>70 s</td>
<td>Option 2</td>
<td>Conditional (weak)</td>
</tr>
<tr>
<td>A33_A123</td>
<td>70 s</td>
<td>Option 2</td>
<td>Conditional</td>
</tr>
<tr>
<td>A33_A221</td>
<td>90 s</td>
<td>Option 2</td>
<td>No</td>
</tr>
<tr>
<td><strong>A33_A222</strong></td>
<td><strong>90 s</strong></td>
<td><strong>Option 2</strong></td>
<td><strong>Conditional (weak)</strong></td>
</tr>
<tr>
<td>A33_A223</td>
<td>90 s</td>
<td>Option 2</td>
<td>Conditional</td>
</tr>
<tr>
<td><strong>Midday off-peak hour</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A33_O111</td>
<td>70 s</td>
<td>Option 1</td>
<td>No</td>
</tr>
<tr>
<td>A33_O112</td>
<td>70 s</td>
<td>Option 1</td>
<td>Conditional (weak)</td>
</tr>
<tr>
<td><strong>A33_O113</strong></td>
<td><strong>70 s</strong></td>
<td><strong>Option 1</strong></td>
<td><strong>Conditional</strong></td>
</tr>
<tr>
<td>A33_O211</td>
<td>90 s</td>
<td>Option 1</td>
<td>No</td>
</tr>
<tr>
<td>A33_O212</td>
<td>90 s</td>
<td>Option 1</td>
<td>Conditional (weak)</td>
</tr>
<tr>
<td>A33_O213</td>
<td>90 s</td>
<td>Option 1</td>
<td>Conditional</td>
</tr>
<tr>
<td>A33_O121</td>
<td>70 s</td>
<td>Option 2</td>
<td>No</td>
</tr>
<tr>
<td>A33_O122</td>
<td>70 s</td>
<td>Option 2</td>
<td>Conditional</td>
</tr>
<tr>
<td>A33_O123</td>
<td>70 s</td>
<td>Option 2</td>
<td>No</td>
</tr>
<tr>
<td>A33_O221</td>
<td>90 s</td>
<td>Option 2</td>
<td>Conditional (weak)</td>
</tr>
<tr>
<td>A33_O222</td>
<td>90 s</td>
<td>Option 2</td>
<td>Conditional (weak)</td>
</tr>
<tr>
<td><strong>A33_O223</strong></td>
<td><strong>90 s</strong></td>
<td><strong>Option 2</strong></td>
<td><strong>Conditional</strong></td>
</tr>
</tbody>
</table>

Current traffic signal program
Cost-effective signal program

5.5.5 Measurement of Evaluation Criteria

The general descriptions about the traffic flow simulation and the emission modelling in Subsection 5.2.5 also apply to this test site. Besides, the following aspects are pointed out for this test site:

- Traffic simulation models for the midday off-peak hour (12:30 - 13:30) and the evening peak hour (16:30 - 17:30) are developed.

- The neighbouring traffic signal systems in the direction Heinheimer Straße is simulated in the traffic flow simulation model in a simplified form. A fixed time program is simulated without consideration of the traffic responsiveness at neighbouring signal systems. The time conditions are based on those that are in the technical documents with support from the video-based observation. In the other three directions, the neighbouring traffic signal systems are not modelled, and the inflows enter the network stochastically. In reality, vehicles from these three directions do not come in platoons because of two reasons. The neighbouring intersections are either far away or not signalised in the corresponding outflow.
• Pedestrians and cyclists are considered separately in the model. The cyclists cross the intersection either on the separate cycle lanes at the roadside or on the pedestrian crossings. Both ways are simulated in the modelling.

For this test site, the evaluation of alternative traffic signal programs takes all the evaluation criteria that are selected in Section 4.4 into consideration, including accidents. The delays and traffic emissions are estimated using the traffic flow simulation model and the emission model. The accident costs are calculated using the empirical accident data from 2013 to 2015. Although in 2014, the traffic signal programs were revised, including changes in the stage design as explained in Subsection 5.5.4. However, the left-turning vehicles on the main streams are temporally protected with traffic signals both before or after the revision. Those on the minor streams are also signalised in the same way. Therefore, it is assumed that there should be no significant changes in traffic safety after the revision. It can also be confirmed by the trends of accident data in the last years. Although there are certain variations between years, significant changes after 2014 cannot be observed. The calculated accidents using the data from 2013 to 2015 can, therefore, be assigned to the current signal program under operation (the alternative A33_A213 or A33_O213). For other alternative signal programs listed in Table 33, there are no significant changes in the way how left-turning streams are temporally protected. According to this, it is assumed that the accident costs of other signal programs are the same as those of the current signal program (the alternative A33_A213 or A33_O213).

5.5.6 Data Processing and Ranking of Alternative Traffic Signal Programs

At this typical four-leg intersection, the total traffic volumes are respectively 4080 p/h in the evening peak hour and 3479 p/h in the midday off-peak hour. The compositions in two time periods are as follows:

- 9% pedestrians and cyclists + 23% persons in public transport + 68% persons in motorised private transport and heavy transport in the evening peak hour
- 11% pedestrians and cyclists + 19% persons in public transport + 70% persons in motorised private transport and heavy transport in the midday off-peak hour

The persons in motorised private transport and heavy transport are also dominant at the A33, similar to the other test sites. However, the distribution of road users among different types differs significantly to the modal split of the City of Darmstadt. The modal split relates to the trips made by citizens. It usually serves as a basis to understand how different traffic modes are used while planning and managing transport infrastructures. According to Blees and Wieskotten (2011, p. 8), the environment-friendly modes including walking (27.1%), cycling (14.8%) and public transport (13.3%) take up more than half of the trips in Darmstadt. There is a large share of walking and cycling. However, the traffic counts in this study show that this share is significantly lower at an intersection. It is mainly because trips by walk or cycle cover generally short distances and pass through less traffic signal systems. This finding supports the idea to consider the number of persons in traffic modes while designing traffic signal control at pedestrian crossings or intersections.

Results for the evening peak hour

Based on the results of the traffic flow simulation, the emission modelling and the accident analysis, the total cost at this test site is within the range of 315 to 380 €/h. The total cost is significantly higher than those calculated for signalised pedestrian crossings partially due to a higher number of road users and also longer delays. The delays generally become longer since there are more streams and more conflicts. The conflicting streams are released one after each other to ensure safety.

18 The values are based on the traffic volumes returned by traffic flow simulation as output.
The current signal program under operation in the evening peak hour is A33_A213. Total cost of 347 €/h is calculated for this signal program. The distribution of different cost components is shown in Figure 28.

![Figure 28: Distribution of the costs for the alternative signal programs A33_A213, A33_A222 and A33_A211 (own illustration)](image)

For this signal program, delay costs take up more than half of the total cost. Furthermore, they are dominated by the delay costs for public transport and motorised private transport. Fuel and environmental costs are about one-third of the total cost. The rest is accident costs, which takes up 13% and has an important role at this intersection. The civil construction office of Darmstadt confirmed that the traffic safety situation at this intersection needs to be improved. The distribution of cost components at this intersection differs significantly to that at the pedestrian crossing, where fuel and environmental costs are dominant.

Under equal weighting for all cost components, the traffic signal program A33_A222 with the total cost of 315 €/h is most cost-effective among all the investigated signal programs. In comparison to the A33_A213, the delay costs for motorised private transport decrease by 16% with the introduction of a new stage design and the weaker priority for public transport. Among them, the new stage design brings...
more reduction. Slight reductions can also be observed in the delay costs for walking, public transport, heavy transport as well as the environmental costs for PM emissions and fuel costs. The distribution of different cost components remains similar.

In order to analyse the impacts of **public transport priority** on calculated costs, another signal program A33_A211 is compared with the program A33_A213. The distribution of cost components is shown in Figure 28. The cycle time and the stage design of these two signal programs are the same. The only difference is whether public transport is prioritised at this intersection or not. In comparison to the A33_A213, the following changes in costs are observed for the A33_A211:

- increase of delay costs for public transport about 15 €/h
- decrease of delay costs for motorised private transport about 12 €/h
- decrease of delay costs for heavy transport about 1 €/h
- decrease in fuel costs about 2 €/h

The results show that the **public transport priority** does not cause disadvantages for the whole traffic system at this test site. Instead, it leads to a shift of delays from public transport to other travel modes (especially motorised private transport). It is consistent with the transport politics of government to favour the environment-friendly modes.

Figure 29 shows the impacts of **public transport priority** on the delays for public transport and motorised private transport. Three signal programs, A33_A211, A33_A212 and A33_A213, are compared. The difference between them is the intensity of public transport. As shown in Figure 29, public transport priority reduces the average delay for public transport passengers significantly but leads to an increase in delays for persons in motorised private transport. For this test site, it would bring no apparent benefits to the whole traffic system, if the conditional public transport priority is weakened by including queue lengths in the relevant traffic control logic.

![Figure 29: Impacts of public transport priority on the delays at the A 33 (own illustration)](image)

**Results for the midday off-peak hour**

In the midday off-peak hour, the total number of road users that pass the A 33 is about 15 % lower than that in the evening peak hour. The reduction results partially from the decrease in the number of cars. It is consistent with the traditional **definitions of peak and off-peak hour**. The number of passengers in public transport reduces as well. However, that is mainly due to the reduction of the occupancy rate as assumed in Section 4.6. The number of vehicles is slightly higher in the midday off-peak according to the timetable of bus lines. The number of pedestrians, cyclists and heavy transport vehicle drivers remain constant in both periods. The traffic flow simulation shows that the delays for different traffic modes are generally lower in the midday off-peak hour. One reason for that is the better traffic flow quality due to the decrease in the number of cars.
The evaluation results can reflect the changes in the different aspects mentioned above. The total cost calculated for different signal programs is within the range of 235 to 256 €/h, lower than that in the evening peak hour. The **current signal program** in the midday off-peak hour A33_O113 has a total cost of 251 €/h while the **cost-effective signal program under the equal weighting** A33_O223 has the lowest cost of 235 €/h.

The **distribution of cost components** remains similar to that in the evening peak hour. Two signal programs A33_O113 and A33_O223 are shown in Figure 23 as examples. Around half of the total cost comes from delay costs. On the second place, the fuel and environmental costs take up about one-third of the total cost. The accident costs take up 13 to 14%.

Based on the evaluation results, **similar recommendations** can be drawn for traffic signal control in the midday off-peak hour like those in the evening peak hour. First, although public transport priority can cause a disadvantage to motorised private transport, its benefits outweigh the negative impacts. Therefore, public transport priority is beneficial for the whole transport system at this test site from an overall point of view. Second, applying the new stage design alternative 2 can reduce the total cost.

### 5.5.7 Sensitivity Analysis

At this test site, all the selected evaluation criteria defined in Section 4.4 serve as the input for the evaluation. **Sensitivity analyses** are conducted except for the accident cost rates. As explained in Subsection 5.5.5, same accident costs are assumed for all investigated signal programs. Hence, variations of accident cost rates would not influence the ranking of signal programs.

The results show that the **ranking of signal programs** is not sensitive to the following attributes:

- the delay cost rate for walking
- the delay cost rate for cycling
- the delay cost rate for heavy transport
- the environmental cost rates for PM emissions
- the environmental cost rate for NO\textsubscript{x} emissions
- the environmental cost rate for CO\textsubscript{2} emissions
- the cost rate for fuel consumption

One example is shown in Figure 31. The exemplary results shown in the figure correspond to the evening peak hour. It is shown in the diagram for CO\textsubscript{2} that the ranking of signal programs according to the total cost remains stable along with changes in the corresponding cost rate.

For the other attributes, the ranking of signal programs would change if the values of input attributes vary up to ±50%. They are all relevant to public transport and motorised private transport. Three of them are shown as examples in Figure 31. The changes in the rank order can be read in the graphics.

A signal program without public transport priority (A33_A221) would become the most cost-effective under one of the following situations:

- if the delay cost rates for public transport is reduced by more than 33%
- if the delay cost rates for motorised private transport increases by more than 55%
- if the average occupancy rate of buses is lower than 26 p/veh
- if the average occupancy rate of cars is more than 2.1 p/veh

For the evening peak hour, it is currently unrealistic that the average occupancy rate of cars is more than 2.1 p/veh. However, when the buses that pass this intersection have low occupancy rates, a situation-responsive adjustment of traffic signal control might bring benefits to the whole transport system at the test site. That is also the case if the cost rates or the special weighting for evaluation criteria are adapted.

Figure 31: Sensitivity of the total cost to changes in the exemplary attributes for the A 33 (own illustration)
However, promotion of public transport is more commonly the political goal of government. Under this context, a signal program with public transport priority is preferred.

5.6 Test Site 4: Hügelstraße/ Karlstraße (A 81)

5.6.1 Description of the Investigation Area

The traffic signal system A 81 is located on the city ring road of Darmstadt. As shown in Figure 32, the shape of the intersection is not typical. It can be divided into two parts that are separated away from each other. As a result, traffic flows are relatively complex. Both Hügelstraße and Kirchstraße are part of the city ring where vehicles only flow in one way. Most vehicles come from Hügelstraße and turn in three directions, namely Kirchstraße, Karlstraße and Nieder-Ramstädter Straße. Another inflow is Karlstraße. Vehicles from Karlstraße can either turn right to the Nieder-Ramstädter Straße or go straight forward to Kirchstraße. They have to pass two signal heads in order to get on the city ring. The third inflow from Nieder-Ramstädter must first turn on Karlstraße (following a give way sign) and then go further to the city ring (signalised). A public transport stop is located immediately before the stop line of Schulstraße. There are several pedestrian crossings at the intersection due to the complex shape. The geometric design of the intersection is shown in Figure 32.

Figure 32: Layout plan of the A 81 (source: adapted from the layout plan provided by the City of Darmstadt)

The city ring road Hügelstraße-Kirchstraße is a main axis for motorised private transport, where high traffic volumes are expected in both morning and evening peak hours. The routes Schulstraße-Karlstraße and Schulstraße-Nieder-Ramstädter Straße are the important axes for public transport, on which three
tram lines and a bus line operate in both directions. As shown in Figure 32, these two axes are conflicted. The A 81 operates under a **traffic-actuated signal program** with **absolute priority to public transport**. The absolute public transport priority would sometimes lead to long queues in Hügelstraße in peak hours. In off-peak hours, this problem is not so serious due to the reduction in traffic volumes.

About 300 m before the stop line of Hügelstraße is the exit of the city tunnel - Wilhelminenstraße. Directly at the tunnel exit, the **monitoring station** "Darmstadt Hügelstraße" collects **air quality** data continuously. It is the only monitoring station in the city that is located at roadside. The air quality measured here has exceeded the threshold value of NO\textsubscript{x} in the recent years. The leading cause is high emissions from motorised vehicles. Other causes for an extremely high air pollution level here are the slope at the tunnel exit, the speed limit of 30 km/h and the street canyon along the road (HMUKLV, 2015, pp. 21-22). Sometimes the queue on Hügelstraße may be long enough to reach the monitoring station and can influence the air quality data as well.

### 5.6.2 Data Collection

The city planning office of Darmstadt provided the **traffic volumes** of motorised vehicles. The traffic count was conducted on 10 November 2011. An evening peak hour from 16:45 - 17:45 and an off-peak hour from 13:00 - 14:00 are selected for further evaluation. The directional flow volume diagrams for vehicles in these two time periods are shown in Figure 33. The cyclists that ride on roadways are included here. The patterns of inflows to this intersection are based either on on-site observations or traffic signal programs provided by the civil engineering office of Darmstadt.

![Figure 33: Directional traffic volume diagrams for vehicles of the A 81 (own illustration)](image)

A **traffic count** was conducted additionally on 30 March 2017 in the selected periods aiming to collect traffic volumes of pedestrians and cyclists that use pedestrian crossings. The weather was dry with the temperature between 17 to 28 °C. The results of this traffic counting are shown in Figure 34.
Similar to the traffic signal system A 33, the timetable of public transport lines and traffic accident data were collected for further evaluation.

### 5.6.3 Examination of the Goal System and Evaluation Criteria

The predefined goal system and evaluation criteria can be fully applied at this test site. The three main goals are: satisfaction of mobility needs, increase of traffic safety and reduction of environmental pollution. All the predefined evaluation criteria are considered.

This test site is located at a crossing point of a main axis for public transport and the city ring. Public transport priority is applied currently to ensure a smooth progression of public transport with minimal delays at traffic signal systems. However, long queues at approaches may occur as a result. A fair balance between the related benefits and drawbacks is necessary. Besides, the city ring is along a street canyon. There is a large amount of emissions from vehicles due to high traffic volumes on the city ring. At the same time, the dispersion of air pollutions is strongly influenced. Both the public transport priority and the environmental aspect require a special consideration at this test site.

### 5.6.4 Development of Alternative Traffic Signal Programs

The focus of the evaluation at this test site lies first on how different forms of public transport priority would affect other traffic modes. As shown in Table 34, three forms of public transport can be considered for designing traffic signal programs.

An absolute public transport signal priority is characterised by zero delay for public transport vehicles (FGSV, 1999, p. 20). Under the current operation of this intersection, it can be almost realised. The public transport vehicles run on separate lanes and send their requests for green time through both preregister detectors and main register detectors. It has significant influences on the traffic flow quality and traffic emissions, especially those on the ring road. The public transport priority can be weakened...
Table 34: Features considered for designing alternative traffic signal programs for the A 81 (own illustration)

<table>
<thead>
<tr>
<th>Feature</th>
<th>Options</th>
</tr>
</thead>
<tbody>
<tr>
<td>Public transport priority</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>Conditional</td>
</tr>
<tr>
<td></td>
<td>Absolute</td>
</tr>
<tr>
<td>Green split(^a)</td>
<td>O1  O2  O3  O4  O5  O6  O7  O8  O9  OX</td>
</tr>
</tbody>
</table>

\(^a\) O is the abbreviation for option.

by suppressing the requests if long queues occur on the ring road. For this test site, the limit is set to 150 m. This form of public transport priority is named conditional public transport priority here. The last form is without public transport priority.

It is observed at the intersection that occasionally the green time of minor streams is not used efficiently. Sometimes the signals for minor streams remain green although no vehicles are coming in these directions towards end of the stage. The corresponding stages can be terminated early and the green time in the main streams (three streams coming from Hügelstraße) becomes longer as a result. That leads to a better traffic flow in the main streams and reduces the queue lengths in Hügelstraße. Therefore, different options of the green split are tested by changing the time conditions for the stages of minor streams. The end time of the stage for minor streams (T4 and T5 in the technical documents) are changed gradually. T4 represents the earliest time point for that stage while T5 the latest time point. Different options for green split that are shown in Table 34 correspond to the following T4 and T5 values:

- Option 1 (O1): T4 = 52 s, T5 = 59 s
- Option 2 (O2): T4 = 54 s, T5 = 61 s
- Option 3 (O3): T4 = 56 s, T5 = 63 s
- Option 4 (O4): T4 = 58 s, T5 = 65 s
- Option 5 (O5): T4 = 60 s, T5 = 67 s
- Option 6 (O6): T4 = 4 s, T5 = 11 s
- Option 7 (O7): T4 = 6 s, T5 = 13 s
- Option 8 (O8): T4 = 8 s, T5 = 15 s
- Option 9 (O9): T4 = 10 s, T5 = 17 s
- Option X (OX): T4 = 12 s, T5 = 19 s

The options can be divided into two groups. O1 to O5 are for the alternative signal programs in the evening peak hour while O6 to OX for those in the midday off-peak hour. For those in the same group, the smaller T4 and T5 are, the earlier the stage for minor streams can be terminated, the longer the green time of main streams can be.\(^{19}\)

By combining these two features, alternative signal programs are developed each for the evening peak hour and the midday off-peak hour. They are shown in Table 35.

5.6.5 Measurement of Evaluation Criteria

General aspects of the traffic flow simulation and the emission modelling are described in Subsection 5.2.5. The specific aspects for the A 81 are pointed out as follows:

- The traffic simulation models are related to two time periods: the evening peak hour from 16:45 - 17:45 and the midday off-peak hour from 13:00 - 14:00.
- For the approach Hügelstraße, the adjacent intersections are simulated in a simplified way. It is because the vehicles that come from this direction travel mostly in a platoon. The time conditions

\(^{19}\) The length of green time also depends on the traffic loads on the mains streams themselves.
Table 35: List of the alternative traffic signal programs for the A 81 (own illustration)

<table>
<thead>
<tr>
<th>Alternative ID</th>
<th>Features</th>
<th>Public transport priority</th>
<th>Green split</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Evening peak hour</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A81_A11</td>
<td>No</td>
<td></td>
<td>Option 1</td>
</tr>
<tr>
<td><strong>A81_A12</strong></td>
<td>No</td>
<td></td>
<td><strong>Option 2</strong></td>
</tr>
<tr>
<td>A81_A13</td>
<td>No</td>
<td></td>
<td>Option 3</td>
</tr>
<tr>
<td>A81_A14</td>
<td>No</td>
<td></td>
<td>Option 4</td>
</tr>
<tr>
<td>A81_A15</td>
<td>No</td>
<td></td>
<td>Option 5</td>
</tr>
<tr>
<td>A81_A21</td>
<td>Conditional</td>
<td></td>
<td>Option 1</td>
</tr>
<tr>
<td>A81_A22</td>
<td>Conditional</td>
<td></td>
<td>Option 2</td>
</tr>
<tr>
<td>A81_A23</td>
<td>Conditional</td>
<td></td>
<td>Option 3</td>
</tr>
<tr>
<td>A81_A24</td>
<td>Conditional</td>
<td></td>
<td>Option 4</td>
</tr>
<tr>
<td>A81_A25</td>
<td>Conditional</td>
<td></td>
<td>Option 5</td>
</tr>
<tr>
<td>A81_A31</td>
<td>Absolute</td>
<td></td>
<td>Option 1</td>
</tr>
<tr>
<td>A81_A32</td>
<td>Absolute</td>
<td></td>
<td>Option 2</td>
</tr>
<tr>
<td>A81_A33</td>
<td>Absolute</td>
<td></td>
<td>Option 3</td>
</tr>
<tr>
<td><strong>A81_A34</strong></td>
<td><strong>Absolute</strong></td>
<td></td>
<td><strong>Option 4</strong></td>
</tr>
<tr>
<td>A81_A35</td>
<td>Absolute</td>
<td></td>
<td>Option 5</td>
</tr>
<tr>
<td></td>
<td>Midday off-peak hour</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A81_O16</td>
<td>No</td>
<td></td>
<td>Option 6</td>
</tr>
<tr>
<td>A81_O17</td>
<td>No</td>
<td></td>
<td>Option 7</td>
</tr>
<tr>
<td>A81_O18</td>
<td>No</td>
<td></td>
<td>Option 8</td>
</tr>
<tr>
<td>A81_O19</td>
<td>No</td>
<td></td>
<td>Option 9</td>
</tr>
<tr>
<td>A81_O1X</td>
<td>No</td>
<td></td>
<td>Option X</td>
</tr>
<tr>
<td><strong>A81_O36</strong></td>
<td><strong>Absolute</strong></td>
<td></td>
<td><strong>Option 6</strong></td>
</tr>
<tr>
<td>A81_O37</td>
<td>Absolute</td>
<td></td>
<td>Option 7</td>
</tr>
<tr>
<td><strong>A81_O38</strong></td>
<td><strong>Absolute</strong></td>
<td></td>
<td><strong>Option 8</strong></td>
</tr>
<tr>
<td>A81_O39</td>
<td>Absolute</td>
<td></td>
<td>Option 9</td>
</tr>
<tr>
<td>A81_O3X</td>
<td>Absolute</td>
<td></td>
<td>Option X</td>
</tr>
</tbody>
</table>

Current traffic signal program
Cost-effective signal program

are based on on-site observations and signal programs documented in the technical documents. The traffic responsiveness of neighbouring traffic signal systems is not simulated. At other approaches, vehicles do not travel in platoon due to the low number. They just enter the network stochastically.

• The start point for the delay measurement of public transport in the approach Schulstraße is located directly after the public transport stop. The reason is to avoid including delays caused by public vehicles stopping at the bus stop in the delay measurement related to traffic signal control.

• The current signal program under operation was developed using software GEVAS in the year 1993. It contains a complicated control logic for traffic-actuated signal program. The control logic is documented in a display form that is different from the standardised forms suggested by FGSV (2015b, pp. 46-47). It is, therefore, necessary to transform it in a form that is compatible with VisVAP. During the transformation process, the meanings of original commands are kept unchanged as much as possible. A validation is conducted by comparing a clip of signal time plan in the
simulation with that in the reality. The model in the afternoon off-peak hour is approved by the staffs of civil engineering office of the city who are responsible for operating the traffic signal systems.

The accident costs are considered in the evaluation at this test site. The empirical accident data from 2013 - 2015 are used to calculate the accident costs. Since there are no structural differences in stage design between alternative signal programs, no changes in accident costs are assumed. The calculated accident costs for the current signal program apply also to other alternatives.

5.6.6 Data Processing and Ranking of Alternative Traffic Signal Programs

As explained in Subsection 5.6.1, high traffic volumes are observed at this test site because of its location at a crossing point of main axes for both motorised private transport and public transport. The total traffic volumes of 6517 p/h in the evening peak hour and 5010 p/h in the midday off-peak hour are highest among all the investigated test sites. The composition of road users are as follows:

- 9% pedestrians and cyclists + 37% persons in public transport + 54% persons in motorised private transport and heavy transport
- 8% pedestrians and cyclists + 35% persons in public transport + 57% persons in motorised private transport and heavy transport

The motorised private transport is still dominant among all traffic modes. It is followed by the share of public transport passengers, which is not only higher than that at the A 33 but also the mode share of trips by public transport in Darmstadt. Similar to the A 99 and A 33, the share of pedestrians and cyclists is significantly lower than their mode share in Darmstadt.

The distribution of road users is influenced strongly by the assumed occupancy rates of different vehicle types. The data shown above are based on the occupancy rates in Table 15 and 16.

Results for the evening peak hour

The more road users and vehicles that pass the higher the total cost. Therefore, the cost for the A 81 is highest among all the four investigated test sites. For the current traffic signal program in the evening peak hour, the total cost at the A 81 is 457 p/h. The distribution of various cost components is shown in Figure 35. The distribution is similar to that at the A 33. The largest part of the cost (about 58%) comes from the delay costs, most of which are furthermore for motorised private transport. The fuel and environmental costs take up about 39%. The accident costs are only 3% of the total cost, which is much lower than that at the A 33. Therefore, this cost component plays a minor role at this test site.

It needs to be pointed out that the delays for public transport measured at this test site result not only from the waiting time before the traffic signal system, but also partially from the start-up process after leaving the station. In the software Vissim, the loss of time of public transport vehicles due to deceleration and acceleration at stops is included in the delay measurement as well. Therefore, the pure delays resulting from traffic signal control are actually lower than the values shown above. However, this would not influence the comparison of alternative signal programs for this test site.

Under equal weighting for all cost components, the signal program A81_A12 with a total cost of 404 €/h is cost-effective among all investigated variants. It has the following features:

- no public transport priority
- shorter green time for minor streams

Figure 35 shows the distribution of cost components for this signal program. Delay costs take up a large part of the total cost. However, the delay costs for public transport are more than double the
amount of the current signal program, since the average delays for public transport increase sharply if no priority is given to them at the intersection. The advantages are a reduction in the delay costs for motorised private transport, fuel and environmental costs locally.

The public transport priority is an important measure to promote the sustainable development of transport systems by attracting more people using this environment-friendly travel mode instead of private vehicles. On a macroscopic level, it is beneficial for the environment. However, at the local level where the public transport priority is implemented, this would possibly have negative impacts on the traffic flow quality and, therefore, lead to more local air pollutant emissions. This thesis also confirms this statement.

Although a traffic signal program without public transport priority is cost-effective under equal weighting according to the evaluation results for the evening peak hour, a strong public transport would already be preferred, if a moderate particular weight of about 1.2 would be applied on the delay costs of public transport. Under this context, the cost-effective signal program would change to A81_A31. The distribution of cost components for this variant is similar to that for the current signal program A81_A34,
as shown in Figure 35. The difference of this alternative to the A81_A34 is that the green time for minor streams is shorter. As observed from the traffic flow simulation model, there are often no vehicles approaching the intersection from the minor streets at the end of their green time. The green time that is not efficiently used can be instead allocated to the main streams. It would generally improve the traffic flow quality on the main streams and reduce the queue lengths. It further results in a reduction in the delay costs for motorised private transport, heavy transport as well as fuel and environmental costs.

In principle, no particular weights should be applied. In special cases, a moderate adjustment of particular weights can be undertaken if there are reasonable and acceptable justifications for that. At the A81, a moderate particular weight for public transport (about 1.2) can be justified by the fact that this intersection is located on a main axis for public transport. In order to ensure the smooth operation of public transport, a moderate weight is acceptable. Besides, the evaluation results are based on the assumed occupancy rates of public transport vehicles. If the occupancy rates increase moderately, a signal program with absolute priority for public transport would be preferred, even if there is no particular weight for it. Therefore, more comprehensive knowledge of occupancy rates of public transport can support the decision-making process for designing traffic signal control. It is desirable to differentiate between traffic periods, intersections or even public transport lines.

As explained in Subsection 5.6.3, another focus of this test site is laid on the environmental protection. If the air quality threshold values are exceeded or estimated to be exceeded at the monitoring station nearby, a particular weighting can be applied to reduce fuel consumption and emissions to improve the situation. As a result, a signal program with fewer emissions (in this case the program A81_A12) would be preferred. A reduction of air pollutant emissions from 6 to 10% can be achieved by changing the signal program. However, an adjustment of the particular weight should be dynamic and responsive to the real-time situation in this case.

With the evaluation results, it can be investigated how different forms of public transport priority influence delays for different road users. Figure 36 shows a comparison of three signal programs with different priority levels for public transport in traffic signal control: A81_A14 no priority, A81_A24 with the conditional priority and A81_A34 with the absolute priority. As shown in Figure 36, the delays for public transport decrease as the priority level for public transport becomes stronger. With regards to the investigated signal programs, applying the conditional public transport can already save long delays. The difference in delays between the conditional and absolute public transport priority is minimal. Of course, this statement depends strongly on under what conditions traffic control devices ignore requests from public transport vehicles.

![Figure 36: Impacts of the public transport priority on delays at the A 81 (own illustration)](image)

Results for the midday off-peak hour

The traffic volumes are significantly lower in the midday off-peak hour than the evening peak hour, except for those of heavy transport. A better traffic flow can be observed, which means shorter delays for
all road users as well as lower fuel consumption and air pollutant emissions at the test site. As a result, there is a significant reduction in the total cost per hour. The total cost of the current signal program A81_O38 is 265 €/h. The cost-effective signal program under equal weighting in the midday off-peak hour is A81_O36, whose total cost is 264 €/h. The difference in costs between both signal programs is minimal.

Figure 37 shows a comparison of the distribution of cost components between both signal programs. They are almost identical. Around half of the total cost comes from delay costs. The fuel and environmental costs with a percentage of 44 % take up the second largest share. The rest 4 % results from accident costs. The distribution changes slightly in comparison to that in the evening peak hour.

According to the evaluation results, an absolute public transport priority is generally recommended for traffic signal control at the A 81 in the midday peak hour. Unlike in the evening peak hour, no particular weight for public transport is required. The green split for minor roads can be adapted to reduce the total cost slightly. However, the effects are negligible.

If a particular weight for fuel and environmental costs (factor more than 2) is applied, a signal program with lower emissions should be chosen in purely mathematical terms according to the results. A reduction of air pollutant emissions for about 2 to 3 % can be achieved by changing the signal program. The further impact on local air quality is, however, questionable. In the meanwhile, the delays for public transport would be increased significantly. In this case, an adjustment of the signal program can barely be justified. Therefore, the evaluation results should not be used in purely mathematical terms to support designing traffic signal control. It is also important to analyse the results comprehensively in order to a transparent and reasonable trade-off process.
5.6.7 Sensitivity Analysis

Sensitivity analyses show that the ranking of signal programs is sensitive to changes in the following evaluation criteria if their values vary within the predefined range of values:

- the delay costs for public transport and motorised private transport
- the occupancy rate of public transport vehicles

It is both valid in the evening peak hour and the midday off-peak hour. How the evaluation results respond to changes in these cost components in the evening peak hour are shown in Figure 38 as an example. The critical turning points for different cost components can be read from the diagrams. With regards to the delay costs for public transport, the turning point lies between the range of 20 to 30%. For motorised private transport, the turning point lies between the range of −30 to −20%. The turning point for the average occupancy rate of public transport is 98 p/h for trams and 49 p/h for buses. The average occupancy rate of public transport vehicles used in this thesis is only based on estimations according to experiences. There is a lack of reliable reference for it. Therefore, it is desirable to get a better knowledge of the occupancy rate by collecting empirical data in future research.

Figure 38: Sensitivity of the total cost to changes in the exemplary attributes for the A 81 (own illustration)

To some other evaluation criteria, the ranking of signal programs does not change when their values vary within the same range as above. They include:

- the delay costs for walking, cycling and heavy transport
- the environmental costs for PM, NO\textsubscript{x} and CO\textsubscript{2}
- fuel costs
A diagram for the CO$_2$ emissions in the evening peak hour is shown in Figure 38 as an example. It can be seen that the ranking of signal programs remains stable, although the cost rate for CO$_2$ emissions change in the defined range.

The occupancy rate of cars does not belong to the two groups mentioned above. In the evening peak hour, it is found that the ranking of signal programs is not sensitive to changes within the range 1.0 to 2.0 p/h. Currently, it is unlikely that occupancy rate falls outside this range in peak hours, since commuting traffic is dominant in this traffic time. In the midday off-peak hour, a turning point of about 1.9 p/h is observed. However, the occupancy rate according to the collected data on-site is far below this value.

### 5.7 All Test Sites: Analysis of the Correlations between Evaluation Criteria

Besides delay costs, fuel and environmental costs are also important cost components that should not be ignored in the evaluation of traffic signal control. Previous studies show that there are close relationships between delays and air pollutant emissions (or fuel consumption). The proposed method of measuring emissions and the related costs might be considered as being too complicated. Some experts might think that choosing just one major criterion such as the delay might be enough to consider the whole situation. Therefore, the correlations between these cost components are investigated using the evaluation results of all test sites. The purpose is to check, whether it is possible to simplify the evaluation process by estimating fuel and environmental costs using delay costs and adding both to get the total cost. Figure 39 shows the correlations between delay costs and the associated fuel and environmental costs for public transport, motorised transport and heavy transport separately.

![Figure 39: Correlations between delay costs and the associated fuel and environmental costs (own illustration)]
Results in only two of the four test sites -A 33 and A 81- are relevant for public transport. As shown in Figure 39, the data points gather in groups. The data clouds for the A 33 are located on the left and top of those for the A 81. It means that the fuel and environmental costs at A 33 are generally higher than those at A 81 even if similar delay costs are calculated. One reason can be a difference in the vehicle composition of public transport vehicles between both test sites. All the public transport lines that pass the A 33 are buses that emit air pollutants locally. However, at the A 81, three of the four public transport lines are trams that are electrically driven and do not emit air pollutants locally. The data clouds for the A 33 (or the A 81) can be further separated into two groups. One group is built up by data points relevant to the evening peak hour while the other the midday off-peak hour. Inside each group, a linear correlation between delay costs and the associated fuel and environmental costs can be observed. Similar results can also be observed for motorised private transport and heavy transport. For these two criteria, the results of the test sites A 99 and A 7 are relevant additionally. The data points gather in groups depending on the test site and traffic time. Significant differences can be made between the signalised pedestrian crossings and the intersections. The data points of the A 33 and A 81 can be further divided into two groups.

In conclusion, it is not possible to develop one linear function between delay costs and the associated fuel and environmental costs that are generally valid for all cases. The correlation varies between different types of traffic signal systems, traffic periods and traffic volumes. However, if there exist several test results for several traffic signal programs of a signal system already, it is possible to derive a linear function based on these available data. It can further be used to estimate the fuel and environmental costs for other signal programs under the same situation. It is recommended to use the emission modelling to estimate fuel consumption and air pollutant emissions and consider them in the evaluation of traffic signal control. The future development of vehicle fleet and their emission factors should also be taken into consideration, if relevant.

5.8 Conclusions

The following conclusions are drawn based on the application of the evaluation method D-MoTSE on test sites:

- **The number of persons that are present at traffic signal systems has significant impacts on the design of traffic signal control.**

  Traffic volumes are an essential input for the design and the evaluation of traffic signal control. A calculation of the traffic volumes in persons instead of vehicles can give a better overview of all traffic modes at a traffic signal system. According to the evaluation results, both the total number and the distribution of persons among traffic modes vary significantly between different test sites. They also have unique daily patterns. However, at all four investigated test sites, the number of persons in motorised private transport is dominant.

- **The distribution of persons among traffic modes is significantly different from the traditional modal split.**

  Traditionally, the modal split is calculated using the number of trips with different modes on a macroscopic level. It is generally used to analyse the travel behaviour of residents and guide the planning of transport facilities. In this study, the distribution of persons among different modes at test sites is also calculated based on the traffic volumes and the predefined occupancy. It is observed that the share of non-motorised modes is much lower at each intersection than in the modal split. The main reason is that trips by walk or cycle cover generally short distances and pass through less traffic signal systems.

- **Although the distribution of cost components varies depending on the type of intersection and the traffic signal program, some general statements can be made.**
The evaluation results show that energy consumption and environmental costs take up at least one-third of the total cost, and should, therefore, not be neglected in the evaluation of traffic signal control. Delay costs are another essential cost component. Accident costs are relatively a small share in comparison to the other two components. However, this statement about accident costs is based on only two test sites because of the missing data at the other two sites. Energy consumption and environmental costs are dominant at signalised pedestrian crossings, while delay costs dominate at intersections.

- **Under an equal weighting of all evaluation criteria, it is optimum for the whole traffic system if the traffic signal system at a signalised pedestrian crossing is coordinated with neighbouring intersections.**

At signalised pedestrian crossings, integration into the coordination with neighbouring intersections can significantly reduce the delay costs for motorised private transport, but may lead to higher costs for crossing pedestrians and cyclists. Under an equal weighting of all evaluation criteria, a signal program with coordination is optimum for the whole traffic system. A high particular weight for pedestrians (and cyclists) is necessary in order to reduce the delays for crossing pedestrians and cyclists.

- **At signalised intersections, no general recommendations can be given for the design of traffic signal control.**

Under an equal weighting of all evaluation criteria, the cost-effective solution according to the evaluation method is different between two investigated signalised intersections. The design of traffic signal systems at intersections varies from case to case. It can also be observed that public transport priority can significantly reduce the delays for public transport and the related delay costs. It can but does not necessarily cause disadvantages for the whole traffic. Instead, it leads to a shift of delays from public transport to other modes.

- **Generally speaking, there is no particular weighting of evaluation criteria and their related costs.**

Particular weighting of evaluation criteria should be avoided as much as possible since it causes bias to evaluation results. Only in a particular case, the weight can be adjusted moderately under the support of plausible planning or political reasons. A careful justification is necessary.

- **It is not possible to replace the emission modelling with more simplified calculation method that estimates emissions based on the correlation between delays and emissions.**

Although there are close correlations between delays and emissions at each test site, there is no linear function that is generally valid for all cases. The correlation varies depending on the type of a traffic signal system, the traffic period and the traffic volumes. Therefore, the emission modelling is still recommended for measuring air pollutant emissions in the evaluation of traffic signal control.
6 Recommendations for Applying the Evaluation Method in Practice

6.1 Introduction

The primary goal of this chapter is to discuss how the evaluation method D-MoTSE developed in this study can be further applied to the practice of transport planning and traffic engineering. The evaluation method described in Chapter 4 has already been applied to four case studies, as illustrated in Chapter 5. They are either single intersections or road sections. Based on the experiences gained from the case studies, Section 6.2 describes the application areas of D-MoTSE. Later on, Section 6.3 discusses the opportunities that promote the its application as well as the potential challenges in the application process.

6.2 Application Areas

6.2.1 General Issues

The application areas of D-MoTSE are defined based on an analysis of its basic functions. Its work process is described in Chapter 4. Based on that, its basic functions can be summarised as:

- the **assessment** of the performance of traffic signal systems regarding multiple aspects
- the **presentation** of the evaluation criteria in monetary values and a comprehensive trade-off process between them
- the **comparison** of multiple alternative traffic signal programs/traffic measures related to signal control
- the **selection** of the appropriate alternative

Under consideration of the above-listed functions, four main application areas of D-MoTSE are identified, as shown in Table 36:

<table>
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<th>Application area</th>
<th>Time to conduct</th>
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<td></td>
<td>Planning phase</td>
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<td>Development of the traffic signal control</td>
<td>Offline</td>
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<td>Optimisation of the traffic signal control</td>
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<td>Revision of the traffic signal control</td>
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<tr>
<td>Quality management of the traffic signal control</td>
<td>Offline</td>
</tr>
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</table>

In the upcoming subsections, the application areas are described in details. The descriptions focus on solving four questions: how to apply, when to apply, where to apply and who is involved. Discussions on the online/offline operation and the planning/operation phase are given.
Further differentiation is made between the small scale (single intersections and road sections) and the large scale (corridors and networks). The investigation of a single intersection or a road section is comparatively simple while an application on larger scales (corridors and networks) is more complicated. Several challenges may be faced while applying D-MoTSE on corridors and networks.

First, an appropriate investigation area needs to be defined. Measures on corridors and networks can impact traffic volumes and flows in much larger areas than the exact locations where they are implemented. However, the larger the investigation area is, the more are the efforts required. Therefore, it is a trade-off between the measurement accuracy and efforts while defining the investigation area.

Second, if modelling tools are used for measuring evaluation criteria, decisions should be made as to what detailed they need to perform. For a single intersection or a road section, it is suggested in this study to use microscopic models for both traffic flows and emissions. However, mesoscopic or macroscopic models can be more suitable for investigating corridors or networks. The model scale depends on the size of the investigation area, the available resources for conducting modelling and the targeted accuracy. An individual decision needs to be made for each case.

Third, the superordinate effects of infrastructure projects and traffic control measures are of high importance for the investigation on a large scale. There can be significant changes in traffic volumes or the operation of public transport lines that need to be considered properly in the evaluation process. It is not only a challenge to model these effects accurately but also to integrate them into the evaluation framework. The following items still need to be clarified:

- complex causal relationships between parameters
- additional modelling and measurement tools
- ways to monetise new components (e.g. operation costs of public transport)
- ways to consider long-term cost components

6.2.2 Development of Traffic Signal Control

D-MoTSE can be applied to the development process of traffic signal control. It is applicable not only for planning a traffic signal system at a single intersection or a road section but also for planning multiple traffic signal systems in a corridor or a network.

For the case of a single intersection or a road section, it can be used for the comparison of alternative traffic signal programs and the selection of the most appropriate one for the corresponding traffic signal system. The first step to plan a traffic signal system is to develop the corresponding traffic technical solution (Noll and Albrecht, 2010). When there are multiple alternative signal programs available, D-MoTSE can be used to evaluate their performances regarding the predefined goals. The best solution is then selected based on the evaluation results.

For the case of a corridor or a network, the evaluation target is multiple traffic signal systems. The focus can be laid on a traffic control measure that is planned for the multiple traffic signal systems, e.g. a public transport priority, a coordination and a cycle superhighway. The evaluation method can be applied to evaluate the various impacts of the traffic control measure on different traffic modes and summarise them to an overall result for the whole traffic system. As described in Subsection 6.2.1, the superordinate effects should be considered appropriately. The evaluation results can be further used for comparing the cases with and without the traffic control measure. Recommendations are derived accordingly on whether the traffic control measure should be implemented and how it should be designed.

One option of implementing the evaluation method is to conduct a separate evaluation as done in the framework of this study. The work process is described in Chapter 4. Besides, it is possible to integrate the evaluation method into the existing planning tools for traffic signal systems. The parameters used in D-MoTSE are partially available in the existing tools. There are already interfaces between the planning
tools and microscopic traffic flow models, which are also used in D-MoTSE for measuring delays. Besides, a tool for calculating accident costs and an emission model should also be integrated for evaluating traffic safety and environmental impacts. For the case of corridors and networks, transport demand models are needed additionally and linked to the planning tools in order to model dynamic transport demands. In summary, an additional evaluation module for planning tools of traffic signal systems can be developed based on D-MoTSE in the future.

The development of traffic signal control is conducted offline in the planning phase. So is the evaluation in the framework of the development process as well. The concerned stakeholders are the authority that is responsible for planning and operating traffic signal systems and the engineering office which is responsible for developing traffic signal programs. Furthermore, the companies or institutes that develop planning tools for traffic signal systems can also be involved if the evaluation method is going to be integrated as an additional module.

6.2.3 Optimisation of Traffic Signal Control

One possibility for applying the evaluation method in the optimisation of traffic signal control is to use the concept of D-MoTSE as a reference for building the performance index for the optimisation of traffic signal programs. The performance index is part of the optimisation method that evaluates the performance of the generated solutions. Iteration is conducted to search for the solution with the best performance. Due to the complexity of the evaluation method and the performance index accordingly, a relatively high effort is required to measure the evaluation criteria.

Another possibility for the application is a relative optimisation under consideration of the constraints at intersections. The relative optimisation does not target the most optimal solution of all possible signal programs. Instead, it aims to identify the relative optimal solution among a meaningful solution pool for traffic signal programs. Therefore, it is essential to develop a solution pool that covers a wide range of meaningful alternative traffic signal programs that are suitable for the target signal system (or systems). The framework conditions and goals that are analysed in the first step of the evaluation method can serve as a basis. Then the evaluation method can be applied to select the most suitable solution by comparing the performances of the alternative signal programs in the solution pool. The general work flow, as described in Chapter 4, is applicable here. The main benefit of the relative optimisation is to save the time and cost efforts for the optimisation process. In practice, it is especially meaningful since the authority often has limited resources.

It is possible to apply the evaluation method on the optimisation of a single traffic signal system or multiple traffic signal systems. Besides, the optimisation of traffic signal control can be conducted both offline in the planning phase and online in the operation phase.

An example for the online optimisation in the operation phase can be the adaptive traffic control system. This kind of control system adjusts, in real-time, signal timing plans based on the current traffic conditions, demand, and system capacity (Stevanovic, 2010, p. 5). The performance indices of some established adaptive control systems are summarised in Subsubsection 3.4.2. The performance indices can be widened based on the principles and formulas of D-MoTSE to have a more comprehensive evaluation and optimisation of signal timing plans.

The participated stakeholders can be the authority, the engineering office, as well as the companies or institutes that develop tools for the optimisation of traffic signal control.

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20 It is in the case of a single intersection or a road section.
21 It is in the case of a corridor or a network.
22 It is mostly operated on a large scale. However, at a single intersection or road section is also possible.
6.2.4 Revision of Traffic Signal Control

A revision of the traffic signal control in the operation phase is necessary when there are significant changes in the framework conditions of the corresponding control systems, or acute deficiencies are identified. The primary function of the evaluation method in this context is to compare the performances of the current signal program under operation and other alternative signal programs. Based on the evaluation results, recommendations for revising traffic signal systems can be derived. If there are significant changes in the framework conditions of the corresponding control systems, they can be comprehensively considered in the evaluation method.

The application process in the revision of traffic signal control generally follows the process described in Section 4.12. It is generally similar to that of the development of traffic signal control. An essential difference is that the current signal program under operation can serve as the basis for developing other alternative signal programs. Besides, there are many other data available in the operation phase that can support the evaluation, including the process data of controllers, the operation and defect data, the data from the operation system of public transport and traffic accident data in reality.

Application on a small investigation area or a large area is both possible. The challenges for the application on a large scale are already discussed in Subsection 6.2.1.

The possible stakeholders are the authority that operates traffic signal systems, the engineering office that gives technical support or the company that is responsible for the maintenance of traffic signal systems.

6.2.5 Quality Management of Traffic Signal Control

With the quality management of traffic signal control, it should be achieved that the goals of high traffic safety and good traffic flow are permanently met (FGSV, 2015b, p. 78). As given in the German guideline for traffic signal control (FGSV, 2015b, p. 78), important parameters to evaluate traffic flow quality are delays and the number of stops. Fuel consumption and parameters for air quality are other important parameters that are related to the traffic flow quality. Parameters for traffic safety are the number and the severity of traffic accidents.

The developed evaluation is suitable for the quality management of traffic signal control since it enables a comprehensive evaluation of traffic signal control under consideration of many parameters mentioned above. It is suitable not only in the planning phase but also in the operation phase. In the planning phase, it can be applied to ensure a comprehensive planning of traffic signal systems. In the operation phase, it can be used to examine the impacts of traffic signal systems on different aspects and to check the performance of the current signal program under operation. In the case of inadequate performance, a revision of the traffic signal system is necessary. The description can be found in the corresponding paragraph.

The participated stakeholders for the quality management are the authority that is responsible for the planning and operation of traffic signal systems and the engineering office that is responsible for the planning of traffic signal control.

6.3 Opportunities and Challenges in the Application

Applying D-MoTSE in practice faces both opportunities and challenges from various aspects.

The first aspect concerns the focus of transport politics towards multiple goals and road users. Besides traffic quality and safety, environmental impacts from transport are gaining more and more concern from the political point of view in recent years. Measures have been implemented to reduce emissions from the transport sector and to improve air quality in the urban area, such as low emission zones and
environment-responsive traffic control measures (Boltze, Jiang, et al., 2014; Diegmann, 2014). The environmental alliance, including walking, cycling and public transport, is another major topic of the politic. These traffic modes are given the highest priority in urban street user hierarchy in many countries (E. L. Fischer et al., 2010, p. 12). Besides, the rising awareness of health issues is another important trend in the future changes of lifestyles and values (Boltze, 2016). It also strengthens the need for efficient environmental and climate protection. These trends in transport politics open up the opportunity to comprehensively consider the multiple goals and road users in the design of traffic signal control.

The second aspect is the availability of data that are used in D-MoTSE. Most of them are already collected and used for planning traffic signal control, such as the layout plans of intersections, traffic volumes of motorised vehicles, the timetables of public transport lines and traffic accident data. Besides, these data are also required for other purposes of transport planning and traffic engineering. However, some data are still unavailable, such as the traffic volumes of pedestrians and cyclists as well as the occupancy rates of public transport vehicles. It takes additional efforts to collect these data, which can be a challenge for the implementation in practice. According to Boltze (2016), digitisation and networking are two important trends in the future technological development in the transport section. These two aspects can enable an easier access to the required data and, therefore, promote the usage of D-MoTSE.

The third aspect is the availability of measurement tools. The measurement methods suggested in D-MoTSE include a microscopic traffic simulation model and emission model. The microscopic traffic simulation model is a tool that is commonly owned by traffic engineering offices and widely used for various purposes. Emission models are less common but becoming more important as environmental issues are gaining more concern in transport politics. The required measurement tools can be more widely available in the future, along with the further development of digitisation and networking in the future. Owning the necessary modelling tools is not a big challenge, but developing models for concrete cases is. It takes lots of efforts not only to build models but also to verify them. For this purpose, additional data are required, such as the process data of traffic signal systems, video recording of the test sites and data about travel speed. It also means more challenges in collecting data.

The fourth aspect is the possibility to integrate the developed method in the existing planning tools for traffic signal systems. It can be treated as a chance for its implementation in practice. The tools often already have own modules to evaluate (or optimise) traffic signal programs and have interfaces to microscopic traffic simulation models. Take two widely implemented tools in Germany, LISA+ and Crossig, as an example. Both programs can simulate traffic signal control logics and have interfaces to the microscopic traffic simulation model Vissim. LISA+ also has evaluation and optimisation function for signal programs.

The difficulty to evaluate safety aspects can be treated as a challenge for implementing D-MoTSE in practice. The main difficulty is to quantify the effects of traffic control measures on traffic safety and quantify the changes in accident costs. There are very few measurement methods and reference values available.

Valuing superordinate effects is another challenge for implementing D-MoTSE on corridors or networks. First, it is difficult to determine to what extent the effects are considered. Second, interfaces between transport demand models and microscopic traffic flow models are required. Third, it is required to quantify the operation of public transport and apply furthermore on a microscopic level.

At last, another challenge comes from the organisation to implement D-MoTSE. Extra staffs or costs may arise from its implementation. Besides, close cooperation between multiple stakeholders is necessary since the evaluation method covers a wide range of transport aspects. Possible stakeholders include transport authorities, traffic engineering offices and public transport operators, for example.
6.4 Conclusions

The following conclusions can be made based on the qualitative analysis on the application of D-MoTSE in practice.

- **The evaluation method can be widely implemented in the planning and the operation phase of traffic signal systems concerning their development, optimisation, revision and quality management.**

  For all four application areas, the core working process for applying the evaluation method remains similar and generally follows the work process described in Section 4.12. There can be some differences in the data collection and the development of alternative signal programs depending on the time (planning or operation phase) and the individual features of each case. It is possible to either conduct the evaluation separately or integrate it into the planning tools of traffic signal systems and the adaptive signal control.

- **Application of the evaluation method on a large investigation area (a corridor or a network) is possible but faces several challenges.**

  The evaluation method can be applied both on a small and a large application area. The challenges for applying it on a large area include the definition of the appropriate investigation area, the selection of the suitable modelling tool and the consideration of superordinate effects.

- **The future technological development in the transport sector and the changes in lifestyles and values can promote the usage of D-MoTSE.**

  With the future technological development in the transport sector, such as digitalisation and networking, the required data and measurement methods for conducting the evaluation can be more easily accessible. Besides, the rising concern on environmental and climate protection as well as the rising awareness of health issues are essential future changes in lifestyles and values. All these factors can promote the usage of D-MoTSE.

- **Further research on D-MoTSE is necessary since its application still faces challenges from multiple aspects.**

  Challenges for the application include high efforts required to develop validated simulation models for test sites, the difficulties in measuring traffic safety, the difficulties in quantifying superordinate effects and the requirement on close cooperation between multiple stakeholders. Further research is, therefore, necessary in order to clarify these issues.
7 Conclusions and Outlook

7.1 Conclusions

Recently, the welfare of various road users and the various impacts of road transport are gaining more concern from the political point of view while designing traffic signal control. In correspondence to this, this thesis has developed an evaluation method for traffic signal control that integrates multiple evaluation criteria and traffic modes into one framework and values them quantitatively. The developed evaluation method was further applied to four single traffic signal systems as case studies. Furthermore, a qualitative analysis was conducted on the potential application of the evaluation method in practice. The main results gained from the development and the application of the evaluation method are summarised in the following paragraphs as key statements with supplementary explanations.

• Currently, the evaluation of traffic signal control is often one-dimensional without sufficient consideration and a fair balance between various impacts on multiple traffic modes.

  In general, there are four main goals for traffic signal control, including satisfaction of mobility needs, increase of traffic safety, reduction of environmental pollution as well as improvement of economic efficiency. In the meanwhile, traffic signal systems serve users of different traffic modes, including walking, cycling, public transport, motorised private transport and heavy transport. Conflicts of interest may occur not only between different goals and their belonging criteria but also between different traffic modes, which need to be considered comprehensively and transparently in the evaluation of traffic signal control. A fair balance is necessary. However, the review of the existing evaluation methods shows often one-dimensional focus on the traffic flow quality and the limited multi-modal analysis. In general, the deficiencies identified in the existing evaluation method confirm the need to develop a new evaluation method.

• The developed evaluation method can provide a comprehensive judgement on the overall performance of traffic signal control through the monetisation and the weighted aggregation of different evaluation criteria for multiple traffic modes.

  The developed evaluation method integrates multidimensional evaluation criteria in its framework in order to have a comprehensive assessment of traffic signal control. The selected evaluation criteria include the average delay for road users of different traffic modes, the number of traffic accidents, slight injuries, serious injurious and deaths as well as PM, NO\textsubscript{x}, CO\textsubscript{2} emissions and fuel consumption. The microscopic traffic flow simulation and the emission modelling are generally suggested for measuring the evaluation criteria related to traffic flow quality and environmental aspects both in the planning and operation phase.

  The measured evaluation criteria in original values are further monetised using established cost rates that are derived from the existing literature for a simple aggregation and a good comparison. Particular weights are then assigned to each cost component while aggregating them to the total cost. The aim of introducing particular weights in the evaluation is to reflect the priority for specific traffic modes or aspects due to political or planning reasons. Separate consideration of cost components and their corresponding particular weights helps to make the trade-off process transparent and comprehensive. It must be emphasised that a deviation of the particular weights from the equal weighting should be avoided as much as possible. Besides, the cost rates and particular weights can be adjusted dynamically under different situations so that the evaluation results can respond to the real-time changes in traffic, environmental or other situations.
Additionally, it is possible to consider the potential superordinate effects, such as traffic shifts and the impacts on public transport operation, in the developed evaluation method. However, it must be emphasised that some other measures are more suitable than traffic signal control in affecting people’s mode choices, such as pricing, regulatory policies and information. At the end of an evaluation, a sensitivity analysis is conducted to test the robustness of the evaluation results and the derived recommendations for designing traffic signal control.

- The evaluation method can be widely implemented in the planning and operation phase of traffic signal systems concerning their development, optimisation, revision and quality management.

The four main application areas of the developed evaluation method are the development, optimisation, revision and quality management of traffic signal control. Although there may be some differences in the data collection and the development of alternative signal programs, the core working process of applying the evaluation method remains similar. It is possible to either conduct the evaluation separately or integrate it into the planning tools of traffic signal systems and the adaptive signal control. The evaluation method can be both applied on a small or a large investigation area. However, the application on a large application faces challenges concerning the definition of the appropriate investigation area, the selection of the suitable modelling tool and the consideration of superordinate effects. In the future, the developed evaluation method gets more chances for application since the future technological development in the transport section and the changes in lifestyles and values can promote its usage.

- The application of the developed evaluation method on case studies shows that the number of persons that are present at a traffic signal system has a significant impact on the design of traffic signal control.

A calculation of the traffic volumes in persons instead of vehicles can give a better overview of the road users of all traffic modes at a traffic signal system. They can serve as a primary input for the design and evaluation of traffic signal control. According to the results of four case studies, both the total number and the distribution of persons among traffic modes vary significantly between different test sites. They also have unique daily patterns. However, the distribution of persons among different traffic modes at test sites is quite different to the traditional modal split calculated using the number of trips in the way that the share of walking and cycling is much lower. The main reason is that trips by walk or cycle cover generally short distances and pass through less traffic signal systems.

- It is observed from the evaluation results that energy consumption and environmental costs are an essential cost component and should not be neglected in the evaluation of traffic signal control.

The evaluation results show that energy consumption and environmental costs take up at least one-third of the total cost, and should, therefore, not be neglected in the evaluation of traffic signal control. At signalised pedestrian crossings, energy consumption and environmental costs are even dominant among all cost components. The emission modelling is recommended for measuring air pollutant emissions in the developed evaluation method. Although there are close correlations between delays and emissions at each test site, there is no linear function that is generally valid for all cases. Therefore, a simplified calculation of emissions based on delays is not possible.

- The evaluation results can be used for the comparison of alternative traffic signal programs and the selection of the optimum solution for a traffic signal system. Recommendations for designing the traffic signal control can be derived accordingly.

According to the evaluation results at two signalised pedestrian crossings, integration into the coordination with neighbouring intersections can significantly reduce the delay costs for motorised
private transport, but may lead to higher costs for crossing pedestrians and cyclists. Under an equal weighting of all evaluation criteria, a signal program with coordination is optimum for the traffic signal system at a pedestrian crossing. A high particular weighting for pedestrians (and cyclists) is necessary in order to further reduce the delays for crossing pedestrians and cyclists. At signalised intersections, it can be observed that public transport priority can significantly reduce the delays for public transport and the related delay costs. It can but does not necessarily cause disadvantages for the whole traffic. Instead, it leads to a shift of delays from public transport to other modes. However, no general recommendations can be provided for the design of traffic signal control at signalised intersections. The appropriate solution varies from case to case.

• **Generally speaking, an adjustment of the particular weighting for evaluation criteria should be avoided.**

Generally, there should be an equal weighting of all evaluation criteria so that the evaluation results are not biased towards any specific goal. Only in special cases, the weighting can be adjusted moderately with the support of plausible planning or political reasons. Careful justification is always necessary.

### 7.2 Outlook

The developed evaluation method provides a fundamental framework on how to combine multiple criteria concerning different goals and traffic modes in the evaluation of traffic signal control. A successful application still faces challenges from multiple aspects. A further improvement of the method is, therefore, expected in multiple directions.

• **Further research on the evaluation of traffic safety is desirable.**

More accurate quantification of safety costs can improve the accuracy of evaluation results. In the existing research, it has not been deeply investigated what the impacts of planned measures on traffic safety and the related costs are. There are also great difficulties to quantify those impacts. Further research on this issue can be conducted based on empirical accident data.

• **It is desirable to get more data about the occupancy rates of public transport vehicles.**

The number of persons that are present at a traffic signal system has a significant impact on the design of traffic signal control. As a crucial data input for the evaluation method, it is closely related to the prioritisation of public transport at traffic signal systems. There is a lack of reliable data on the occupancy rates of public transport that can be used in this study. It is, therefore, desirable to get more data in the future application of the evaluation method. It is even better if there could be detailed occupancy rates of public transport vehicles that vary according to time and lines. They are especially useful for an online application of traffic signal control, but currently not available.

• **The consideration of superordinate effects in the evaluation needs to be further explored.**

Further exploration of this topic is possible in many directions. Here, only two points are pointed out as an example. First, the combination of multiple modelling tools on different levels for assessing the traffic-related parameters, e.g. the transport demand model and the microscopic traffic flow simulation model, requires further exploration. The working process needs to be defined. The data input and output of each model need to be cleared, as well as the interface between them. Second, the assessment of the operation of public transport needs to be clarified. The questions that need to be clarified include: how to quantify the changes in operation and staff plan of public transport, how to value the related costs and how to assess the secondary impacts on the attractiveness of public transport mode and the total mode split.
• The evaluation method can be further developed so that it can give an absolute statement about the performance of traffic signal control.

A possibility for further development is to judge the performance of traffic signal control based on the costs per person, such as the average delay/average accident/average environmental/total cost per person. An essential task will be to define the threshold costs that are used to categorise the performance (e.g. excellent, good, satisfied, insufficient). Implementation of this evaluation method on a large number of case studies can gather useful information to achieve it. The threshold values in HCMs can also be used as a reference.

• The application of the evaluation method in practice can be further explored.

An in-depth investigation of this topic can increase the chances for a successful application of the method and promote its usage. Following questions need to be clarified: how to integrate the evaluation method in the existing planning and management process of traffic signal systems, what hardware and software facilities are necessary for its application, what required input data are available and what is missing, what are the cost and work efforts for applying the method in practice.

In summary, all the topics mentioned above require the support from relevant case studies. It is, therefore, desirable to conduct more case studies, from small intersections to large networks, in order to improve the evaluation method and widen its application areas.
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List of Abbreviations

AADT  Average Annual Daily Traffic.
AHP  Analytic Hierarchy Process.
ALPR  Automatic Licence Plate Recognition.

BALANCE  Balancing Adaptive Network Control Methode.
BASl  Bundesanstalt für Straßenwesen.
BMVI  Bundesministerium für Verkehr und digitale Infrastruktur.
BOStrab  Verordnung über den Bau und Betrieb der Straßenbahnen.
BVWP  Bundesverkehrswegeplan.

DeGEval  Gesellschaft für Evaluation.
DM  Deutsche Mark.

EAÖ  Empfehlungen für Anlagen des öffentlichen Personennahverkehrs.
EFA  Empfehlungen für Fußgängerverkehrsanlagen.
EPICS  Entire Priority Intersection Control System.
ERA  Empfehlungen für Radverkehrsanlagen.
EWS  Empfehlungen für Wirtschaftlichkeitsuntersuchungen an Straßen.

FCD  Floating Car Data.
FGSV  Forschungsgesellschaft für Straßen- und Verkehrswesen.

HAWK  high intensity activated crosswalk.
HBEFA  Handbook Emission Factors for Road Transport.
HBS  Handbuch für die Bemessung von Straßenverkehrsanlagen.
HCM  Highway Capacity Manual.
HDV  heavy duty vehicle.
HEATCO  Developing Harmonised European Approaches for Transport Costing and Project Assessment.
HVS  Das Handbuch für die Bewertung der Verkehrssicherheit von Straßen.

LCV  light commercial vehicles.
LOS  level of service.

MiD  Mobilität in Deutschland.
MOTION  Method for the Optimisation of Traffic Signals In On-line Controlled Networks.
OPAC  Optimisation Policies for Adaptive Control.

PELICAN  pedestrian light-controlled crossing.

PrT  motorised private transport.

PUFFIN  pedestrian user-friendly intelligent.

PuT  public transport.

RAS\textbf{t} 06  Richtlinien für die Anlage von Stadtstraßen.

RLSA  Richtlinien für Lichtsignalanlagen.

RLS-19  Richtlinien für den Lärmschutz an Straßen.

RLuS  Richtlinien zur Ermittlung der Luftqualität an Straßen ohne oder mit lockerer Randbebauung.

SCOOT  Split Cycle Offset Optimisation Technique.

StVG  Straßenverkehrsgesetz.

StVO  Straßenverkehrs-Ordnung.

TCQSM  Transit Capacity and Quality of Service Manual.

TNO  Netherlands Organisation for Applied Scientific Research.

TRANSYT  Traffic Network Study Tool.

UBA  Umweltbundesamt.

US-HCM  United States version of HCM.

UTOPIA  Urban Traffic Optimisation by Integrated Automation.
Appendices

A Measurement Methods

A.1 Calculation

Method in HBS

FGSV (2015a) describes a method to assess the delays for different road users and queue lengths at intersections, which serve as a basis for evaluating the LOS of road infrastructures. The required input data for assessment include traffic volumes, the geometric design, the signal timing and other conditions. An interim result of the assessment is the saturation degree of green time, which can be used further to assess the efficiency of a traffic signal system. For public transport vehicles on separated lanes, the average delay can be derived from the red time defined in the traffic signal program. For pedestrians and cyclists, the maximal delay is calculated and used instead as the evaluation criteria. The calculation method in HBS has limited application areas. It is not suitable for applying on adaptive traffic signal control with a very complicated structure and multiple intervention possibilities.

Derivation from delays and stops

A direct calculation of comfort is difficult in the planning stage. It relates strongly to other traffic parameters such as the delays and the number of stops. A rough estimation of comfort based on them is generally possible. However, the result has a relatively low accuracy since comfort is a qualitative parameter influenced by many other factors.

Method in HVS (draft)

A draft version of the handbook HVS described a method to assess and optimise the safety level of a road infrastructure (Weber, 2012). It was developed by a project group of BASt. The method in HVS uses the safety degree as the criterion to describe the safety level (Bark et al., 2008). It is derived from two cost components. The first one is basic accident cost rates that are predefined in the handbook and applicable for a type of intersection with the standardised design. The second is a group of surcharges to the basic cost rates if specific infrastructure elements are missing and the safety level is influenced accordingly.

Accident analysis with data under similar situations

The accident analysis is implemented widely to identify the safety deficiencies of road infrastructures in the operation stage. The basis for the accident analysis is existing accident data that are registered by the police. However, such kind of data basis is missing in the planning stage. Instead, established data under a similar situation can be used for a rough orientation of the accident costs. As an example, Baier et al. (2012) evaluated the impacts of the forms of left-turning vehicles on the safety level of intersections. The results can be used as an orientation for other intersections.

Evaluation of safety level using point system (qualitative)

There are a lot of factors that may influence the safety level of intersections, including traffic parameters, the geometric design and other environmental conditions. Analysing the influencing factors using a point system may give a qualitative orientation of the safety level. An exemplary study is Cheranchery et al. (2015), which developed such a point-based evaluation method for bus stations in India.
Method in RLuS 2012

The method in FGSV (2012b) is used to estimate the ambient air quality at road sections with a speed limit of 50 km/h where there are no or loosened neighbouring buildings. The method can be implemented in other areas under the usage of tunnel, intersection and shielding module. But it does not aim at an exact calculation of the ambient air quality. Instead, it just gives a rough estimation of the annual average value and the number of days when legal threshold values are exceeded.

Method in RLS-19

The method in RLS-19 is used in Germany as the standard method to quantify the noise level in the transport sector. At intersections, an additional surcharge is applied to consider the impacts of intersections on noise. However, its value depends not on the settings of traffic signal control. In the international context, there are many other methods to calculate the noise in the transport sector available, including ISO9613-2 (international), MPB/XPS 31-133 (France) and TNM (USA) (Probst, 2010).

A.2 Modelling (Online and Offline)

Traffic flow simulation

Microscopic traffic flow simulation can measure traffic parameters in a more detailed manner than the method in HBS. It can not only simulate the individual behaviours of single vehicles and their drivers as well as the interactions between them. Network elements are not only considered but also drawn graphically in the simulation. Virtual detectors can be set up in the simulation in a similar way as the detector systems in reality. The recorded data by detectors can be used not only for controlling traffic signal systems but also for analysing traffic flows. Besides, the simulation enables a virtual observation and a recording of traffic flows in networks. The simulation results cover up a wide range of traffic parameters, which can be further differentiated according to traffic modes, types, investigation areas and time. Besides, vehicle trajectory data are documented in the simulation and serve further as the input for emission modelling. There are many established simulation software programs in the scientific and commercial context. Vissim developed by PTV AG is a widely implemented software in Germany. Other well-known examples are Crosim, Transms, Matsim, Integration, Hutsim and Sumo (Dallmeyer, 2014).

Modelling of accident frequency

Only a few studies about modelling the accident frequency are found in the literature. An exemplary study is Aurich (2013), which developed a model to predict the number of accidents within the main road network in the downtown area of Dresden city using generalised linear regression analysis. The applicability of the method on other cases was not examined in the study. Archer and Kosonen (2000) has analysed the potential of applying the traffic flow simulation on the analysis of traffic safety. The main identified problems are the identification of influential factors on traffic safety and the accurate modelling of travel behaviours with sufficient complexity in the simulation model.

Emission modelling

Emission models can be distinguished between macroscopic and microscopic emission models depending on their integration level. Macroscopic models estimate the emission factors of fuel combustion based on strongly integrated traffic situations (Kohoutek, 2010, p. 34). Then, the total emissions are calculated using the emission factors, the AADT and the share of heavy transport. In Germany, Austria and Switzerland, HBEFA is a widely implemented macroscopic emission modelling of road transport. In microscopic models, the emissions from fuel combustion are however calculated under consideration of the behaviours of individual vehicles in a predefined investigation period (Kohoutek, 2010, p. 34). The input data are the detailed speed-time profile of individual vehicles that are collected with the traffic survey.
or the traffic flow simulation. Widely implemented examples of emission modelling include VERSIT+, PHEM and the microscopic part of MOVES. The microscopic emission modelling is more applicable for investigations related to traffic signal systems than the macroscopic simulation since the aggregated traffic situations do not comply with the detailed level of traffic signal control.

**Modelling of ambient air quality with dispersion models or with statistical models**

Dispersion models are an important tool to estimate ambient air quality based on the physical and chemical mechanisms about how air pollutants disperse in the ambient environment. There are many existing examples for dispersion modelling, including IMMIS\textsuperscript{Luf t}, PROKAS\_B, CPB, OSPM, LASAT and MISKAM (Neunhäuserer et al., 2011). Another possibility is to use statistical models that are based on the statistical cause-effect-relationships between ambient air quality and other factors. An exemplary study is Kohoutek (2010, pp. 36-39) that developed such kind of models using the multiple regression analysis. An overview of other related studies is given in (Kohoutek, 2010). Due to the complex mechanisms of air pollution dispersion and a large number of influencing factors, modelling of ambient air quality requires a high effort for data collection and processing.

### A.3 Measurement

**Derivation from existing data**

It is possible to derive traffic parameters from process data of traffic control devices, operation and fault data as well as data from the operation control system of public transport. Process data can be used to measure many parameters that describe traffic flows, such as the travel time of public transport, maximal delays for pedestrians and cyclists, the saturation degree and others (Bley and B. Friedrich, 2016). However, not all parameters can be derived in this way, such as the average delay for vehicles. The analysis of operation and fault data aims mainly to evaluate the operating status and the causes for deficient quality of traffic flows (FGSV, 2014). For public transport, the computer-aided operation control system can document the real-time location of public transport vehicles. Accordingly, delays for them can be derived based on real-time location data. The occupancy of vehicles can also be gathered by the control system if the corresponding devices are installed. It requires a low effort to collect the above-mentioned data that already exist in the control systems, no matter for traffic signal control or public transport.

**Observations**

Observations aim to collect the external characteristics and visible traffic behaviours on roads (FGSV, 2012b). The following parameters related to traffic safety can be measured through observations: e.g. situation responsive compliance to traffic rules, analysis of conflicts as well as distance, speed and acceleration behaviours. They can be further used to estimate the safety level of an intersection. Observations can be conducted by observers on-site or through video devices. Both options require high efforts.

**Use of measurement devices**

Measurement devices can be applied to gather traffic parameters on site. The measurements can be conducted automatically or manually. Automatic devices can be applied for example to measure local travel speeds of vehicles. There are different types of devices to choose from which have different levels of accuracy: radar, induction or video devices. Radar devices are in priority if the results should have a high accuracy (FGSV, 2012b, p. 50). Manual measurements need to be conducted by people on site. Possible devices are stopwatches and radar pistols.
Surveys

Traffic surveys are the main method to measure comfort in the operation stage since personal opinions and wishes of road users can be gathered through this method. It can also be applied to estimate traffic safety. However, the results are relatively subjective as road users are asked about their feelings of safety on roads in surveys. Surveys can be conducted in various places. Accordingly, surveys can be differentiated between households surveys, surveys at activity places, surveys in traffic systems, company surveys and surveys of vehicle owners (FGSV, 2012b). No matter at which place, high efforts are required if interviews are conducted on-site by staffs.

Measurement runs

Measurement runs with vehicles can be used to measure not only traffic parameters, such as travel time, speeds and the number of stops but also emission data. Vehicles installed with measurement devices can run through the whole investigation area and document the results for test runs, which have a high accuracy (Boltze, Kohoutek, and Krüger, 2011). However, the number of test runs are limited and inaccuracy may arise due to the relatively small sample size if the results are used for general issues.

Measurement at roadside

Measurement devices can be installed on the roadside to measure the ambient air quality and noise level at hotspots. There exists already a wide monitoring network in Germany with more than 600 stations, which measure ambient air quality continuously. Measured air pollutants include particles (PM$_{10}$, PM$_{2.5}$), NO$_2$, O$_3$ and others. The data have different types (average value, number of exceedance days) and can be aggregated on different levels (e.g. hourly, daily, monthly and yearly). The air quality data are available online. It takes low efforts to obtain and apply the data. Besides the long-term monitoring stations, mobile measurement devices can be applied in case of individual investigations. The advantages of mobile devices are the flexibility of the application. However, their application period is limited and high efforts are required.

Vehicle pattern recognition

The vehicle pattern recognition can be applied to measure travel time and speeds of vehicles on road sections. The principle of this method is to recognise a group of vehicles at two measuring cross-sections that are located several kilometres between each other. The travel time is calculated as the difference between the time when the vehicles are recognised at the first and the second cross-section (FGSV, 2012b, pp. 50-51). The travel speed is derived with the calculated travel time and the distance between cross-sections. Vehicle pattern recognition can be conducted by induction loops. Although induction loops are already installed at many signalised intersections, it still requires high efforts to conduct this kind of analysis.

Automatic Licence Plate Recognition

Automatic Licence Plate Recognition is used to measure the travel time and speeds of vehicles on road sections or in networks. The principle of this method is to document the licence plates of all vehicles at the beginning and the end of the measurement sections. Accordingly, the time when each vehicle enters or leaves a measurement section can be derived. The time difference between them is the travel time of the vehicle on that measurement section. Licence plates recognition is conducted normally through video techniques. Under consideration of the economic aspects, this measurement method should only be applied to very comprehensive and specific tasks. (FGSV, 2012b, p. 51)
Analysis of Floating Car Data

Floating car data can be used to calculate travel speeds and time (Haspel and Nöth, 2007). The principle of this method is to identify the location of vehicles within predefined time intervals and calculate traffic parameter on that basis. As an example, Neumann and Wagner (2012) has used the floating car data to estimate queue lengths at traffic signals. Collecting and analysing floating car data requires generally high efforts.
### B Summary of Possible Evaluation Criteria

<table>
<thead>
<tr>
<th>Main goals</th>
<th>Parameters</th>
<th>Evaluation criteria</th>
<th>Related traffic modes</th>
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<tbody>
<tr>
<td>Satisfaction of mobility needs</td>
<td>Delay for vehicles</td>
<td>Average delay for vehicles [s]</td>
<td>Motorised private transport</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Maximal delay for vehicles [s]</td>
<td>Heavy transport</td>
</tr>
<tr>
<td></td>
<td>Delay for individuals</td>
<td>Average delay for individuals [s]</td>
<td>Public transport</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Maximal delay for individuals [s]</td>
<td>Cycling</td>
</tr>
<tr>
<td></td>
<td>Number of stops</td>
<td>Average number of stops [ ]</td>
<td>Walking</td>
</tr>
<tr>
<td></td>
<td>Queue lengths</td>
<td>Average queue lengths at approaches [m]</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Comfort</td>
<td>Maximal queue lengths at approaches [m]</td>
<td></td>
</tr>
<tr>
<td>Increase of traffic safety</td>
<td>Number of traffic accidents</td>
<td>Number of traffic accidents (annual, three years or five years) [ ]</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Number of slight injuries</td>
<td>Number of slight injuries (annual, three years or five years) [ ]</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Number of serious injuries</td>
<td>Number of serious injuries (annual, three years or five years) [ ]</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Number of deaths</td>
<td>Number of deaths (annual, three years or five years) [ ]</td>
<td></td>
</tr>
<tr>
<td>Reduction of environmental pollution</td>
<td>Emissions of air pollutants</td>
<td>PM emissions from vehicles [g]</td>
<td>Heavy transport</td>
</tr>
<tr>
<td></td>
<td></td>
<td>NOx emissions from vehicles [g]</td>
<td>Motorised private transport</td>
</tr>
<tr>
<td></td>
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<td>PM ambient concentration [µg/m³]</td>
<td>Walking</td>
</tr>
<tr>
<td></td>
<td></td>
<td>NOx ambient concentration [µg/m³]</td>
<td>Cycling</td>
</tr>
<tr>
<td></td>
<td>Noise level</td>
<td>Noise level [dB(A)]</td>
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<tr>
<td></td>
<td>Energy concentration</td>
<td>Fuel consumption of combustion vehicles [l]</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>Power consumption of electric vehicles [kW·h]</td>
<td></td>
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<tr>
<td></td>
<td>CO2 emissions</td>
<td>CO2 emissions from vehicles [g]</td>
<td>Motorised private transport</td>
</tr>
<tr>
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<td>Average travel speed</td>
<td>Average travel speed in network [km/h]</td>
<td>Walking</td>
</tr>
<tr>
<td></td>
<td>Saturation degree of green times</td>
<td>Volume-capacity-ratio [ ]</td>
<td>Cycling</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Occupancy time of detectors [ ]</td>
<td>Public transport</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Comparison of volum-capacity ratios between phases and signal groups [ ]</td>
<td>Motorised private transport</td>
</tr>
</tbody>
</table>
### C Emission Factors for Resuspension and Wear

Table 37: Emission factors for resuspension and wear corresponding to traffic situations of HBEFA 3.1
(source: Schmidt, Düring, and Lohmeyer, 2011, p. 63)

<table>
<thead>
<tr>
<th>Traffic situation</th>
<th>EF for resuspension and wear [mg/km]</th>
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<tbody>
<tr>
<td></td>
<td>Light transport</td>
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<tr>
<td>All rural traffic situations independent from speed limit and LOS</td>
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</tr>
<tr>
<td>URB/MW/, URB/Semi-MW/ independent from speed limit and LOS</td>
<td>30</td>
</tr>
<tr>
<td>URB/Distr/xx/Freeflow independent from speed limit</td>
<td>26</td>
</tr>
<tr>
<td>URB/Distr/xx/Heavy independent from speed limit</td>
<td>33</td>
</tr>
<tr>
<td>URB/Distr/xx/Saturated independent from speed limit</td>
<td>35</td>
</tr>
<tr>
<td>URB/Distr/xx/St+Go independent from speed limit</td>
<td>45</td>
</tr>
<tr>
<td>URB/Local/xx/Freeflow independent from speed limit</td>
<td>26</td>
</tr>
<tr>
<td>URB/Local/xx/Heavy independent from speed limit</td>
<td>33</td>
</tr>
<tr>
<td>URB/Local/xx/Saturated independent from speed limit</td>
<td>40</td>
</tr>
<tr>
<td>URB/Local/xx/St+Go independent from speed limit</td>
<td>45</td>
</tr>
<tr>
<td>URB/Access/30/Freeflow</td>
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<tr>
<td>URB/Access/40/Freeflow</td>
<td>30</td>
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<tr>
<td>URB/Access/xx/Freeflow for speed limit $\geq$ 50 km/h</td>
<td>33</td>
</tr>
<tr>
<td>URB/Access/xx/Heavy independent from speed limit</td>
<td>35</td>
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<tr>
<td>URB/Access/xx/Saturated independent from speed limit</td>
<td>45</td>
</tr>
<tr>
<td>URB/Access/xx/St+Go independent from speed limit</td>
<td>45</td>
</tr>
<tr>
<td>URB/Trunk-City/xx/Freeflow independent from speed limit</td>
<td>26</td>
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<tr>
<td>URB/Trunk-City/xx/Heavy independent from speed limit</td>
<td>33</td>
</tr>
<tr>
<td>URB/Trunk-City/xx/Saturated independent from speed limit</td>
<td>40</td>
</tr>
<tr>
<td>URB/Trunk-City/xx/St+Go independent from speed limit</td>
<td>45</td>
</tr>
</tbody>
</table>

**Area**: urban (URB) and rural  
**Road type**: Motorway (MW), semi-Motorway (Semi-MW), distributor (Distr), local collector (Local), access road in residential area (Access) and city trunk road (Trunk-City)  
**LOS**: freeflow, heavy, saturated as well as stop and go (St+Go)
D Results of Sensitivity Analyses

A 99 morning peak hour

Delay cost rates and the particular weights for walking and cycling

Delay cost rates and the particular weight for motorised private transport

The delay cost rate and the particular weight for heavy transport

Environmental cost rates and the particular weight for PM emissions

The environmental cost rate and the particular weight for NO\textsubscript{x} emissions

The environmental cost rate and the particular weight for CO\textsubscript{2} emissions

The cost rate and the particular weight for fuel consumption

The average occupancy rate of cars

A 99 midday off-peak hour

1. Delay cost rates and the particular weight for walking and cycling
2. Delay cost rates and the particular weight for motorised private transport
3. The delay cost rate and the particular weight for heavy transport
4. Environmental cost rates and the particular weight for PM emissions
5. The environmental cost rate and the particular weight for NO$_x$ emissions
6. The environmental cost rate and the particular weight for CO$_2$ emissions
7. The cost rate and the particular weight for fuel consumption
8. The average occupancy rate of cars

- A99_O321
- A99_O331
- A99_O412
- A99_O422
A 7 morning peak hour
A 7 midday off-peak hour

The delay cost rate and the particular weight for walking

Delay cost rates and the particular weight for motorised private transport

The delay cost rate and the particular weight for heavy transport

Environmental cost rates and the particular weight for PM emissions

The environmental cost rate and the particular weight for NO\textsubscript{x} emissions

The environmental cost rate and the particular weight for CO\textsubscript{2} emissions

The cost rate and the particular weight for fuel consumption

The average occupancy rate of cars

\[\text{A7\_O221, A7\_O231, A7\_O312, A7\_O322}\]
A 33 evening peak hour

The delay cost rate and the particular weight for walking

The delay cost rate and the particular weight for cycling

Delay cost rates and the particular weight for public transport

Delay cost rates and the particular weight for motorised private transport

The delay cost rate and the particular weight for heavy transport

Environmental cost rates and the particular weight for PM emissions

The environmental cost rate and the particular weight for NOx emissions

The environmental cost rate and the particular weight for CO2 emissions

A33_A111  A33_A112  A33_A113  A33_A121  A33_A122  A33_A123
A33_A210  A33_A211  A33_A212  A33_A213  A33_A221  A33_A222  A33_A223
A 33 midday off-peak hour
A 81 evening peak hour
A 81 midday off-peak hour
E Alternative Signal Programs for Test Sites

The Appendix E can be found under the following link:

https://tudatalib.ulb.tu-darmstadt.de/handle/tudatalib/2568