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Turbulence in traffic at motorway ramps and its impact on traffic operations and safety

Aries van Beinum

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Turbulence in Traffic at Motorway Ramps and its Impact on Traffic Operations and Safety

Proefschrift

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Preface

Early 2000, when I was performing the final internship of my secondary vocational education, I spent several months on the construction site of a new motorway. During this internship I was intrigued by the design of this project. At this point I could never have imagined that now, almost 19 years later, I would finish writing a dissertation that improves our knowledge regarding motorway design.

During my (long) educational career I had the privilege of meeting many people with different backgrounds and points of view, based on different experiences. Someone told me that the most important thing is to listen, because one can learn from everyone. This I always kept in mind and I found it to be most certainly true. Given all that I have heard along the way, I tried to overcome the differences between science, engineering and practice regarding motorway design in this thesis. I am truly grateful to have had this opportunity.

Performing this research wouldn't have been possible without the support of sponsors. First of all I would express my gratitude to Rijkswaterstaat. Gerald and Alex, I am very grateful for your support from the start, for entrusting this responsibility to me and for your efforts to arrange the necessary funding at Rijkswaterstaat. I would like to thank Witteveen+Bos for giving me, as one of its employees, the opportunity to spend several days a week on this project. Otto and Karin, your moral support, your belief in me and your willingness to invest in my ambitions mean a lot to me. I would also like to thank the department of Transport & Planning of Delft University of Technology and SWOV for opening your doors for me. Fred, Serge and Henk, thank you for providing supervision and an inspiring research environment. I have always felt very welcome at your offices and much appreciated all the help I received from your colleagues.

I would also like to thank the members of my committee. The meetings in which all of us were present may have been fewer than planned, but I enjoyed every one of them. Haneen, you have been a great supervisor! You have managed to make a scientist out of an engineer. You have put great effort in providing me with input and feedback, which I always appreciated. This helped me to think in a scientific manner and the progress I have made over the years is mostly because of you. Fred and Serge, you have both been a great inspiration by the way you think and approach problems. It was sometimes a challenge for me to manage the differences in your views and opinions, but in the end it helped me to approach problems from different angles.

During the process I have had the privilege to work with different talented master students. Marco, Maarten, Matthijs, Erik and Afroditi, your efforts on investigating, programming and testing different research methodologies have helped me a lot. So thank you for your effort and your interest in my research. Furthermore, I enjoyed being part of your master thesis projects, and experience you developing form student into an engineer.

The most exciting part of this research was the data collection and especially the three days of helicopter flights. Edwin, Jan and Kees, thank you for your efforts in this challenging project. It has been a privilege to work with professionals like you.

And, of course, I thank my life companions, my darling wife and my wonderful son. Nadia, you have always been there for me, although my thoughts have not always been with you. I am really grateful for having you in my life and I thank you for your out-of-the-box ideas that have challenged me so many times. And Joah, thank you for your drawings in my note book. I was filled with joy every time I came across them.

Outside of those who are mentioned above, were many other people who supported me. My dear family, friends, colleagues and roommates, thank you for your interest, motivation and moral support!

Above all, I humbly thank my Lord, God almighty, who gave me the intellect to do this project, who stood by me to give me peace and comfort and who carried me in times I needed Him most.

Aries van Beinum, October 2018

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1. Introduction

"The modern design of motorways is the result of a progressive development in history, which occurred primarily as an interaction between changing transportation needs and technical capabilities to meet those needs. The first way of transport was by going on foot, where in some cases animals were used. The invention of the wheel made it possible to use carriages. For a long time, only gravel roads were used. In the middle of the 17th century the first paved roads were built in the Netherlands. In these roads the constructive element was the most important aspect. Taking care of the geometric aspect started around 1920 in countries with a certain degree of motorization. Requirements regarding alignment, cross section, beacons etc. were developed, to ensure traffic flow and road safety. In present time an additional emphasis is placed on the integration of the road into its environment."

This citation is drawn from the first Dutch guideline for designing motorways: the "Richtlijn voor het Ontwerpen van Autosnelwegen"[1] (ROA) (Rijkswaterstaat, 1975) and it gives a brief description of the progress in history of transportation infrastructure development until 1975. These developments also led to changes in the road network. Where there used to be only one type of road in the past, nowadays there is a functional categorization of roads within the road network, where two major functions are distinguished for traffic: to flow and to exchange. These are very different functions, and they each require a specific infrastructure, a specific design and specific use requirements to make safe(r) road traffic possible (Wegman et al. 2008).

Within the categorization of roads, a motorway fulfils the function of facilitating traffic flow. To this end the HCM (HCM 2000) defines a motorway as: *"A divided highway with full control of access and two or more lanes for the exclusive use of traffic in each direction. Motorways provide uninterrupted flow. There are no signalized or stop-controlled at-grade intersections, and direct access to and from adjacent property is not permitted. Access to and from the motorway is limited to ramp locations. Opposing directions of flow are continuously separated by a raised barrier, an at-grade median, or a continuous raised median. Operating conditions on a motorway primarily result from interactions among vehicles and drivers in the traffic stream and among vehicles, drivers, and the geometric characteristics of the motorway"*.

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[1] Translated: "Guideline for the design of motorways"

By separating vehicles, that move at a high speed and in opposing directions, a motorway is relatively safe (Wegman et al. 2008). Because of the high travel speeds on motorways, it is important that the design of the road is predictable for its users. This means that the design needs to support the user's expectations of the road. The design of all road elements need to be in line with these expectations and should therefore be uniform throughout the motorway network (Wegman et al. 2008). To secure uniformity in motorway design, Rijkswaterstaat (the National Roads Authority within the Dutch Ministry of Infrastructure and Water Management) started to develop motorway design guidelines in the 1970s (Rijkswaterstaat 1975). These guidelines were partly based on the US guidelines, such as: the "Policy Geometric Design Highways" by the American Association of State Highway Officials (AASTHO) and the "Highway Capacity Manual" (HCM) by the Transportation Research Board (TRB). Other examples are the "Richtlinien für die Anlage von Autobahnen" (RAA 2008) in Germany, and the "Design Manual for Roads and Bridges" (DMRB 1994) in Great Britain.

Design guidelines guide designers in their work and, as a result, limit their solution space to a certain extent. The rationale is to present a recognizable road design to road users and to build road user expectations about the road course through consistency and continuity of road design elements in combination with traffic rules and regulations (Wegman et al., 2008). As a result road users will make more correct and safe decisions, and thus less errors in traffic. This will result in lower risks. This approach is even more important in a high speed environment, as is the case on motorways.

Originally, the Dutch guidelines were only used by Rijkswaterstaat, to share information regarding design policy, decisions made in the past and standard design solutions. The developments in technology and the different changes in Rijkswaterstaat's policy regarding motorway design, have led to several revisions of the motorway design guidelines: in 1992 (Rijkswaterstaat 1992), in 1999 (which was never published), in 2007 (Rijkswaterstaat 2007), and recently in 2015 and 2017 (Rijkswaterstaat 2017). In these years not only the guidelines changed, but also the traffic on motorways due to changing characteristics of vehicles and the penetration of technology in vehicles (e.g. ADAS, Advanced Driver-Assistance Systems). The guidelines however, did not develop as rapidly as technology and to this day large parts of the design guidelines remain unchanged since the first guidelines from the 1970s. Because of this, the validity of the current Dutch guidelines can be questioned.

Besides technology, also the way in which the guidelines are used have changed. The older versions did not prescribe one specific solution for a specific situation and left room for design choices and considerations. This works well if the design process is aimed at reaching a high level of quality, in terms of safety and capacity, within reasonable costs.

A change in policy in 2004 made Rijkswaterstaat decide to focus mainly on their main task: network management. The goal of this change was to deliver more quality with fewer people (Rijkswaterstaat 2004). In line with this decision, Rijkswaterstaat's main concern regarding motorway became the function of the road. The infrastructural design was no longer a main concern. The ROA was revised accordingly and this revision resulted in the "Nieuwe Ontwerprichtlijn voor Autosnelwegen"[2] (NOA) (Rijkswaterstaat 2007). This guideline provided even less standard solutions and was aimed to give more room to make a functional trade-off for design choices. The following quote from the NOA depicts this nicely: "*In the NOA, the road designer does not stand alone. The new guideline makes sure that the designer has access to all information that is needed to be prepared for the job. Clarity about how a design fits the goals regarding, for example, mobility and environment. But also about providing infrastructure and traffic management, agreements on a governmental level or the community, construction costs and life-cycle costs.*"

In line with the goal to provide more quality with fewer people, Rijkswaterstaat decided to outsource tasks like design, construction and maintenance works to private contractors (Rijkswaterstaat 2004), within so-called "Integrated Contracts". These contracts are tendered. Nowadays, the design, and thus the functional trade-off for choices in motorway design solutions, has become more and more the responsibility of private companies. But due to the competition between tender competitors, there is a risk that reducing costs gets a higher priority than providing a high level of quality and safety. To manage this risk, a clear description of the required level of quality, in terms of consistency and continuity of road design elements, traffic safety and motorway capacity is desired.

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[2] Translated: "The new design guideline for motorways"

The developments in technology and policy (outsourcing of design responsibility), led Rijkswaterstaat to revise the motorway design guideline once again. The goal of this revision was twofold (CROW 2009):

- to make it suitable as a set of requirements in terms of traffic safety and capacity;
- to provide the (theoretical) background behind the guideline, in order to understand why certain design choices are or can be made.

During the revision it became clear that, despite a long tradition of research within Rijkswaterstaat, a solid and comprehensive theoretical, or evidence based background was missing for different parts of the guidelines (Uittenbogerd and Van Beinum 2010). Among these were:

- the validity of turbulence distances in relation to the flow/capacity rate and for motorways with more than two lanes;
- the required length for mandatory lane-changes in relation to the flow/capacity ratio and the length of weaving segments.

For these topics, it was decided to perform additional research to provide a solid theoretical and empirical underpinning for supporting the guideline, and to change the guideline according to research findings if necessary. This research has, in particular, focussed on the concept of *turbulence* near on-ramps, off-ramps and weaving segments. A further explanation of what this concept entails, is given in the following section.

1.1. General concept of turbulence

General characteristics of turbulence

The concept of turbulence, as it is used in motorway design guidelines, not only in the Netherlands but also elsewhere, implies a disturbance in the traffic stream, that is caused by vehicles that make route choice related lane-changes, causing additional lane-changes, speed changes, and headway changes by other surrounding road users. These type of lane-changes occur at locations on the motorway, where the number of motorway lanes changes. These locations are referred to as “discontinuities”. Changing lanes, however, is a legitimate manoeuvre on a motorway. Turbulence is therefore regarded to be a common and unavoidable phenomenon in a traffic stream (HCM 2010), and will have a higher magnitude around motorway discontinuities (Kondyli and Elefteriadou 2011).

Definition of turbulence

In literature turbulence is mentioned, yet no explicit definition for turbulence is given. Only the effects and characteristics of turbulence are mentioned. These are some examples:

- *"Weaving segments require intense lane-changing manoeuvres as drivers must access lanes appropriate to their desired exit leg. Therefore, traffic in a weaving segment is subject to lane-changing turbulence in excess of that normally present on basic freeway segments. This additional turbulence presents operational problems and design requirements"* (HCM 2010);
- *"Ramp-freeway junctions create turbulence in the merging or diverging traffic stream. In general, the turbulence is the result of high lane-changing rates. The action of individual merging vehicles entering the traffic stream creates turbulence in the vicinity of the ramp. Approaching freeway vehicles move toward the left to avoid the turbulence. Thus, the ramp influence area experiences a higher rate of lane-changing than is normally present on ramp-free portions of freeway"* (HCM 2010);
- turbulence can be captured by four variables: *"(1) variation in speeds in the left and interior lanes, (2) variation in speed in the right lane, (3) variation in flow in the left and interior lanes, and (4) variation in flow in the right lane"* (Golob et al. 2004).

The implications of turbulence

Kondyli and Elefteriadou (2012) found that turbulence due to merging manoeuvres initiates 110 m upstream of the on-ramp gore. According to the (HCM 2010), the area in the vicinity of a ramp that is influenced by merging traffic stretches from about 460 m (1.500 ft.) upstream to 460 m downstream of the gore. To the best of our knowledge other literary sources that describes the start or the end of a raised level of turbulence are not available. Furthermore, parts of the motorway that suffer high levels of turbulence more often function as bottlenecks and show higher crash rates, compared to road segment with low turbulence (Abdel-Aty and Pande 2005; HCM 2010; Golob et al. 2004; Lee et al. 2003a; Lee et al. 2002).

Impact of road design and driver behaviour on turbulence

The level of turbulence can be influenced by the design of the road. According to the guidelines, the level of turbulence is expected to increase when the available length for performing route choice related lane-changes decreases. Therefore, turbulence has to be taken into account for ramp spacing (HCM 2010; AASHTO 2001; RAA 2008; Rijkswaterstaat 2007; DMRB 1994). To determine the correct ramp distance, it is important to have knowledge about the location where the level of turbulence starts to increase upstream of a discontinuity, and where the turbulence dissolves downstream of a discontinuity. Furthermore, when two discontinuities are located close to each other, their turbulence impact areas might overlap. This concept is shown in figure 1.1. for an on-ramp that is succeeded by an off-ramp. In this case, knowledge about the implications for traffic operations and traffic safety of the overlap and the severity of this overlap is required.

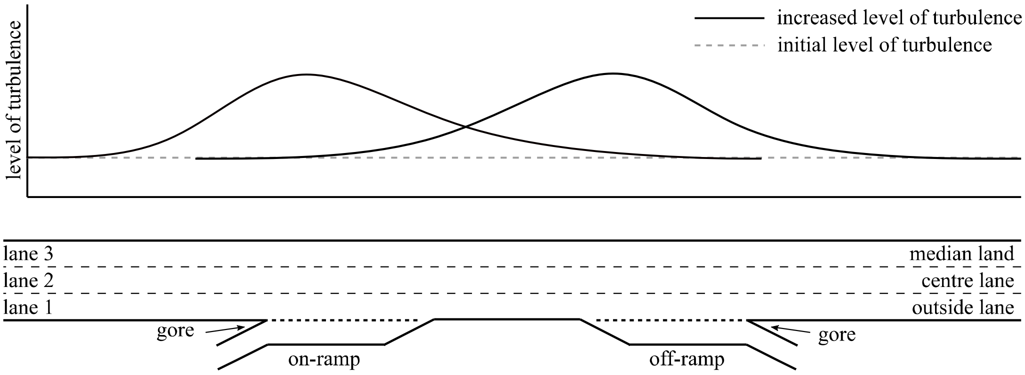


Figure 1.1. Concept of the level of turbulence around succeeding ramps.

Besides the design of the road, the level of turbulence can also be influenced by driving behaviour. This behaviour is influenced by traffic rules that apply for motorway traffic. For motorway traffic in The Netherlands, two specific rules are relevant for the level of turbulence near motorway ramps: the right-side rule (i.e. keeping-right) and the legal speed limit.

According to the right-side rule it is mandatory for drivers in The Netherlands to change lanes to the right when there is sufficient space to do so. Overtaking takes place on a left lane. The legal speed limit for passenger cars (100/120/130 km/h) differs from the limit for trucks (80 km/h) and buses (100 km/h, sometimes 80 km/h). The differences between the legal speed limits for passenger cars and trucks/buses generate different travel speeds for different lanes. In combination with the right-side rule, a separation of traffic over the lanes can be observed, where trucks/buses drive mostly on the rightmost lane and passenger cars drive mostly on the leftmost lane(s).

When exiting a motorway, faster vehicles need to mix with slower vehicles upstream of the ramp, which requires changes in speed. When entering a motorway, a driver with a high desired speed will try to make additional lane-changes towards the left side of the motorway in order to avoid driving behind slower driving vehicles on the rightmost lane.

Methods to quantify the impact of turbulence on operations and safety
Several methods to assess traffic operations and traffic safety exist today, such as the use of microscopic simulation programs, surrogate safety measures, crash prediction models and driver simulators. Traditionally, the safety of roads is assessed by studying crash statistics. However, crash statistic are only available for existing roads and existing situations, and crash data is not always sufficient due to small sample sizes and low quality (i.e. underreporting). These limitations make crash statistics unsuitable for assessing traffic safety implications for different designs.

An alternative method in which microscopic simulation software is combined with surrogate safety measure methodologies, is expected to be the most promising way forward. By doing that, road characteristics, traffic characteristics and microscopic behaviour can be taken into account to evaluate the safety and capacity of a certain motorway segment.

1.2. Turbulence in design guidelines and practice

Motorway design guidelines aim to provide standard 'one-size-fits-all' solutions with standardized dimensions that guarantee consistency in road geometry and provide safe motorways with a sufficient level of service (Rijkswaterstaat 1992). Though sometimes, the preferred solution that is included in the guideline, cannot be realized in practice due to a lack of physical space. This is especially the case in densely populated and urbanized areas, like many areas in The Netherlands.

A common example is a weaving segment that is located in a 2x2 lane motorway, with a standard length of 500 m. When the motorway is expanded to a 2x3 lane motorway, the desired length of the weaving segment becomes 600 m (Rijkswaterstaat 2017). To increase the length of the segment, it might be necessary to move (at least) one of the ramps, which requires additional costs and effort. In such cases, deviation from the guidelines is considered. However, the quantitative implications in terms of impact on traffic operations and traffic safety of such deviations are not provided by the current design guidelines (Wegman 2010). When it comes to ramp spacing, a thorough understanding of turbulence (and its influence on traffic operations and traffic safety) is critical, in order to be able to make the right trade-off for the design choices in these situations.

1.3. Focus of this thesis

Problem statement

In different countries different approaches are used in guidelines for dealing with turbulence (AASHTO 2011; RAA 2008; HCM 2010; Rijkswaterstaat 2017; DMRB 1994). And to the best of our knowledge only one example is available in literature that describes the start and end of a raised level of turbulence (Kondyli and Elefteriadou 2012). Furthermore, the guidelines do not indicate the implications on traffic operations and traffic safety when deviating from the guidelines. Therefore, there currently are two major problems for applying current motorway design guidelines with respect to turbulence:

- a solid theoretical and empirical underpinning regarding the required length for a raised level of turbulence is lacking;
- a thorough understanding of the (quantitative) implications in terms of impacts on traffic operations and traffic safety, when deviating from the design guidelines, is missing.

These problems hamper a well-considered trade-off between different design variants. In order to make a quantitative trade-off, a method is needed to assess the (expected) level of turbulence for an existing situation or for a specific motorway design (existing only on paper), and to evaluate the implications of design decisions on traffic operations and traffic safety. This method should take into account both the geometrical road design elements as well as the traffic and driver behavioural elements. This method is meant to be a valuable asset for improving the current motorway design guidelines, by providing the empirical and theoretical underpinning of the guideline and by being able to evaluate motorway designs with respect to turbulence.

Goal and research questions

The goal of this thesis is twofold. The first and primary goal of this thesis is to gain empirical knowledge about the characteristics of turbulence. From a motorway design perspective, knowledge is desired especially about the distance from a discontinuity where turbulence starts and dissolves, and knowledge of the manner in which driving behaviour near ramps and weaving segments is affected by the road design and the amount of traffic. The secondary goal of this thesis is to provide a tool to assess the level of turbulence (resulting from a specific motorway design) and its impact on traffic operations and traffic safety.

Following these two goals and the problem statement, the following research questions are formulated:

- What are the characteristics of turbulence?
  - How can turbulence be defined and quantified?
  - Which driver manoeuvres contribute to turbulence, and how?
  - How is the level of turbulence affected by motorway design and traffic flow?
- How can the implications of turbulence on traffic operations and traffic safety be quantified?
  - What are the most suitable methods to quantify the implications of turbulence on traffic operations and traffic safety?
  - How well do the currently available methods perform, in terms of reliability and predictive validity?
  - Which improvements to the currently available methods are needed, in order to provide a tool capable of quantifying the implications of turbulence on traffic operations and traffic safety realistically?

Research scope

In this thesis turbulence in motorway traffic is studied from a traffic engineering perspective, based on empirical traffic data. Driver behaviour aspects (such as driver task performances) and human factors are not taken into account. This study focuses mainly on the application and evaluation of existing theories and methods on new, unique, empirical data. It does not focus on developing new theories. Also, the functioning of the current system is evaluated, without emerging technologies, such as driver assistance or automated driving. Furthermore this thesis is limited to:

- turbulence around on-ramps, off-ramps and weaving segments on motorways in The Netherlands;
- turbulence during normal weather conditions (i.e. average wind conditions, no rain/snow, etc.);
- turbulence during day time;
- turbulence in free flow traffic conditions.

1.4. Research approach

Since turbulence is created by driving manoeuvres that are performed by individual drivers, detailed information on the driving behaviour of individual drivers over a considerable length of the motorway is needed to be collected. To get a good indication on the length of motorway for which data of individual drivers is needed, the location where the level of turbulence increases and dissolves was studied. This was done by analysing empirical loop detector data from multiple on-ramps and off-ramps in The Netherlands. Based on these findings, requirements for the field measurements were set. During the field measurements, data of vehicle positions (all vehicles) within a specific part of the motorway, was collected over a specific period of time. This type of data is called trajectory data and a large quantity of empirical trajectory data was collected at several on-ramps, off-ramps and weaving segments in The Netherlands. These locations had a different number of lanes, traffic flow intensities, percentage of heavy vehicles, and legal speed limits. This information was then used to:

- gain a more thorough understanding of the different driving manoeuvres which contribute to turbulence;
- investigate whether the currently available microscopic simulation software packages are able to simulate driving behaviour around ramps realistically;
- investigate whether a commonly used microscopic simulation software package is able to quantify the implications of driving behaviour around ramps on traffic safety.

This study was performed in a step-wise approach, which is graphically displayed in figure 1.2.

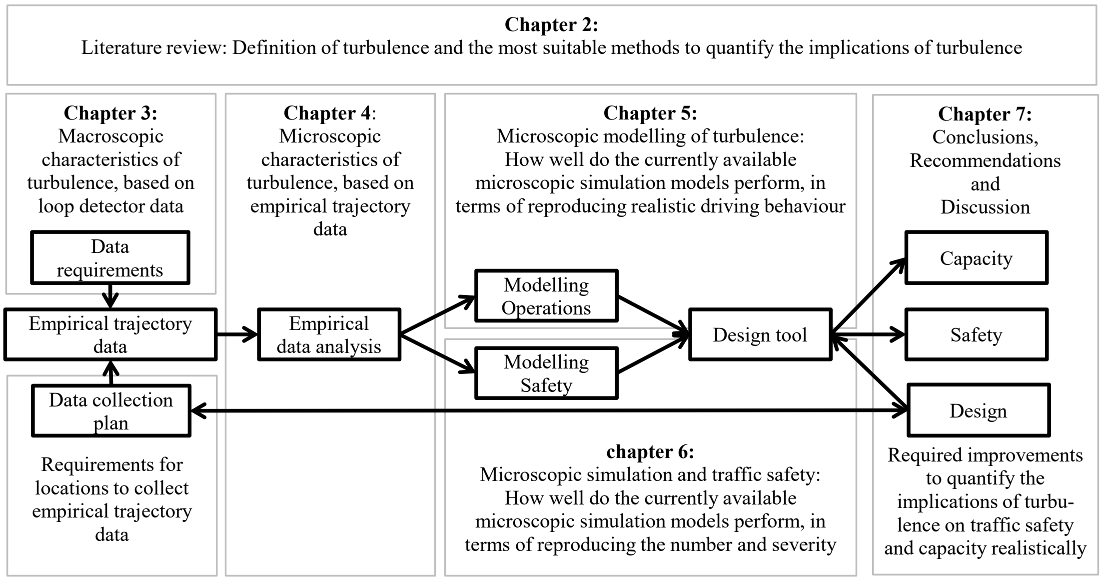


Figure 1.2. Study overview.

1.5. Research contributions

1.5.1. Scientific contributions

For this thesis a unique set of empirical data was collected, using a camera mounted underneath a hoovering helicopter. This dataset contains precise vehicle location information (*x,y,time*) of each individual vehicle at fourteen different locations in The Netherlands: three on-ramps, three off-ramps and eight weaving sections. Each location has different characteristics in terms of: traffic volume, legal speed limit, number of motorway lanes, length of acceleration or deceleration lane and percentage of heavy vehicles. For each location approximately thirty minutes of data was collected over a distance of approximately 1,500 m. The size, quality and characteristics of this data set are unprecedented and give new, unique, insights in the empirical characteristics of turbulence.

The dataset enabled us to evaluate the level of realism of several commonly used evaluation methods and tools, in a way that we were not able to do before. This thesis shows the strength and weaknesses of the currently commonly used microscopic simulation models, and shows the areas of concern when applying these models to assess different designs in terms of turbulence and its effect on traffic operations and traffic safety. These findings offer new input for the debate regarding the use and validity of surrogate safety measures, and the debate regarding the predictive validity (in terms of driving behaviour) of the currently available microscopic simulation models.

Furthermore this study provides useful recommendations for improving our current microscopic simulation models and highlights important areas of concern when working with empirical trajectory data.

1.5.2. Practical contributions

This thesis provides new insights in the empirical characteristics of turbulence. It shows which elements of driver behaviour affect turbulence around ramps and how this behaviour is influenced by road design. Furthermore, this thesis gives detailed information on how driver behaviour around ramps is simulated by state-of-the-art microscopic simulation models.

The results of this thesis are useful for evaluating and improving the motorway design guidelines for ramp spacing and weaving segment length, which are both based on turbulence. Furthermore, the results of this thesis give insight into valuable areas of concern for using the currently available microscopic simulation software packages as a design tool, to assess the implications of different motorway design variants on traffic operations and traffic safety.

1.6. Reading guide

The outline of this thesis is based on the structure as presented in figure 1.2. Chapter 2 contains a literature review, in which a critical assessment of methodologies for traffic operations and traffic safety evaluations of motorway turbulence is performed. Chapter 3 gives an indication on where the increased level of turbulence starts and ends, based on empirical loop detector data. Based on these results fourteen different locations were selected for the collection of empirical trajectory data. The analysis of this dataset is described in chapter 4. Chapter 5 describes whether the currently available microscopic simulation software packages are suitable for simulating driving behaviour around ramps realistically. Chapter 6 describes to what extent a currently available and widely applied microscopic simulation software package is able to quantify the implication of driving behaviour around ramps on traffic safety. The main conclusions of all the performed studies are discussed in chapter 7, in which also recommendations are given, regarding the desired tool to assess the level of turbulence (resulting from a specific motorway design) and its impact on traffic operations and traffic safety.

Chapter 2 was first published in "Transportation Research Record: Journal of the Transportation Research Board" (A. van Beinum, H. Farah, F. Wegman, and S. Hoogendoorn. 2016. "Critical Assessment of Methodologies for Operations and Safety Evaluations of Freeway Turbulence". Transportation Research Record: Journal of the Transportation Research Board 2556:39-48. doi: 10.3141/2556-05).

Chapter 3 was first published in "Transportmetrica A: Transport Science" (A. van Beinum, M. Hovenga, V. Knoop, H. Farah, F. Wegman, and S. Hoogendoorn. 2017. "Macroscopic Traffic Flow Changes around Ramps". Transportmetrica A: Transport Science:1-32. doi: 10.1080/23249935.2017.1415997).

Chapter 4 was first published in “Transportation Research Part C: Emerging Technologies” (A. van Beinum, H. Farah, F. Wegman, and S. Hoogendoorn. 2018. “Driving behaviour at motorway ramps and weaving segments based on empirical trajectory data”. Transportation Research Part C: Emerging Technologies 92:426-441. doi: https://doi.org/10.1016/j.trc.2018.05.018).

2. Literature review study

This chapter was first published in "Transportation Research Record: Journal of the Transportation Research Board" (Van Beinum, A., H. Farah, F. Wegman, and S. Hoogendoorn. 2016. "Critical Assessment of Methodologies for Operations and Safety Evaluations of Freeway Turbulence." Transportation Research Record: Journal of the Transportation Research Board 2556:39-48. doi: 10.3141/2556-05).

Abstract

Turbulence in traffic is a commonly known phenomenon, but the exact characteristics of this phenomenon are not yet clear. It reflects individual changes in speed, headways, and lanes in the traffic stream. The currently used motorway design guidelines prescribe different measures for handling turbulence, such as sufficient ramp spacing, and spacing between road discontinuities. In situations where the available space between discontinuities is scarce, it might be necessary to make a trade-off between costs and safety/operation. For a valid trade off more insight is needed on the safety and operations effects when one deviates from the guidelines. A lot of research was done on the different causes of turbulence and their effect on safety and operation. This chapter proposes a theoretical framework for turbulence phenomenon that facilitates the comparison of the available methodologies that can be used to evaluate a motorway design on the matter of turbulence and its impact on traffic operations and safety. The main finding of this review is that the currently available methodologies lack the ability to evaluate the impact of motorway turbulence on operations and safety simultaneously. Different recommendations to overcome limitations of current methodologies and further research possibilities to improve these methodologies are given.

2.1. Introduction

Entering and exiting traffic from ramps and weaving areas will affect the traffic density on the motorway. Especially on the right lane. This change in density may cause motorway traffic to react, for example: changing lanes to a lane with a lower traffic density. Other reactions can be decelerating or accelerating in order to increase or decrease the headway with the vehicle in front (HCM 2010). This phenomena is called 'turbulence' and it is mentioned several times in literature (Abdel-Aty and Pande 2005; Golob et al. 2004;

Kondyli and Elefteriadou 2011, 2012; Lee et al. 2003a) and in guidelines (HCM 2010; AASHTO 2001; DMRB 1994).

The concept of turbulence is used consistently and this suggests a clear definition of turbulence. But neither the existing guidelines nor the literature define exactly what turbulence is. There is however a general agreement in literature on two main characteristics regarding turbulence: turbulence is a common phenomenon in a traffic stream (HCM 2010), and will have a higher magnitude around motorway discontinuities, such as on-ramps (Kondyli and Elefteriadou 2011), off-ramps, weaving areas, left side lane reductions, etc.. Also turbulence is stated to have a negative impact on traffic safety and traffic operations (Abdel-Aty and Pande 2005; HCM 2010; Golob et al. 2004; Lee et al. 2003a).

According to design guidelines turbulence has to be taken into account for ramp spacing (HCM 2010; AASHTO 2001; RAA 2008) and the spacing of discontinuities (Rijkswaterstaat 2007; DMRB 1994). To do this guidelines prescribe certain distances, but the scientific justification is lacking. The AASHTO for example uses a set of values for minimum ramps terminals spacing (AASHTO 2001). The Dutch motorway guidelines (Rijkswaterstaat 2007) prescribe turbulence lengths for the spacing of discontinuities. In none of the guidelines the origin of the prescribed lengths is referenced.

In densely populated areas, such as the Netherlands, the space for new motorways is scarce. In some motorway design cases it was decided to deviate from the guidelines in order to be able to realize the desired interchange connections. In such cases it is tempting to accept a shorter length than prescribed. However, the implications for traffic safety and operations of deviating from the guidelines are not fully understood. A thorough understanding of turbulence, and its influence on traffic safety and traffic operations is critical in order to be able to make the right trade-off for the design choices in these situations.

The main aim of this chapter is to review the currently available methodologies to assess the impact of turbulence in motorway traffic on traffic safety and traffic operations. The different methodologies are described and compared. Recommendations are given on how to use a wide range of different existing methods, and how to combine methods when assessing designs on operations and safety at the same time. The main focus of this review is turbulence in motorway traffic around on-ramps, off-ramps and weaving areas.

This review starts with a background on the turbulence phenomenon and its influence on traffic safety and traffic operations. The second part gives an overview of the available methods to quantify turbulence. The available methodologies for assessing the impact of turbulence on operations and safety are described and compared in the third and fourth part. This review ends with conclusions and gives recommendation for further research.

2.2. Background

In motorway design the use of guidelines, manuals and standards in the design process is common. Documents such as the Highway Capacity Manual (HCM) and the 'AASHTO Green Book' in the USA, (AASHTO 2001), the 'Richtlinien für die Anlage von Autobahnen (RAA)' (RAA 2008) in Germany, the 'Design Manual for Roads and Bridges (DMRB 1994)' in Great Britain and 'Nieuwe Ontwerprichtlijnen voor Autosnelwegen (NOA)'(new design guidelines for motorways) (Rijkswaterstaat 2007) in The Netherlands are prescribed in order to maintain consistency in road geometry and to provide safe motorways with sufficient level of service (Rijkswaterstaat 1992).

One of the important geometric elements in motorways is ramp spacing and the length of weaving areas. The basic principle in the design of these elements is that there should be sufficient spacing between succeeding ramps in order to cope with turbulence in the traffic stream.

Different approaches for dealing with turbulence are used in the different guidelines. For example: the AASHTO Green Book uses a set of minimum values for ramp spacing and the Dutch guidelines use a criteria called Turbulence length, which is the required length between succeeding discontinuities. The prescribed lengths differ per type of discontinuity and also per guideline. For example, table 2.1 shows the different prescribed distances between an on-ramp followed by an off-ramp (measured from nose to nose).

country	distance	design criteria
The Netherlands (Rijkswaterstaat 2007)	750 m	design speed
Germany (RAA 2008)	1100 m*	minimum value for isolated intersection planning
USA (AASHTO 2001)	600 m**	road category: freeway
	480 m***	road category: freeway
UK (DMRB 1994) , Vol.6, Sec. 2, Cpt 4.7	450 m****	3.75V, where V = design speed = 120 km/h

Table 2.1. Distance between On-Ramp and Off-Ramp Prescribed in Different Guidelines; * 250 m acceleration lane + 600 m between acceleration and deceleration lane + 250 m deceleration lane; ** system to service interchange (weaving); *** service to service interchange (weaving); **** may be increased to the minimum requirements for effective signing and motorway signalling.

Despite the differences between the different approaches, the general concept behind ramp spacing and weaving areas in all the above guidelines is that the traffic stream will encounter a raised level of turbulence around motorway discontinuities. Turbulence will intensify when the available road length for lane changing becomes shorter. This should be taken into account by applying sufficient ramp spacing. This concept is supported by literature (Bared et al. 2006; Pilko et al. 2007).

In literature and guidelines turbulence is mentioned but no explicit definition for turbulence is given. These are some examples in which turbulence is mentioned:

- "Weaving segments require intense lane-changing manoeuvres as drivers must access lanes appropriate to their desired exit leg. Therefore, traffic in a weaving segment is subject to lane-changing turbulence in excess of that normally present on basic freeway segments. This additional turbulence presents operational problems and design requirements" (HCM 2010);
- "Ramp-freeway junctions create turbulence in the merging or diverging traffic stream. In general, the turbulence is the result of high lane-changing rates. The action of individual merging vehicles entering the traffic stream creates turbulence in the vicinity of the ramp. Approaching freeway vehicles move toward the left to avoid the turbulence. Thus, the ramp influence area experiences a higher rate of lane-changing than is normally present on ramp-free portions of freeway" (HCM 2010);
- turbulence can be captured by four variables:" 1) variation in speeds in the left and interior lanes, 2) variation in speed in the right lane, 3) variation in flow in the left and interior lanes, and 4) variation in flow in the right lane" (Golob et al. 2004).
- "Turbulence is (among other things) defined by headway changes and a changed distribution of traffic over the different motorway lanes. Corresponding aspects of driving behaviour are for example deceleration, evasive actions or (anticipating) lane changes" (Rijkswaterstaat 2007).

Since there is no explicit definition for turbulence available, a definition is still to be suggested. A non-turbulent traffic state can be considered as a state in which all vehicles on a road maintain the same relative distance and speed to others over a certain length of a road section and for a period of time. A turbulent traffic state can then be considered as the state in which speed, headway and the lateral position change over time, due to driver actions such as acceleration, deceleration and lane-change. Since acceleration, deceleration and lane-changes are common driver actions, turbulence can be considered as always present in the traffic stream (HCM 2010).

Therefore, a more specific definition of turbulence in the vicinity of discontinuities (such as ramps) is proposed in this chapter as following:

- Turbulence:
    - individual changes in speed, headways, and lanes (i.e. lane-changes) in a certain road segment, regardless the cause of the change;
- Level of Turbulence:
    - the frequency and intensity of individual changes in speed, headways and lane-changes in a certain road segment, over a certain period of time.

2.2.1. Theoretical Structure for Turbulence

The Level of Turbulence is expected to increase before (upstream of) and to decrease after (downstream of) a ramp or a weaving area. This phenomena is described by Hovenga (2014) who found that turbulence starts more or less about 500 meter upstream and ends more or less about 800 downstream from an on-ramp nose. Kondyli and Elefteriadou (2012) found that turbulence due to merging manoeuvres initiates 110 m upstream of the nose. According to the HCM (2010) the merge influence area will occur about 460 m (1.500 ft.) upstream and 460 m downstream of the nose. To the best of our knowledge other literature that describes the start or the end of a raised level of turbulent traffic is not available.

Based on this concept a raised level of turbulence is for this study divided in three parts:

1. Upstream of (before) the ramp;
2. At the ramp;
3. Downstream of (after) the ramp.

At ramps and weaving areas drivers will execute their strategic route navigation decisions, which will lead to mandatory lane changes, in order to be able to enter or exit the motorway (Minderhoud and Bovy 2001). These lane changes make other drivers react (Kondyli and Elefteriadou 2011), which results in turbulent traffic (HCM 2010). The proposed structure for turbulence is shown in figure 2.1 and considers the three parts.

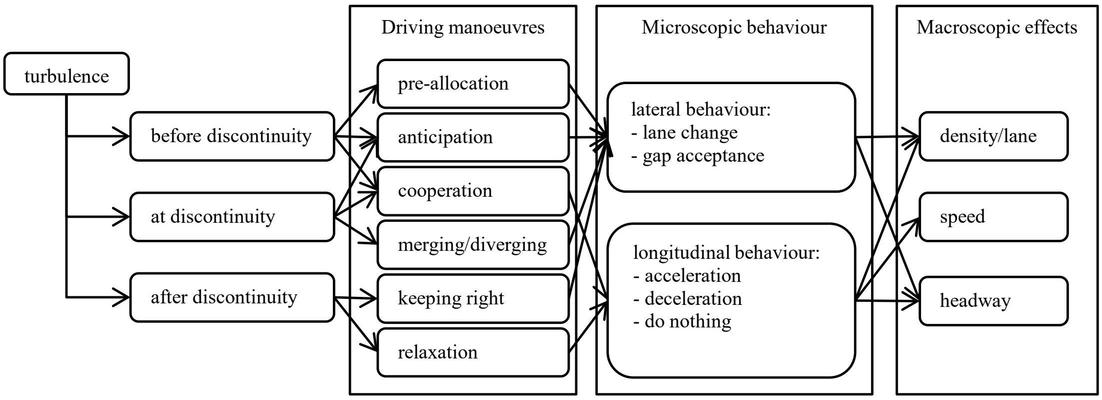


Figure 2.1. Theoretical structure for turbulence.

Lane changes upstream of a ramp are considered to be pre-allocating behaviour, where the driver choses a lane in a tactical sense before the ramp, or cooperative behaviour. Anticipation is behaviour where an on-ramp a driver chooses to change lanes to the left to give way to the entering traffic (Kondyli and Elefteriadou 2009, 2012) or decelerate in order to enlarge the headway with the vehicle in front after a new vehicle has merged in (Hidas 2005). Or drivers might increase their headway to give way to entering traffic. This phenomena is called a cooperative lane change (Hidas 2005; Schakel et al. 2012) or courtesy yielding (Daamen et al. 2010). Downstream of a ramp lane changes may occur due to the right side rule, which prescribes that drivers should change lanes to the right when possible. Downstream of a ramp drivers might decelerate to increase the headway to their leading vehicle. This phenomena is called relaxation (Schakel et al. 2012; Laval and Leclercq 2008).

The different manoeuvres can be clustered in different types of microscopic behaviour: lateral or longitudinal. The first considered lateral behaviour is lane change, which can be classified as free, forced or cooperative (Hidas 2005). Lane changing and merging are closely related to gap acceptance and tactical lane choice. These can be considered as integrated behaviour (Toledo et al. 2005). Longitudinal behaviour is classified as acceleration, deceleration, or do-nothing (Koutsopoulos and Farah 2012). Lateral and longitudinal behaviour can be integrated in order to get a complete description of merging behaviour (Toledo, Koutsopoulos, and Ben-Akiva 2007; Toledo et al. 2009).

Microscopic behaviour results in macroscopic effects. For example a lane changes will result in a changed density per lane and a changed headway distribution. Acceleration and deceleration might also result in a changed headway distribution, but result also in changing speed differences between different vehicles as illustrated in figure 2.1.

2.2.2. Impact of turbulence

The general hypothesis for the research on turbulence is that the level of turbulence is affected by certain conditions, such as road design, traffic characteristics (HCM 2010), environmental aspects (such as weather and daylight), and drivers' population characteristics. These conditions affect driving behaviour. The resulting manoeuvres drivers take affect traffic safety and operations (Abdel-Aty and Pande 2005; HCM 2010; Golob et al. 2004; Lee et al. 2003a).

Figure 2.2 shows that certain conditions (road design, traffic and environment) affect (microscopic and macroscopic characteristics reflecting results of) driver behaviour (such as the choice of driving speed, headway, gap acceptance) which in turn effects the motorway operations and safety. In reverse, some effects may influence driving behaviour. For example, if the traffic stream becomes more turbulent, drivers may tend to drive more cautiously and lower their driving speeds. At the same time a low level of safety and operations might move the respective authorities to invest in improving the motorways' infrastructure by reconstructing some geometric design elements or adopt some new traffic management measures.

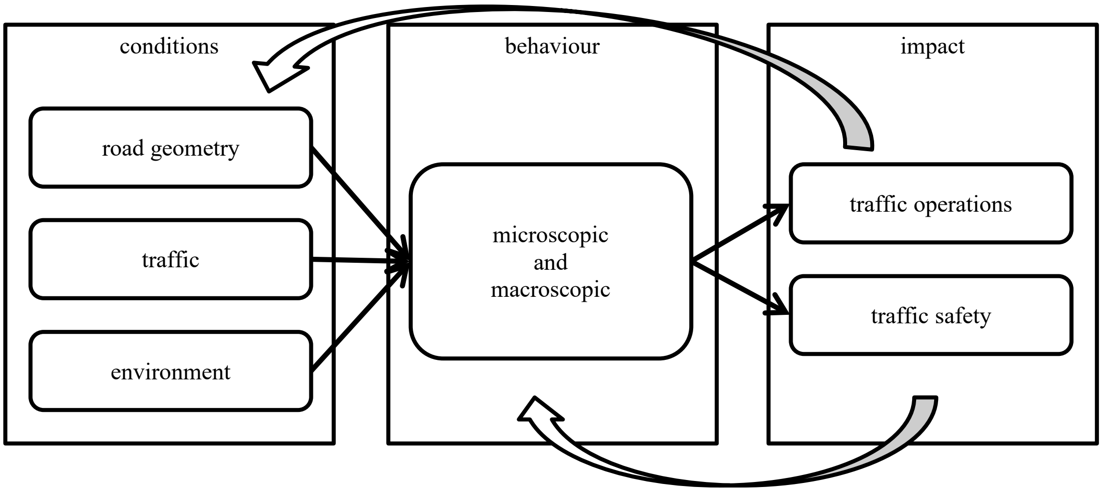


Figure 2.2. General concept of the effects of turbulence.

2.2.3. Problem definition

It is clear that turbulence is a complex phenomenon with different causes and impacts. To the best of our knowledge no literature is available which assesses all the causes of turbulence, the influence of road design and traffic conditions on turbulence and its impact on operations and safety. Therefore, it is argued that there is a lack of knowledge with respect to understanding the interaction of the causes and their impact on turbulence. This creates a twofold problem: 1) It is unknown if the current design guidelines lead to an optimal design; 2) It is unknown what the implication of deviating from the guidelines is and what impact this has on safety and operation.

Therefore, there is a need for a method to assess the (expected) level of turbulence for a design (only existing on paper), or an existing situation, and to evaluate the implications of design decisions on traffic safety and traffic operations. This method should take into account both the geometrical road design elements as well as the traffic and driver behavioural elements.

2.3. Methodologies to collect data related to turbulence

This section is dedicated to the different methods to collect data that could be used to quantify turbulence in motorway traffic. We will consider loop detectors, video cameras, driving simulator and instrumented vehicles.

2.3.1. Loop detectors

Macroscopic traffic state variables such as density, speed and headway distributions can be measured using loop detectors (Xu et al. 2012; Treiber et al. 2000). Loop detector data represents vehicle passages and, depending on the type of loop detector, information such as speed and vehicle length. The data is usually aggregated to a fixed time period. Examples of chosen time periods are 30 seconds (Abdel-Aty, Uddin, et al. 2005; Abdel-Aty et al. 2004; Abdel-Aty and Pemmanaboina 2006; Abdel-Aty, Pande, et al. 2005), 1 min (Piao and McDonald 2008; Hovenga 2014). The advantage of using loop detector data is its accessibility. Loop detector data from Dutch motorway for example can be accessed real time online. The disadvantage of using loop detector data is that detailed data of individual manoeuvres, such as lane change, acceleration and deceleration, cannot be collected.

2.3.2. Video cameras

Video footage can be used to generate trajectory data, which gives detailed time/space information of individual vehicles. From this data turbulence related driver manoeuvres such as merging, overtaking and acceleration can be studied in a detailed way. Three examples of studies on Dutch motorways are given. Daamen et al. (2010) studied merging behaviour at two Dutch on-ramps and compared the empirical results to applied theories in existing microscopic simulation models. They found that that gap acceptance theories using a certain critical gap are not able to represent the observed behaviour. Hoogendoorn et al. (2011) used the same data as Daamen et al. (2010) to propose a new approach to model and simulate car-following behaviour. Marczak et al. (2013) combined the Dutch data with data from Grenoble (France) to study gap acceptance. They observed differences in the driver's behaviour on the two locations: the merging drivers in Grenoble (France) tend to be more aggressive, i.e. accepting smaller gaps than in Bodegraven (Netherlands).

Cameras can be mounted on a high observation point such as a helicopter (Hoogendoorn et al. 2003), a drone (Voorrips 2013) or a building/structure (NGSIM 2015).

The advantage of trajectory data is that it gives insight in the actual movements of vehicles. But it doesn't give any information about the underlying psychological driver behaviour, it is relatively expensive to collect, and the data processing is time consuming. Thus, most studies that used trajectory data included limited number of sites.

2.3.3. Driving simulators

A driving simulator consists of a vehicle mock-up with a functional steering wheel, indicators, pedals and a shift stick. The simulator attempts to emulate a real driving environment. Behavioural aspects can be researched using data from a driving simulator. Two examples are given of motorway turbulence related studies. Van Winsum and Heino (1996) studied time-headway during car-following and braking response. De Waard et al. (2009) studied the impact of proportion of HGVs, length of the acceleration lane and the speed of the driver ahead on the workload of elderly drivers, and the benefits of in-car support systems, when merging into motorway traffic.

The driving simulator has several advantages: the ability to test a wide variety of different existing and non-existing road design layouts, control of the intervening variables and it is a safe environment. One of the disadvantages of driving simulators is that its measurements are taken from a simulated environment and does not reflect drivers' behaviour exactly as in reality, since drivers do not face a real risk of a collision which might bias the observed behaviour (Farah et al. 2009). There is therefore a need to validate the results from the simulator with real life data. Furthermore, the other vehicles designed in a driving scenario although designed to behave "intelligently" do not represent real behaviour of humans.

2.3.4. Instrumented vehicle and naturalistic driving

Driver behaviour data from a real life traffic environment can be acquired by the use of an instrumented vehicle. An instrumented vehicle is equipped with sensors and radars that can record data relevant to the vehicle itself and also relative speeds and distances from other vehicles (McDonald et al. 1997). All the behavioural aspects of the driver, such as driving speed, acceleration, deceleration, steering action, longitudinal and lateral position, can be measured comparable to the driver simulator. Such a vehicle was assembled and used by TRG Southampton (Brackstone et al. 2002; Wu et al. 2003) for studying car following on UK motorways. Another study is conducted in Germany, where trajectory data from a radar equipped vehicle was used to calibrate car following models (Kesting and Treiber 2008).
A drawback of using an instrumented vehicle is the experimental and non-naturalistic setting in which the data is gathered. This might have an effect on the behaviour of the participants and as a result bias the data.

As opposed to the experimental approach using an instrumented vehicle, naturalistic driving can be measured by drivers who operate daily using their own vehicles that have been equipped with specialized sensors, and recording equipment. Drivers operate their vehicle during normal driving routines while data is collected continuously. Olson et al. (2009) and Blanco et al. (2011) studied driver distraction in commercial motor vehicle operations and the impact of time-on-task on the risk of safety-critical events in the '100-car Naturalistic Driving Study'. Chong et al. (2013) used data from naturalistic driving to propose a model to simulate driver behaviour in terms of longitudinal and lateral actions in two driving situations, namely car-following situation and safety critical events. Another example is the Strategic Highway Research Program (SHRP2) Naturalistic Driving Study (NDS) project (Antin 2011). The NDS database contains comprehensive video and vehicle sensor data collected from drivers and their vehicles over a three year period in six locations across the United States. The database contains data from 5.4 million trips taken by 3,147 volunteer drivers for between 4 and 24 months each nearly 50 million miles of driving (NDS 2015). The advantage of naturalistic driving is that the resulting data is reliable and comes in large quantities. The disadvantage is that vehicles need to be equipped and operated. This requires a relatively big organizational effort. However, the rapid advancement in sensing and communication technologies is expected to facilitate these studies in the future.

2.4. Methodologies to assess traffic operations

Turbulent traffic has a negative effect on road capacity (HCM 2010). Numerous studies, for example (Cassidy et al. 2002; Chung et al. 2007; Coifman and Kim 2011; Treiber et al. 2000), have focused on explaining the mechanisms of driving in turbulent traffic and are based on traffic data such as loop detector data and individual vehicle trajectories. Traffic flow theories are derived from traffic data. These theories are used to describe traffic behaviour in a mathematical sense by developing models. These models try to emulate the lateral and longitudinal behaviour of drivers. A review of the lateral behaviour models (lane change and gap acceptance) was made by (Rahman et al. 2013), while a review on longitudinal behaviour models was made by (Hoogendoorn and Bovy 2001). Integrated models were also developed where lateral and longitudinal models are combined (Toledo et al. 2009). These models can be used in microscopic simulation models, which simulate driving behaviour for certain situations.

Following is a summary of the two most common methodologies for analysing the impact of turbulence on traffic operations: (ex-post) data evaluation and (ex-ante) Microscopic simulation models.

2.4.1. Traffic data evaluation

The most direct way to study traffic operations is by studying traffic data. Several examples of studies are available in the literature. Coifman et al. (2005) used trajectory data to study the impact of lane change manoeuvres on congestion. Laval and Leclercq (2010) used trajectory data collected from a motorway to study driver behaviour to explain the formation and propagation of stop-and-go waves in congested motorway traffic. They found that difference in driving behaviour, ranging from aggressive too timid, seems a more appropriate cause for traffic oscillations than seeking lane change opportunities or acceleration and deceleration characteristics.

This conclusion is also found in a follow-up study in which more trajectory data from multiple locations is used (Laval 2011).
Zheng et al. (2011a) found that lane changing is a possible trigger for the deceleration waves in traffic at bottlenecks. They applied the Wavelet Transform method on Next Generation Simulation (NGSIM) empirical trajectory data. In a follow-up study in which the same method was used on a larger trajectory dataset, comparable conclusions were drawn (Zheng et al. 2011b).
Treiber et al. (2000) used loop detector data from multiple German motorways to study congestion characteristics. Their data suggests that the congested states depend not only on the traffic situation but also on the specific infrastructure. Coifman et al. (2005) used loop detector data to study traffic flow characteristics at bottle necks. In this study and a follow-up study (Coifman and Kim 2011) they found that the road capacity downstream of a bottleneck is reduced due to lane changing traffic.

2.4.2. Microscopic simulation models

The HCM suggests that traffic simulation can be used to assess the traffic operations performance of roads (HCM 2010). A few examples of micro simulation software packages mentioned in literature are: CORSIM (Sun and Kondyli 2010), VISSIM (Chih-Sheng and Nichols 2015), PARAMICS (Dijkstra 2011), AIMSUN (Young et al. 2014), ARTEMiS (Hidas 2005), TRITONE (Astarita et al. 2012) and FOSIM (Dijker and Knoppers 2004). FOSIM is the prescribed microsimulation package for motorway assessments in The Netherlands.

The use of microscopic simulation software for evaluating a design is part of the regular motorway design process. Most of these applications do not result in scientific papers. However some examples of design evaluations, related to motorways, are found in the literature. Garber and Fontaine (1999) used CORSIM to evaluate the performance of different interchange types under different magnitudes of traffic. Based on these results guidelines for intersections were developed. Wang et al. (2014) used VISSIM for estimating the capacity of a weaving segment. They calibrated VISSIM with a capacity accuracy of about 90%, using 5 minute aggregated data recorded by videos and data from loop detectors. Martínez et al. (2011) used VISSIM to elaborate recommendations about the best motorway exit ramp layout. They calibrated VISSIM for speed distributions gained from video recordings. Sharma and Chatterjee (2007) used VISSIM to compare two alternative interchange designs: diverging diamond and conventional diamond interchange to help in providing guidelines to the decision makers for selecting the best alternative.

In the above mentioned studies microscopic simulation programs have proven to be powerful methodologies for assessing and comparing different designs on the matter of operations. Especially macroscopic features are captured well. Current microscopic simulation programs however are not suitable for studying microscopic behaviour and the effect of more detailed road geometry aspects, such as alignment, shoulders and super elevation. Most – if not all – microscopic models have problems in terms of their predictive validity. Research has shown that microscopic behaviour, such as gap acceptance, is not simulated accurately (Daamen et al. 2010). It is however possible to calibrate a program, but even after calibration the results may vary up to 10% from measured data (Wang et al. 2014).

2.5. Methodologies to assess traffic Safety

In recent years a lot of research was done to gain more understanding about the factors that affect traffic safety by combining traffic flow characteristics, road characteristics and crash statistics. This has resulted in multiple methodologies that can be used to assess traffic safety.

2.5.1. Crash prediction models

Crash prediction models are used to study the factors that affect the number of crashes occurring on a specific (stretch of) road over some specified time period (week, month, year, number of years). In general, the most basic crash data consist of crash location; date and time; crash severity; collision type; and basic information about the roadway, vehicles, and people involved. The HSM (2010) Part C provides detailed steps for applying a predictive method for estimating expected average crash frequency of a network, facility, or individual site. The types of roads considered range from suburban arterials to rural multilane highways.

The use of crash statistics has a number of drawbacks: 1) only available for existing roads and existing situations (Dijkstra 2011); 2) crash data are not always sufficient due to small sample sizes leading to inconclusive results, and the lack of details to improve our understanding of crash failure mechanism and especially the driver crash avoidance behaviour (Tarko et al. 2009; Laureshyn et al. 2010); 3) accidents are rare events, making it troublesome to base traffic safety analyses at individual sites on accidents only (Laureshyn et al. 2010); 4) not all crashes are reported and the level of underreporting depends on the accident's severity and types of road users involved (Laureshyn et al. 2010; Anastasopoulos et al. 2008; Archer 2005) and 5) the lack of details to improve our understanding of crash failure mechanism and especially the driver crash avoidance behaviour (Tarko et al. 2009).

For the description of the relationship between different elements many different types of models were developed (HSM 2010). A good overview on the available models, used data and their advantages and disadvantages is made by Lord and Mannering (2010). Different data issues are mentioned. For a detailed description of these data issues and the modelling methods which were developed the reader is referred to the overview by Lord and Mannering (2010).

All models are developed using crash statistics and traffic volumes, but the use of detailed traffic data and road geometry data depends on the focus of the research. There are some examples of studies that focus on estimating safety around motorway ramps and interchanges (Guo 2012; Bared et al. 2006; Pilko et al. 2007). The use of large datasets with many aspects makes it possible to examine the relationships between many different variables. For example Garber and Ehrhart (2000) examined 44 variable combinations. To avoid circumstantial correlation only evidential differing variables can be chosen. This is a problem when more subtle variations, such as a slight reduction in ramp spacing, need to be investigated. The desired level of statistical validation requires sufficient data. When it comes to road geometric elements it is quite often difficult to get sufficient data on this (Pilko et al. 2007; Guo 2012). Other models were developed to predict the crash likelihood based on real-time traffic flow variables measured from loop detectors. These studies used matched case-control methodology for the model development (Abdel-Aty et al. 2004; Roshandel et al. 2015; Shi and Abdel-Aty 2015).

2.5.2. Surrogate safety measures

Because of the stated drawbacks of using crash statistics and the desire to take behaviour of individual drivers into account, researchers studied the possibility to replace and complement the traditional crash statistics with a surrogate (Laureshyn et al. 2010; Tarko et al. 2009). The surrogate was found in traffic safety indicators, which increase the possibility of: 1) evaluating traffic safety changes more efficiently and in a shorter time; 2) elaborating the relation between design elements and risk 3) more thoroughly understanding the relationships between behaviour and risk and 4) a better understanding of the processes characterizing the normal traffic and critical situations including crashes and near crashes.

In order to do so, researchers tried to find measurable aspects in the traffic stream by which traffic safety can be quantified. The most frequently used measure is the Time To Collision (TTC) value at an instant t is defined as: "the time that remains until a collision between two vehicles would have occurred if the collision course and speed difference are maintained" (Minderhoud and Bovy 2001). Minderhoud and Bovy (2001) proposed two additional safety indicators based on the TTC: the TET (Time Exposed Time-to-collision) and the TIT (Time Integrated Time-to-collision). The duration of exposition to safety-critical time-to-collision values over specified time duration is used here as a safety indicator. The TET is a summation of all moments (over the considered time period) that a driver approaches a front vehicle with a TTC-value below a certain threshold value. The TIT is the integral of the time-to-collision profile. Although explicit thresholds are not mentioned, a general rule is applicable: the higher a TTC-value, the more safe the situation is (Minderhoud and Bovy 2001; Bevrani and Chung 2012).

In the case where the leading vehicle is faster than the following vehicle, TTC index cannot be estimated in a finite number. This is a practical weak point of TTC index because the situation in which two subsequent vehicles following each other at a very close distance, can be considered as unsafe. Even if the leading vehicle drives at a slightly higher speed (Uno et al. 2002). To counter this weak point the Potential Index for Collision with Urgent Deceleration (PICUD) was proposed. This measures evaluates the possibility that two consecutive vehicles might collide, defined as the distance between the two vehicles considered when they completely stop (Uno et al. 2002; Bin et al. 2003).

A further variation of the Time-to-Collision concept is Post-Encroachment Time (PET). This measure is used to measure situations in which two road-users that are not on a collision course, pass over a common spatial point or area with a temporal difference that is below a predetermined threshold (Archer 2005). One study is found in which the PET is calculated for a motorway (Zheng et al. 2014a). The PET was calculated for lane changing traffic. This research concludes that the application of extreme value theory over PETs during lane change manoeuvres provides a promising approach for motorway safety evaluation.

Two other indicators related to braking were introduced: Individual Braking Time Risk (IBTR) and Platoon Braking Time Risk (PBTR) or J-value (Bevrani and Chung 2012). IBTR stands for the likelihood of a rear-end crash if the leading vehicle stops. PBTR stands for the accumulated risk of collision for each vehicle inside a platoon.

Surrogate safety measures can be derived from trajectory data. For the validation of these measures crash statistics can be used. Also a method which does not require crash statistics is developed (Tarko 2012; Zheng et al. 2014a). The most accurate way to derive surrogate safety measures is to use empirical trajectory data (Archer 2005; Louah et al. 2011). Also data from loop detectors can be used (Li et al. 2014), but this kind of data gives less information than trajectory data. An alternative is to generate trajectories with micro simulation models (Bevrani and Chung 2012; Astarita et al. 2012). This method however has a major drawback: the currently available micro simulation programs are not suitable for safety study purposes (Bevrani and Chung 2012).

2.5.3. Assessment of recorded crashes on video

When video recordings of a crash are available a lot of useful information can be gained from these recordings (Davis and Swenson 2006; Bonneson and Ivan 2013). Especially more insights in the conditions preceding the crash. Video footage of crashes can be used to generate individual vehicle trajectories on which microscopic analysis can be performed, such as deriving surrogate safety measures (Oh and Kim 2010; Davis and Swenson 2006; Guido et al. 2010). The SHRP2 NDS study provided event files for approximately 700 crashes and 7,000 near-crashes. These files contain video footage, a trip summary and other data coded manually, such as driver distraction and cell phone use (NDS 2015). But finding footage of specific locations will still take a lot of effort and will result in only a few number of crashes per facility.

2.6. Comparison of different methodologies

The different methods to collect data related to turbulence and the methods that assess the impact of turbulence on traffic operations and traffic safety, as detailed above are compared in table 2.2. The table is organized based on the different aspects described in figure 2.1 and figure 2.2, i.e. conditions and behaviour.

Three different signs are used with the following interpretations: '+' means that the specified method is suitable to take the considered functionality into account, '-' means that the specified method is not suitable to take the considered functionality into account and '+-' means that the specified method can take the considered functionality into account but with a lack of accuracy.

Loop detectors are very useful to acquire empirical macroscopic traffic data from which turbulence related aspects can be studied. However more detailed information, such as driving manoeuvres and microscopic behaviour cannot be measured directly. Video cameras can be used to derive empirical trajectory data which gives detailed information on driver manoeuvres and macroscopic effects. Because of the level of detail of the collected information, the effects of the road geometry on turbulence can as well be studied. Trajectory data are not suitable for explaining the drivers' decisions leading to manoeuvres and turbulence. This can be studied using a driver simulator or an instrumented vehicle. The advantage of the driver simulator is the controlled environment in which also new designs can be studied. The advantage of an instrumented vehicle is that it can study actual road situation with actual traffic. Both the simulator and the instrumented vehicle consider only a single vehicle and its surrounding vehicles, while loop detectors and video cameras consider all vehicles. Therefore, data from loop detectors and video cameras are more suitable to be used for studying the macroscopic effects on turbulence, compared to data from a driver simulator or an instrumented vehicle.

When it comes to assessing the impact of turbulence on traffic operation, analysing empirical traffic data is a good method for this purpose, especially when empirical trajectory data is available. For non-existing situations, such as new designs, microscopic simulation models can be used. These types of models however cannot model all aspects of the roads' geometry and therefore cannot simulate microscopic behaviour as realistically as desired.

Crash prediction models can be used as a method to assess the impact of turbulence on traffic safety. The drawback of this method is that large quantities of data are required to develop a model which can cope with a large set of variables. This is required when studying the effect of road and traffic characteristics on turbulence and its impact on traffic safety. Surrogate safety measures and video assessments give more traffic safety information on an individual vehicle level. Video recordings of crashes can give detailed insights on individual crashes that occurred in the past but give less insight on microscopic traffic conditions and preceding behaviour and manoeuvres. Surrogate safety measures can take the microscopic traffic conditions into account, but lack the capacity of explaining behaviour. Also information regarding road geometry and environment cannot be directly extracted from these methods.

		methodologies to collect data related to turbulence				**methodologies to assess the impact of turbulence**				
		loop detectors	**video cameras (vehicle trajectories)**	**driver simulator**	**instrumented vehicle / naturalistic studies**	**traffic operations**		**traffic safety**		
						traffic data analysis	**simulation models**	**crash prediction models**	**surrogate safety measures**	**crash video assessment**
new design		–	–	+	–	–	+	+	+	–
existing situation		+	+	+–	+	+	+	+	+	+
conditions to take into account	**road geometry**									
	number of lanes	–	+	+	+	+	+	+	+–	+
	shoulder width	–	+	+	+	+	–	+–	–	+
	length of acc./dec. ln.	–	+	+	+	+	+	+–	–	+
	interchange spacing	–	+	+	+	+	+	+–	–	+
	horizontal alignment	–	+	+	+	+	–	+–	–	+
	vertical alignment	–	–	+–	+	+	–	+–	–	–
	super elevation	–	–	–	+	+	–	+–	–	–
	traffic									
	average daily traffic	+	+	+–	+	+	+	+	+	+–
	speed/– differences	+	+	+–	+	+	+	+	+	+–
	density per lane	+	+	+–	+	+	+	+	+	+–
	environment									
	weather conditions	–	+–	–	+	+	–	+–	–	+–
behaviour	driving manoeuvres	–	+–	+	+	+	+–	–	+–	+–
	microscopic behaviour	–	+	+	+	+	+	+–	+	+–
	macroscopic effects	+	+	–	–	+	+	+–	+	+–

Table 2.2. Overview of Available Methodologies.

2.7. Conclusions and recommendations

Turbulence covers different elements of microscopic traffic characteristics such as lane changing, variation in speeds and headways and is the result of a complex combination of different driving manoeuvres. Literature and motorway design guidelines agree that the level, or magnitude, of turbulence is influenced by road design, traffic volume and driver behaviour, and that turbulence has an effect on traffic operations and safety. Although there seems to be an agreement on what turbulence is, there is no definition found which covers all causes and effects of turbulence. Since turbulence is a commonly present in the traffic stream, two definitions are proposed:

- Turbulence:
    - individual changes in speed, headways, and lanes (i.e. lane-changes) in a certain road segment, regardless the cause of the change;
- Level of Turbulence:
    - the frequency and intensity of individual changes in speed, headways and lane-changes in a certain road segment, over a certain period of time.

The level of turbulence is expected to be higher around discontinuities (on motorways) compared to continuous road stretches. Although research and design guidelines agree on the concept of turbulence, a gap can be observed between guidelines and research: where guidelines frequently rely on unreferenced assumptions and rules of thumb, research tries to assess the impacts of different elements of turbulence on traffic safety and traffic operations and the influence of design characteristics on these impacts. Furthermore, the results of research do not seem to fully find their way into the motorway design guidelines. One of the reasons for this may be that the currently available methodologies are not able to combine the effects of road design on turbulence with its impact on both traffic safety and traffic operations.

Several methods to assess traffic operations and traffic safety exist today, such as the use of microscopic simulation programs, surrogate safety measures, crash prediction models and driver simulators. However, each of the methods has its own strengths and weaknesses. Considering these strengths and weaknesses, combining different methods might be a potential solution for this problem, that is worth researching in the future. The overview in table 2.2 suggests that combining microscopic simulation software with surrogate safety measure methodologies is the most promising way forward. By doing that, road characteristics, traffic characteristics and microscopic behaviour can be taken into account to evaluate the safety and capacity of a certain motorway segment. There are however a few challenges that need to be overcome.

The first challenge is that the currently available microscopic simulation programs are not designed for traffic safety studies (Bevrani and Chung 2012). These programs also do not simulate merging behaviour as accurately as desired. This makes them unsuitable for generating trajectory data from which surrogate safety measures can be derived (Gettman and Head 2003; Bevrani and Chung 2012). Also surrogate safety measures seem to be in a theoretical stage, where valid threshold values need still to be set.

For the improvement of the existing microscopic simulation models a more realistic, mathematical description of merging behaviour is needed. Despite the huge improvements in microscopic simulation models' appearance and visualization, the advancement in its traffic behaviour performance is at a much slower pace. For example, the most recent car following model in VISSIM dates from 1999 and AIMSUN uses a car-following model based on the model developed by Gipps (1981).
The most important improvements should be the merging behaviour in itself by using gap selection instead of gap acceptance theory. Other types of behaviour such as pre allocation, courtesy yielding and relaxation phenomena should also be integrated more realistically. But also unsafe situations should be possible to occur in models in order to be able to generate realistic trajectories to derive surrogate safety measures. It is also important to develop mathematical models that take into account, for example, different driving styles and behaviours of drivers and account for drivers' heterogeneity. Also existing or maybe new models should be calibrated and validated by the use of empirical trajectory data. The behavioural aspects can be studied by using driver simulator, instrumented vehicle or a naturalistic driver study.

A second challenge is that good quality empirical trajectory data is scarce. The available trajectory data focusses mainly on the merging area (Daamen et al. 2010; Marczak et al. 2013; NGSIM 2015) and not so much on the areas upstream and downstream of the discontinuity. Therefore new data is needed.

3. Macroscopic characteristics of turbulence

This chapter was first published in "Transportmetrica A: Transport Science" (Van Beinum, A., M. Hovenga, V. Knoop, H. Farah, F. Wegman, and S. Hoogendoorn. 2017. "Macroscopic Traffic Flow Changes around Ramps." Transportmetrica A: Transport Science:1-32. doi: 10.1080/23249935.2017.1415997).

Abstract

Traffic is more turbulent around motorway ramps due to route choice related lane changes and anticipatory or cooperative manoeuvres. These manoeuvres result in changes in speed and headways and have a negative influence on traffic safety and capacity. However, the distance upstream where turbulence starts, and the distance downstream where it dissolves are yet unknown. In this chapter we propose a new method for detecting the start and end distances of turbulence. This method relies on the analysis of large quantities of empirical loop detector data from multiple on-ramps and off-ramps at different sites. By comparing the traffic operations near ramps to those on a regular motorway section, the length of the turbulence influence area can be estimated. The scope of the research is limited to three-lane motorways in The Netherlands, and shows that the distribution of traffic over the motorway lanes is a useful indicator for turbulence.

3.1. Introduction

Entering and exiting traffic on ramps and weaving areas causes lane changes in the traffic flow on motorways. These lane changes are not only performed by entering and exiting traffic but can also be a reaction of through-going traffic attempting to avoid or to make space for the entering traffic. Other behaviours can be decelerating or accelerating to increase or decrease the headway with the vehicle in front (HCM 2010). The collective name given to these responses is 'turbulence', (Abdel-Aty and Pande 2005; Golob et al. 2004; Kondyli and Elefteriadou 2011, 2012; Lee et al. 2003a). Turbulence is a common phenomenon in traffic (HCM 2010).The level of turbulence increases around motorway locations where mandatory lane changes occur, such as at on-ramps (Kondyli and Elefteriadou 2011), off-ramps and weaving areas. Turbulence has been shown to have a negative impact on both traffic safety and traffic operations (Abdel-Aty and Pande 2005; HCM 2010; Golob et al. 2004; Lee et al. 2003a).

In (Van Beinum et al. 2016) we proposed the following definitions for turbulence in the vicinity of discontinuities, such as ramps:

- Turbulence:
    - individual changes in speed, headways, and lanes (i.e. lane-changes) in a certain road segment, regardless of the cause of the change;
- Level of Turbulence:
    - the frequency and intensity of individual changes in speed, headways and lane-changes in a certain road segment, over a certain period.

Turbulence is relevant for road design and should be taken into account by applying sufficient ramp spacing and sufficient road length for weaving traffic (AASHTO 2011; HCM 2010; Rijkswaterstaat 2017; RAA 2008; DMRB 1994). There are different approaches to determine the required distance for ramp spacing (Fitzpatrick et al. 2011), such as decision and manoeuvre time, required length for signposting and providing sufficient weaving length (HCM 2010). The general concept behind these approaches is that turbulence around ramps will intensify when the available road length for lane changing becomes shorter (Bared et al. 2006; Pilko et al. 2007).

The actions of individual merging or diverging vehicles create turbulence near the ramp. The ramp influence area experiences a higher rate of lane-changing than is normally present on ramp-free sections of a motorway (HCM 2010). Thus, the *Level of Turbulence* is expected to increase before (upstream of) and to decrease after (downstream of) a ramp. Kondyli and Elefteriadou (2012) found that turbulence due to merging manoeuvres begins 110 m upstream of the gore. The gore is the painted white triangle which indicates that the road splits or merges. The default design of a motorway interchange is shown in figure 3.1. According to the HCM (2010) the merge influence area occurs between approximately 460 m (1.500 ft.) upstream and 460 m downstream of the gore. To the best of our knowledge other literature that describes the start or the end of a raised level of turbulent traffic is not available.

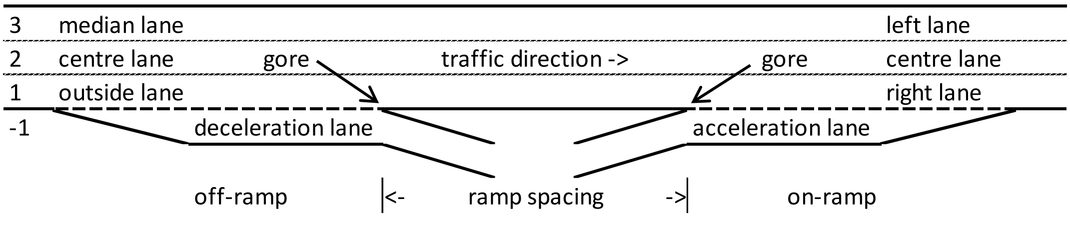


Figure 3.1. The default design for motorway on-ramps and off-ramps.

The goal of this chapter is to provide a method to determine empirically at what distance a raised level of turbulence starts upstream of a ramp and at what distance downstream of a ramp it dissolves. The length-of-motorway over which the level of turbulence is raised is relevant for road design guidelines. The spacing of successive ramps is determined based on this length. This is to prevent that the capacity of the motorway near an on-ramp or an off-ramp decreases too much and becomes a bottleneck when the traffic flow increases. However, little is known about this length, which hampers establishing solid design guidelines. Therefore additional research is needed to gain more knowledge about this length to validate or improve our current motorway design guidelines. This additional research should be based on empirical data and should be generic for different situations, such as different traffic volumes.

3.2. Background

When traffic volume exceed the motorway capacity, traffic congestion occurs and the risk of crashes increases. This often happens in the proximity of on-ramps and off-ramps (Lee and Abdel-Aty 2008) because of the changes in demand and capacity at these locations. For example: the on-ramp flow has an important impact on the formation of the stop-and-go traffic flow near the ramp (Ngoduy 2008; Tang et al. 2009; Tang et al. 2008; Leclercq et al. 2016).

Turbulence which is created by entering or exiting traffic, and the courtesy or anticipatory related manoeuvres which are performed by through-going motorway traffic, reduces the motorway's capacity (Abdel-Aty and Pande 2005; HCM 2010; Golob et al. 2004; Lee et al. 2003a). The Dutch legal traffic regulations state that a lane changing vehicle (for example an entering vehicle) has to give priority to vehicles in the target lane (Knoop et al. 2017; Daamen et al. 2010). Nevertheless, vehicles on that target lane sometimes show courtesy to entering traffic by changing lane towards the median lane and sometimes also by reducing speed to create a larger gap which the entering vehicle can merge into.

At off-ramps exiting vehicles must change lanes to the outside lane of the motorway (if not already driving there) to access the deceleration lane. The increased traffic density on the outside lane and possible deceleration of exiting traffic may cause through-going motorway vehicles to change lanes to the centre or median lane to avoid exiting traffic (HCM 2010; Kondyli and Elefteriadou 2011).

It can be concluded from the above studies that lane changes are an important element of turbulence. In literature, lane changes are categorized as either discretionary, mandatory or cooperative. Discretionary lane changes are performed by drivers to improve their position in the traffic stream (Kondyli and Elefteriadou 2012). Mandatory lane changes are performed as a result of strategic route choice decisions, such as to enter or to exit the motorway (Kondyli and Elefteriadou 2012; Minderhoud 1999). Cooperative lane changing is characterized by a follower that slows down (Hidas 2005) or changes lanes (Daamen et al. 2010; Knoop et al. 2010) to allow the subject vehicle to enter. Also, entering vehicles are sometimes willing to accept very short gaps as they enter the motorway, but 'relax' to more comfortable values shortly thereafter (Laval and Leclercq 2008; Marczak and Buisson 2015; Smith 1985; Sultan et al. 2002).

3.2.1. Conceptual framework of turbulence

The behaviour of individual vehicles (microscopic behaviour) has a macroscopic effect on the traffic stream. For example: a lane change will result in a changed density per lane and a changed headway distribution per lane. Acceleration and deceleration may also result in a changed headway distribution and speed differences between different vehicles. This concept is illustrated in figure 3.2.

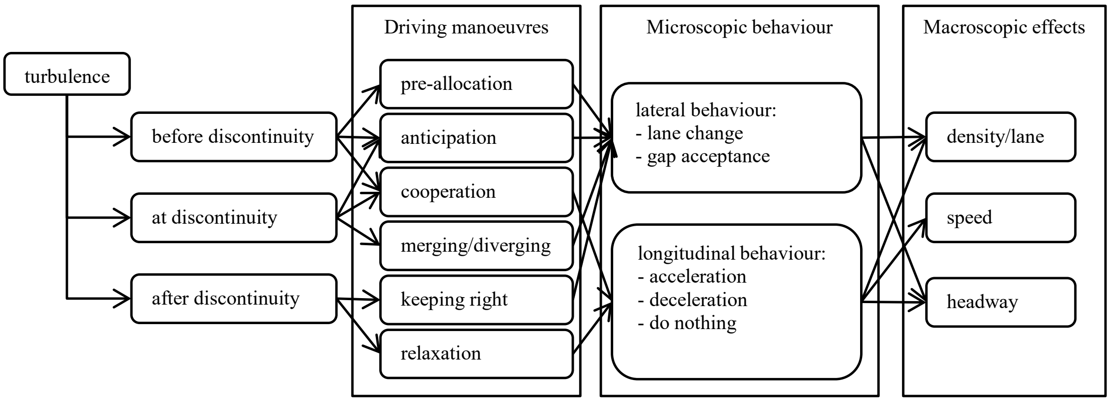


Figure 3.2. Theoretical framework for turbulence (Van Beinum et al. 2016).

According to this theoretical framework, three different macroscopic effects are to be expected to occur at on-ramps and off-ramps: 1) change in density, 2) change in speed, and 3) change in headway (distribution).

Daamen et al. (2010) found that through-going motorway traffic creates room for merging drivers (cooperative lane changing) at the location of the merge by changing lanes from the outside lane to an inside lane of the motorway. This Behaviour will change the distribution of traffic over the different lanes (lane flow distribution), compared to a normal continuous stretch of motorway. It will also result in a lower fraction of flow on the outside lane just upstream of the on-ramp. Knoop et al. (2010) found that the lane flow distribution is different at on-ramps compared to a regular continuous situation for densities greater than 10 veh/km. This is in part explained by cooperative lane changing. They also found that the fraction of flow on the median lane gets higher when the fraction of flow on the outside lane gets lower. The fraction of flow in the centre lane hardly changes. This phenomenon is also mentioned in the HCM (HCM 2010) and also found by (Carter et al. 1999). At off-ramps the opposite takes place. Just upstream of an off-ramp the fraction of flow on the outside lane is expected to be higher compared to an outside lane on a normal continuous stretch of motorway (Amin and Banks 2005).

One common assumption in driving Behaviour is that vehicles drive at a certain desired speed. A well-known theory that describes the macroscopic effects of desired speed is Daganzo's behavioural theory of multi-lane traffic (Daganzo 2002a, 2002b). Daganzo categorizes drivers in aggressive (rabbits) and non-aggressive (slugs) drivers, and categorizes lane types in shoulder lanes and passing lanes. In free flow conditions rabbits will travel faster than slugs, with the rabbits all in the passing lane and the slugs all in the shoulder lane. Nevertheless, several studies have raised some doubts about this theory and suggest, contrary to Daganzo, that drivers are motivated by more than just the desired speed (Amin and Banks 2005; Banks and Amin 2003; Banks et al. 2003). A more complete theory should also consider factors such as lane and ramp configurations, average vehicle spacing, and lane-changing Behaviour. Despite the discussion about the theory it is safe to state that when a driver is not able to drive at the desired speed, a lane change may be imminent if possible.

In the European mainland countries, drivers are bound to the right-side rule by which it is mandatory for drivers to change lanes to the right if there is sufficient space to do so. Overtaking takes place on a left lane. This will naturally result in a situation where faster vehicles drive on the left and slower vehicles drive on the right side of the motorway (Daganzo 2002a). In the vicinity of an on-ramp or off-ramp mandatory lane changes also take place as well as courtesy-related discretionary lane changes. When faster vehicles change lanes towards the outside lane and slower vehicles change lanes towards the median lane, the mean speed on all lanes may change due to the mixing of desired speeds.

3.2.2. Motorway design guidelines

Ramp spacing is an important part in motorway design and in design guidelines. The basic principle is that there should be sufficient spacing between succeeding ramps to cope with turbulence in the traffic stream. Different guidelines use different approaches for dealing with turbulence. For example: the AASHTO Green Book (AASHTO 2001) uses a set of minimum values for ramp spacing and the Dutch guidelines (Rijkswaterstaat 2017) use a criteria called 'turbulence length', which is the required distance between successive discontinuities. The prescribed lengths differ per type of discontinuity and per guideline. For example, table 3.1 shows the different prescribed distances between an on-ramp followed by an off-ramp (measured from gore to gore) according to four different guidelines.

country	distance	design criteria
The Netherlands (Rijkswaterstaat 2007)	750 m	design speed
Germany (RAA 2008)	1100 m*	minimum value for isolated intersection planning
USA (AASHTO 2001)	600 m**	road category: freeway
	480 m***	road category: freeway
UK (DMRB 1994) , Vol.6, Sec. 2, Cpt 4.7	450 m****	3.75V, where V = design speed = 120 km/h

Table 3.1. Distance between On-Ramp and Off-Ramp Prescribed in Different Guidelines; * 250 m acceleration lane + 600 m between acceleration and deceleration lane + 250 m deceleration lane; ** system to service interchange (weaving); *** service to service interchange (weaving); **** may be increased to the minimum requirements for effective signing and motorway signalling.

Literature and guidelines agree on the existence and importance of turbulence and state that a raised level of turbulence is present in a certain influence area upstream and downstream of a ramp. This influence area is relevant for determining the required ramp spacing to avoid traffic operations and traffic safety problems. There is however no consistency when it comes to the length of this influence area. Some recommended values on the length to be considered are given: 457 m downstream of the gore of an on-ramp, and 457 m upstream of an off-ramp (HCM 2010); 110 m upstream and 260 m downstream of the gore of a ramp (Kondyli and Elefteriadou 2012); 150 m upstream / 750 m downstream of an on-ramp and 750 m upstream / 150 m downstream of an off-ramp (Rijkswaterstaat 2017). This inconsistency may be explained by differences in driving Behaviour in different countries, which is a cultural element and in some cases influenced by legislation.

Literature and guidelines show that the level of turbulence is expected to increase upstream and to decrease downstream of a ramp and that changes in lane flow distribution and changes in speed are indicators for turbulence. However, the distance upstream where turbulence starts and the distance downstream where it dissolves are yet unknown. As our study was conducted in The Netherlands we expect that the turbulence influence areas specified in the Dutch design guidelines give a good indication of where a raised level of turbulence starts and dissolves. However, this will be tested in this study.

3.3. Research setup

For this study we used empirical loop detector data from different on-ramps and off-ramps at several three-lane motorways in The Netherlands. These detectors provide 1-minute aggregated flow and mean speed data for each lane, which are used to calculate an approximate density. We have limited this study to free flow conditions only.

Since loop detectors in The Netherlands are spaced with a distance of about 300 - 500 m, it is not possible to observe a detailed gradual change in traffic characteristics. To tackle this problem an innovative approach was applied in which data from different detectors at different sites are combined. The basics of this principle are shown in figure 3.3.

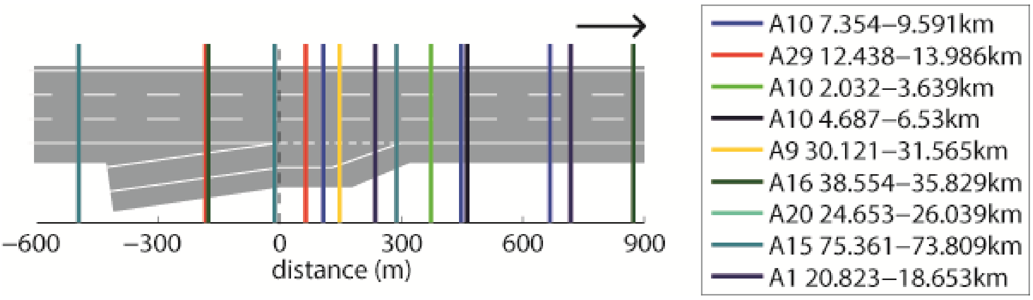


Figure 3.3. Combined loop detectors from different sites.

To the best of our knowledge, no other use of this method is found in the literature. Our hypothesis is that data from loop detectors at different sites can be combined to study changes in the traffic flow for specific situations (e.g. ramps) when road design and traffic flow characteristics are similar. When the driving behavioural patterns of the driver population are similar, the macroscopic traffic flow characteristics at other similar sites will be comparable.

Accurate identification of changes in speed and flow requires that the detectors are spaced at small distances. A lane change takes about 5 s (Hill et al. 2015) which corresponds to a distance of approximately 140 m at 100 km/h. A difference in speed of 5 m/s takes about 150 m at an acceleration or deceleration rate of 1 m/s^2 and an initial speed of 100 km/h. Therefore we aim for a minimum spacing of 150 m between trajectories.

The first step in our research is to test whether combined macroscopic loop detector data, that is collected from loop detectors at different sites, is suitable for studying macroscopic traffic flow changes at specific situations.

The second step in our research is to study the location where a raised level of turbulence starts and where it dissolves by comparing the measured traffic characteristics at a continuous stretch of motorway (basic motorway) to characteristics at ramps (on-ramp and off-ramp). The measured characteristics are the traffic flow distribution and the average speeds at the lane level.

3.4. Data collection and processing

The data was collected using loop detectors from different basic motorways, on-ramps and off-ramps. Loop detector data in The Netherlands is accessible on-line at the NDW website (NDW 2015). To meet the similarity demands for road design characteristics and traffic flow characteristics, various site criteria and data filters were applied. This resulted in a selection of sites, detectors and measurement periods.

3.4.1. Site selection criteria

The different sites must have comparable characteristics, such as design, legal speed limit and traffic composition. The sites should also be at sufficient distance from other motorway elements that could influence the macroscopic traffic characteristics. Criteria were applied for motorway characteristics (number of lanes, presence of peak hour lanes, variable speed limits), design (acceleration/deceleration lane length) and the distance to the nearest discontinuity upstream and downstream.

Number of lanes, Motorway characteristics and Design

Our innovative approach was applied for one common type of motorway in the Netherlands: a standard motorway with three lane carriageways and a legal speed limit of 100 km/h. Motorways which are equipped with peak traffic lanes or variable speed limits were excluded. Since the length of an acceleration lane or deceleration lane is expected to have an important effect on the stability of the main carriageway traffic flow (Ngoduy 2008) sites where the ramp has not been constructed according to the Dutch design guidelines were also excluded. The selected motorways are all located in the western part of The Netherlands.

Distance to the nearest discontinuity upstream and downstream

To prevent the results being biased by other motorway elements further upstream or downstream, sufficient spacing to the nearest discontinuity upstream and downstream is required. The spacing criteria used in this study are the result of a trade-off between a large spacing and the number of sites that meet the criteria. The chosen values are shown in figure 3.4. For an on-ramp the minimal distance downstream to the next discontinuity is 1000 m and the minimal distance upstream is 3600 m, measured from the gore. When these criteria are met, the detectors within the area of 700 m upstream and 2400 m downstream of the gore were used for the experiment. The same principle holds for the selection of on-ramps and off-ramp detectors.

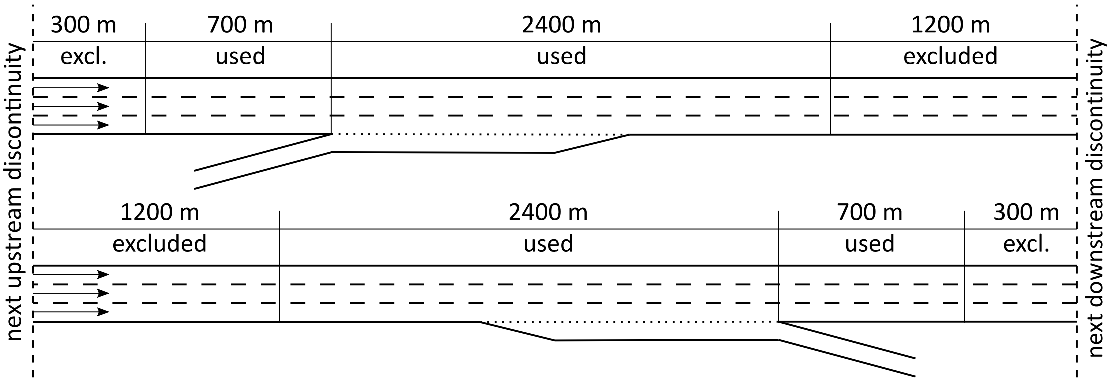


Figure 3.4. Discontinuity spacing criteria of on-ramp and off-ramp.

3.4.2. Data collection and filtering

The measurements were taken at days with comparable conditions, such as: period of year, weather, daylight, amount of commuting and recreational traffic, and traffic density. A total of 34 days were selected. Unrealistic measurements were filtered from the data set.

Weather characteristics

April 2013 and 2014 were selected as input months because these months were neither winter nor summer months, had only few rainy days and had no extreme temperatures. Days with (> 10 mm) rainfall were excluded. In these months the macroscopic traffic flow characteristics were expected to be average.

Traffic characteristics

Only work days were selected. All weekend days and holidays were excluded. Fridays before the holidays were also excluded because traditionally many people in the Netherlands start traveling to their vacation destinations on those days.

Traffic density

Macroscopic changes in the traffic stream take place when vehicles enter or leave the motorway, and when these vehicles influence the driving behaviour of the surrounding vehicles. Therefore, macroscopic traffic conditions depend on the density and the analysis needs to be restricted to a certain density bin. The density should be high enough for entering vehicles to influence through-going motorway traffic. On the other hand, the density should not be too high to avoid measurements in congested traffic conditions. Knoop et al. (2010) found that on a three-lane motorway changes in lane flow distribution are significant for densities between 10 veh/km and 130 veh/km. In our database the measured densities range between approximately 15 veh/km and 80 veh/km (over all lanes). In this study we have chosen three different density bins for the analysis. The study focusses on a moderate density bin of 33 - 39 veh/km. The results for this density were compared to the results for a low density bin (25-27 veh/km) and a high density bin (50-52 veh/km). Although harder to observe directly, density was chosen over traffic flow because density is more reliable for excluding congested traffic conditions than traffic flow.

Unrealistic entries

Unrealistic measurements were excluded from the dataset by applying two filters. The first filter excluded measurements with speeds above 220 km/h or below 80 km/h. High mean speeds could indicate a defect in the loop detector and mean speeds below 80 km/h could indicate congestion. Loops which are suspected to be defective were excluded entirely. The second filter excluded measurements with deviating data characteristics. Two criteria were used: 1) the relation between traffic density and fraction of flow and 2) the speed distribution. The traffic density on a lane is expected to increase when fraction of flow on that lane increases. A different relation could indicate a defect in the loop detector. The speed distribution is expected to have a single peak at approximately 100 km/h (the legal speed limit). A distribution with multiple peaks, or a significantly lower mean could suggest a temporary lower speed limit due to, for example, an incident. All days which showed multimodal distributions were excluded for that specific detector.

Selected sites

The selected detectors, and the characteristics of the filtered data are shown in table 3.2, table 3.3 and table 3.4.

site	road	detector	rel. dist. to first detector [m]	n	speed [km/h]		flow [veh/h]	
					mean	std.	mean	std.
1	A 15	1	0	1,032	102.5	2.98	3,807	186
1	A 15	2	1,100	2,340	102.1	3.09	3,794	195
2	A 4	1	0	3,716	103.1	2.56	3,799	173
2	A 4	2	300	3,778	102.9	2.59	3,796	176
2	A 4	3	600	3,746	103.7	2.69	3,830	175
2	A 4	4	1,100	3,690	100.6	2.73	3,656	172
2	A 4	5	1,500	3,518	101.4	2.69	3,761	175
3	A 15	1	0	1,014	104.0	3.18	3,842	179
3	A 15	2	600	256	103.1	3.14	3,814	189
3	A 15	3	1,100	778	103.1	3.14	3,810	187
3	A 15	4	1,600	402	104.4	3.19	3,851	191
4	A 16	1	0	3,383	100.9	2.69	3,739	178
4	A 16	2	400	3,496	101.5	2.70	3,763	178

Table 3.2. Data characteristics basic motorway.

site	road	detector	dist. to gore [m]	n	speed [km/h]		flow [veh/h]	
					mean	std.	mean	std.
7	A 15	2	-498	1,806	105.5	2.91	3,879	175
2	A 29	2	-186	948	102.4	3.16	3,824	182
6	A 16	2	-177	3,170	100.4	2.95	3,764	184
7	A 15	3	-14	1,953	104.0	2.85	3,830	176
2	A 29	1	63	794	102.0	2.94	3,770	188
1	A 10	2	107	1,755	99.4	2.36	3,627	164
5	A 9	1	146	3,215	97.9	2.12	3,584	155
8	A 1	1	234	3,855	105.7	3.13	3,885	189
7	A 15	1	287	2,888	102.6	3.47	3,713	197
3	A 10	1	373	3,127	104.2	2.95	3,747	181
4	A 10	1	462	3,394	101.9	2.79	3,690	170
1	A 10	1	666	3,689	100.8	2.68	3,663	169
8	A 1	2	717	3,842	106.1	3.04	3,873	189
6	A 16	1	872	4,202	101.3	2.91	3,734	181

Table 3.3. Data characteristics on-ramp.

site	road	detector	dist. to gore [m]	n	speed [km/h]		flow [veh/h]	
					mean	std.	mean	std.
3	A 4	2	-2061	3,746	103.7	2.69	3,830	175
3	A 4	1	-1681	3,778	102.9	2.59	3,796	176
3	A 4	5	-1427	3,716	103.1	2.56	3,799	173
3	A 4	4	-997	3,723	104.9	2.68	3,856	175
5	A 10	5	-991	3,604	104.0	2.77	3,791	173
5	A 10	2	-831	3,471	107.4	2.95	3,917	180
4	A 1	1	-821	3,465	107.0	3.16	3,909	191
5	A 10	3	-700	3,556	102.3	2.94	3,739	174
3	A 4	3	-676	3,675	102.8	2.69	3,767	174
2	A 1	1	-610	1,561	104.0	2.51	3,845	165
5	A 10	6	-571	3,270	96.8	2.84	3,526	166
5	A 10	1	-390	3,126	96.2	2.85	3,493	168
3	A 4	6	-254	3,749	101.6	2.69	3,695	174
2	A 1	2	-222	1,681	103.5	2.58	3,818	166
5	A 10	4	-218	3,281	97.4	2.74	3,509	168
1	A 10	1	-170	3,199	101.2	2.58	3,694	164
1	A 10	3	253	3,230	98.8	2.25	3,620	156
1	A 10	2	676	3,278	97.1	2.41	3,554	159

Table 3.4. Data characteristics off-ramp.

3.5. Results

3.5.1. Combining loop detectors at different sites

The measured fraction of flow on the different lanes of a basic motorway is found to be comparable for different loop detectors at different sites. Figure 3.5 displays the average and the standard deviation of the measured fraction of flow for each basic motorway detector. The continuous lines represent a linear weighted least squares fit. The polynomial coefficients, as well as the RMSE values are displayed in the figure’s legend. The first polynomial coefficient shows that the slope of the line approaches zero. The coefficient for lane 1 does not deviate significantly from zero. The low RMSE values indicate a good fit. Both the slope and the RMSE indicate that different detectors at different sites give comparable results.

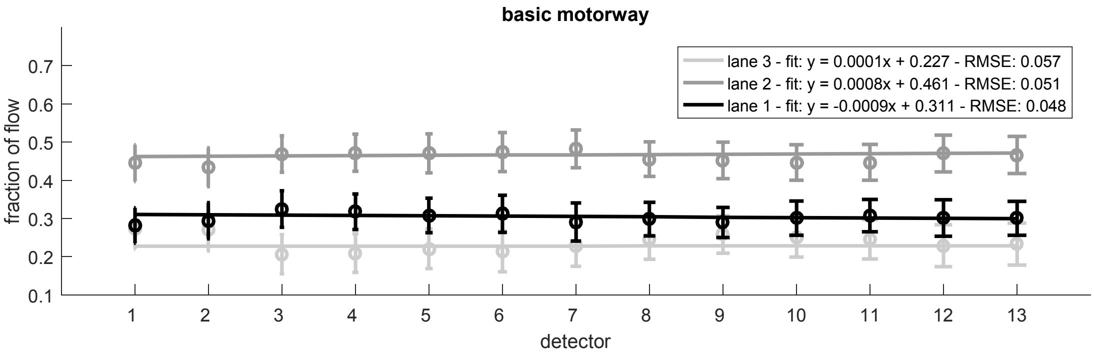


Figure 3.5. Lane flow distribution at a basic motorway.

The measured deviations from the average speeds are all within a range of 3.8 km/h, which is a maximum deviation of 1.9% from the average speed. The mean and standard deviation of the speed measurements are shown in figure 3.6. Again, the continuous line represents a linear weighted least squares fit and the polynomial coefficients, as well as the RMSE values are displayed in the legend. The dotted lines represent the minimum and maximum measured mean speed. The first polynomial coefficient shows that the slope of the line is slightly negative. The slope deviates significantly from zero, which indicates that the measured speeds differ per detector. When site 2 is taken as a reference, table 3.2 shows that the measured mean speed at a single site can range between 100.6 km/h and 103.7 km/h. The measured mean speeds at all the other detectors, except at site 2, are also within this speed range. The measured speeds at site 2 are slightly higher (max. 104.4 km/h).

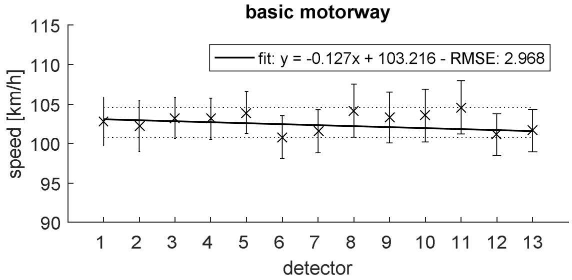


Figure 3.6. Mean and standard deviation of speeds at a basic motorway.

3.5.2. Effects of turbulence

Figure 3.7 shows the mean and standard deviation for the measured mean speeds at on-ramps and off-ramps. The dotted lines indicate the highest and lowest measured mean speed at the basic motorway. It shows that the measured mean speeds at on-ramps and off-ramps vary more than the measured mean speeds at the basic motorway.

The measurements at on-ramps show a drop in speed in the first 200 m downstream of the gore. Further downstream two measurements show a higher speed than measured at the basic motorway. The measured speeds at off-ramps are even more varied. At about 600 m prior to the off-ramp lower speeds are measured compared to the basic motorway. At about 750 m prior to the off-ramp higher speeds are measured and at about 250 m and 650 m downstream of the gore lower speeds are measured.

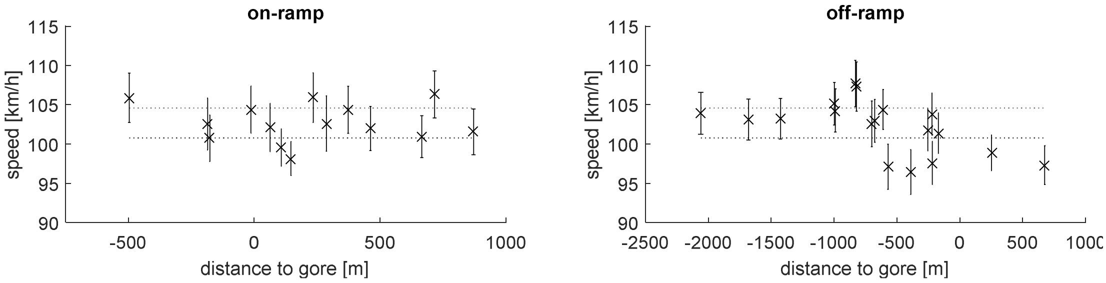


Figure 3.7. Mean and standard deviation of speeds at on-ramps and off-ramps.

The lane flow distribution has been calculated for both the on-ramp and the off-ramp. The fraction of flow is calculated per lane for each detector and is compared to the basic motorway. Figure 3.8 shows the results. The calculated fractions of flow are depicted by an 'o'. The thick line represents a fit (moving average over 5 points) and the dashed line represents the average value measured on the basic motorway.

The results show that the lane flow distribution changes near on-ramps and off-ramps. At on-ramps the changes start at about 300 - 200 m upstream where there is a slight shift of traffic from the right lane towards the left lane. Downstream of the on-ramp gore the fraction of flow on the right lane increases. This effect gradually reduces further downstream and is back to normal at about 900 m downstream.
At off-ramps the changes start about 1,000 m upstream with a slight shift of traffic from the left to the right lane. At 250 m upstream of the gore the change in fraction of flow is at its highest and seems to be gradually reducing further downstream. However, at 600 m downstream the lane flow distribution is still not comparable to that of the basic motorway.

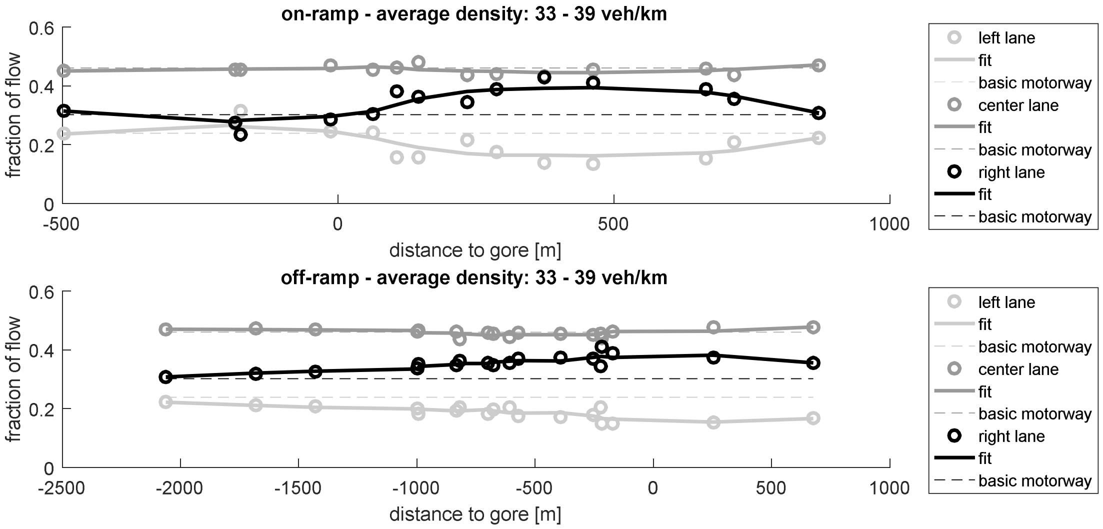


Figure 3.8. Lane flow distribution at ramps.

The lane flow distributions near ramps for lower or higher densities show comparable changes. Figure 3.9 shows the lane flow distribution for a density bin of 25 - 27 veh/km, and figure 3.10 shows the lane flow distribution for a density bin of 50 - 52 veh/km.

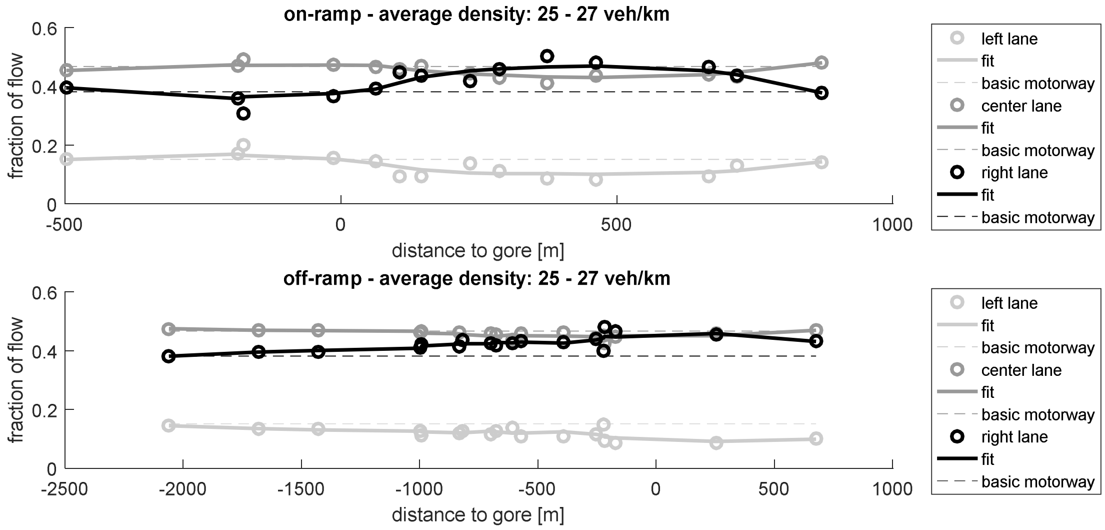


Figure 3.9. Lane flow distribution at ramps with low density.

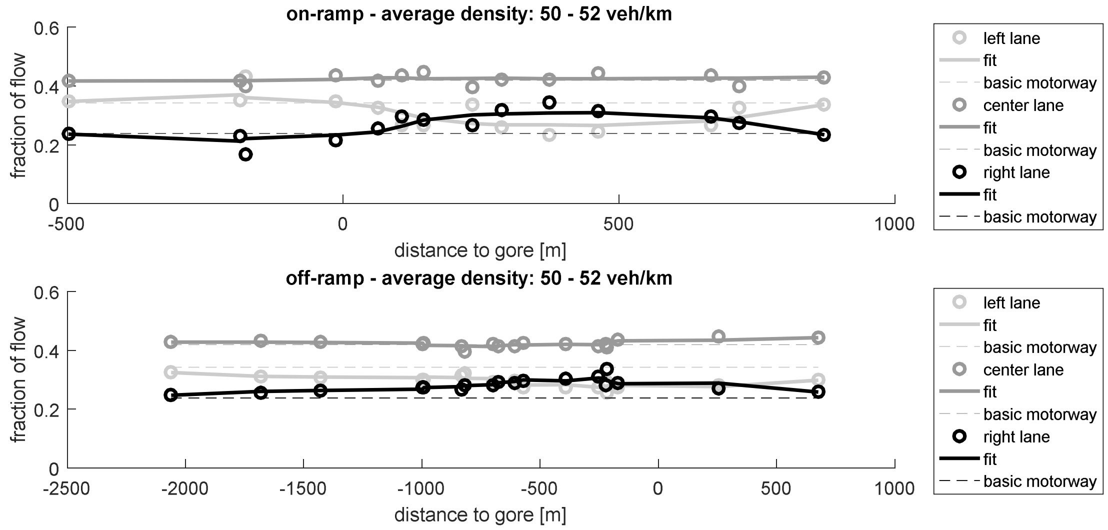


Figure 3.10. Lane flow distribution at ramps with high density.

3.6. Discussion

The lane flow distribution appears to be a macroscopic indicator for turbulence around on-ramps and off-ramps. At on-ramps drivers tend to move to the left just prior to the start of the acceleration lane, which might be the result of cooperative or anticipatory Behaviour. Just downstream of the on-ramp the fraction of flow on the right lane increases, which is most likely the result of entering traffic.

Drivers tend to pre-allocate to the right lane before taking the motorway exit. The first change in fraction of flow is measured at 1,000 m upstream of an off-ramp gore and reaches a maximum on the right lane at the deceleration lane, which is to be expected since most lane changes occur at the deceleration lane. Just downstream of the deceleration lane the fraction of flow on the right lane is expected to decrease again, since exiting traffic will no longer be driving on the right lane. The data however does not show this. The data trend seems to progress towards the original values, but at 600 m downstream of an off-ramp gore the original values are not reached.

This study shows some interesting macroscopic changes in the traffic stream around ramps, compared to a basic motorway section. A change in the lane flow distribution at around 200 m upstream of an on-ramp and 1,000 m upstream of an off-ramp seems very plausible considering that a driver on the motorway who is approaching an on-ramp will only change lanes due to entering traffic if there is any entering traffic. A motorway driver can clearly see entering traffic at about 200 m upstream of the gore. Motorway drivers who want to exit the motorway at the next off-ramp may pre-allocate by changing lanes after the exit sign on the side of the motorway. In The Netherlands the first exit sign is normally positioned at about 1,200 m upstream of an off-ramp. A second exit sign is positioned at 600 m upstream. This is where the change in lane flow distribution is almost at its peak.

The left and the right lane display the majority of changes in the lane flow distribution. The fraction of flow on the centre lane shows hardly any changes and is the highest of the three lanes. These findings are comparable to previous studies (Knoop et al. 2010; Carter et al. 1999; HCM 2010).

Speed is shown to be less stable around on-ramps and off-ramps than at basic motorway sections. Changes in speed are higher around off-ramps than around on-ramps. This could be explained by the difference in type of manoeuvre. Entering the motorway requires accelerating to the legal speed limit while exiting requires decelerating to a safe speed for taking the first curve of the off-ramp after the deceleration lane.

The location of the measured speed drop in the first 200 m downstream of the on-ramp gore corresponds with the location of the acceleration lane and the lower speed may be caused by entering traffic. The location of the speed drop 600 m prior to the off-ramp might be caused by pre-allocating exiting traffic. The higher speeds which are measured at about 750 m prior to the off-ramp might be caused by drivers who want to overtake vehicles that are pre-allocating towards the outside lane.

Our findings regarding the length over which the traffic stream is influenced by a ramp are based on a three-lane standard motorway only, under similar traffic and weather conditions. These findings are not compared to other motorway configurations or measurements in different conditions, therefore they do not describe a general nature of turbulence. In table 3.5 our results are compared to earlier findings. This comparison shows that our findings at on-ramps are comparable to the findings of Kondyli and Elefteriadou (2012) (the upstream value) and the Dutch motorway design guidelines (Rijkswaterstaat 2017). The influence length mentioned in the HCM deviates from our findings. These differences may however be partially explained by cultural differences in driving behaviour.

on-ramp		**off-ramp**		**source**
upstream [m]	**downstream [m]**	**upstream [m]**	**downstream [m]**	
200	900	1,000	–	this study
110	260	–	–	(Kondyli and Elefteriadou, 2012)
460	460	460	460	(HCM, 2010)
150	750	750	150	(Rijkswaterstaat, 2014)

Table 3.5. Ramp influence areas.

No valid off-ramp loop detectors between 700m and 1000m were available and the spread of detectors between -170m and 676m is more than the required 150m. This study therefore does not make clear at which distance the basic motorway values are reached downstream of off-ramps. Another limitation for the off-ramp measurements is that the last 3 data entries (at -170m, 253m and 676m) originate from the same site (site 1). Since the measurements for both speed and lane flow distribution from the downstream off-ramp detectors seem implausible, site 1 may for some reason not be representative. This could be explained by a large number of heavy vehicles, which are not included in this study because the number of heavy vehicles could not be retrieved from the loop detector data. A relatively large number of trucks could explain both the lower measured mean speed and the greater amount of traffic on the right lane.

When our findings are compared to the motorway design guidelines for ramp spacing, it is shown that the use of a single ramp influence length, as assumed in (HCM 2010), does not correspond to the measured change in lane flow distribution. The measured changes in lane flow distribution are not symmetrical distributed around the acceleration or deceleration lane and are different for on-ramps and off-ramps. At on-ramps the lane flow distribution mainly changes downstream of the ramp and at off-ramps it changes mainly upstream of the ramp. This principle corresponds to the method that is used in the Dutch guidelines (Rijkswaterstaat 2017), which uses specific upstream and downstream turbulence lengths which are different for on-ramps and off-ramps. Guidelines that use a fixed distance for ramp spacing, such as (AASHTO 2001; DMRB 1994; RAA 2008) are potentially useful. However, for the case displayed in table 3.1 the desired ramp spacing between an on-ramp followed by an off-ramp the prescribed spacing ranges between 450m and 1,100m. Our findings show a change in lane flow distribution that ends at 900m downstream of the on-ramp and starts at 1,000m upstream of the onramp. This means that a distance of 1,900m is required for a situation with no overlap of ramp influence areas, and therefore none of the mentioned guidelines provides a situation with no overlap of ramp influence areas. This raises the question to what extent these areas can overlap and what the consequences of such an overlap are.

3.7. Conclusions

This study shows that combining data from different loop detectors at different sites is a useful method for studying macroscopic traffic characteristics at comparable sites. Sites with comparable characteristics, such as number of lanes, acceleration and deceleration lane lengths, types of lanes (e.g. peak hour lanes), average flow and speed limits have comparable traffic flow characteristics such as actual speed and distribution of traffic over the different lanes. This enables us to get denser data than the standard interval of 300 - 500 m by which successive loop detectors are spaced.

The results show that the lane flow distribution on a three-lane motorway starts to change at about 200 - 300 m upstream of an on-ramp gore and remains until a maximum of about 500 m downstream of the gore. After 500 m it changes back to a level comparable to that on a basic motorway section. At 900 m downstream of the gore the lane densities are back to the original level. At an off-ramp the fraction of flow starts to change at about 1,000 m upstream of the gore, which corresponds with the first exit sign at 1,200 m upstream of the off-ramp that introduces the upcoming motorway exit. The distance downstream of an off-ramp gore at which the lane flow distribution is back to the original basic motorway values could not be found. This is due to a limited number of loop detectors that fit our selection criteria and probably due to the lack of information about the number of heavy vehicles.

Our findings are useful for reflecting on motorway design guidelines, where the Dutch guideline (Rijkswaterstaat 2017) proves to provide reasonably accurate ramp influence area for a three-lane motorway. However, when it comes to designing a motorway based on turbulence, the question arises to what extent areas with a raised level of turbulence can overlap, this requires further research. Also, our measurements are taken for only one motorway configuration and in good weather conditions. A guideline however, should provide a safe road design for all motorway configurations and should also take into account bad weather conditions. This should be considered when these results are used for design guideline purposes. Further research with an extended scope in configurations and environmental conditions is recommended. Also an attempt to model the driving manoeuvres that lead to the observed phenomena is recommended.

The data showed a change in lane flow distribution and a change in speed compared to a basic motorway. The results show that drivers change lanes from left lane to the centre lane and from the centre lane to the right lane, where the fraction of flow on the centre lane remains constant. However, loop detector data gives no information on the frequency and direction of these lane changes, i.e. from which lane to which lane. Further research on this topic based on individual vehicle trajectory data is recommended.

4. Microscopic characteristics of turbulence

This chapter was first published in "Transportation Research Part C: Emerging Technologies" (Van Beinum, A., H. Farah, F. Wegman, and S. Hoogendoorn. 2018. "Driving behaviour at motorway ramps and weaving segments based on empirical trajectory data." Transportation Research Part C: Emerging Technologies 92:426-441. doi: https://doi.org/10.1016/j.trc.2018.05.018).

Abstract

In the vicinity of ramps, drivers make route choices, change lanes and in most cases also adjust their speeds. This can trigger anticipatory behaviour by the surrounding vehicles, which are also reflected in lane changes and/or changes in speed. This phenomenon is called turbulence and is widely recognised by the scientific literature and various design guidelines. However the knowledge about the characteristics of turbulence is limited. This study investigates the microscopic characteristics of driving behaviour around 14 different on-ramps (3), off-ramps (3) and weaving segments (8) in The Netherlands, based on unique empirical trajectory data collected from a video camera mounted underneath a hovering helicopter. The data analysis reveals that lane changes caused by merging and diverging vehicles create most turbulence, that an increase in the amount of traffic results in a higher level of turbulence and that an increase in the available length for merging and diverging results in a lower level of turbulence. The results of this study are useful for improving the road design guidelines and for modelling driving behaviour more realistically.

4.1. Introduction

In the vicinity of motorway ramps, multiple manoeuvres are performed by drivers who enter the motorway, who exit the motorway, or who cooperate or anticipate on entering or exiting vehicles. These manoeuvres involve lane changes, changes in speed, and changes in headways. This results in changes in lane flow distribution (Knoop et al. 2010; Van Beinum et al. 2017), greater speed variability and changes in headway distribution on the different lanes, with presumably a greater share of small gaps on the outside lane. In the literature and in motorway design guidelines, this phenomenon is referred to as turbulence. According to the Highway Capacity Manual (HCM 2010) turbulence is always present in traffic. A raised level of turbulence is expected around motorway ramps (Van Beinum et al. 2016; HCM 2010) and has a negative influence on the motorway's capacity and traffic safety (Abdel-Aty, Uddin, et al. 2005; Golob et al. 2004; HCM 2010; Kondyli and Elefteriadou 2012; Lee et al. 2003b, 2003a; Chen and Ahn 2018). In free flow conditions the level of turbulence is expected to increase a few hundred meters upstream of a ramp and to dissolve a few hundred meters downstream of the ramp (Van Beinum et al. 2016). This concept is shown in the theoretical framework in figure 4.1.

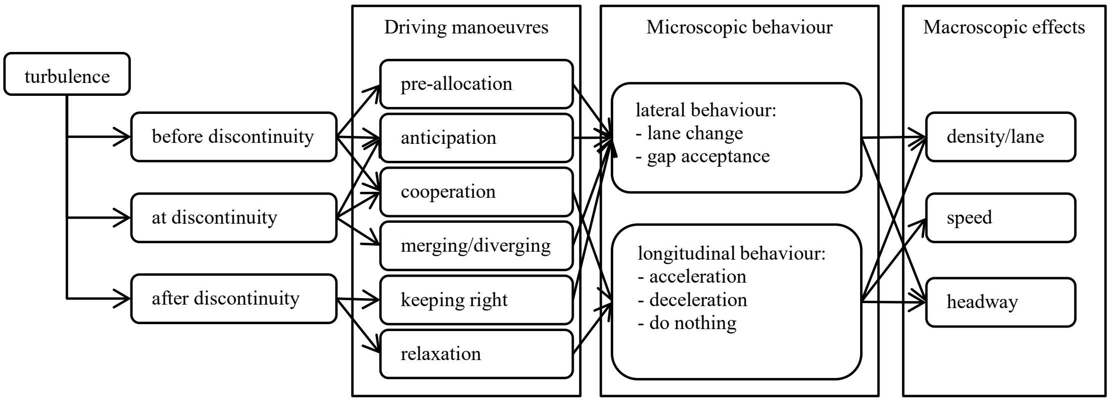


Figure 4.1. Theoretical framework for turbulence (Van Beinum et al. 2016).

Both literature and freeway design guidelines agree that the level of turbulence is influenced by road design, traffic volume, and driver behaviour. Several researchers have tried to assess the impacts of different manoeuvres on traffic safety and traffic operations and the influence of design characteristics on these aspects. An overview of these studies is given in (Van Beinum et al. 2016). The available research on the characteristics of turbulence is limited and different values for the location where turbulence starts and ends are found in different studies (HCM 2010; Kondyli and Elefteriadou 2012; Van Beinum et al. 2017). Also the available research regarding the microscopic characteristics of the different manoeuvres is limited. To gain a better understanding of the different manoeuvres that contribute to turbulence more research is needed, preferably based on empirical data. Following this, the main research questions of this study are:

- How and to what extent do the different manoeuvres contribute to the raised level of turbulence?
- How is the raised level of turbulence affected by the amount of traffic and the motorway's design characteristics?
- Where does the raised level of turbulence start and end?

To answer these questions, the driving behaviour of the vehicles that perform the different manoeuvres was studied. For this study we have collected empirical trajectory data of individual vehicles at 14 different on-ramps (3), off-ramps (3) and weaving sections (8) in The Netherlands. The data was collected under free flow conditions, using a video camera mounted under a hovering helicopter.

The insights from this research can be used to improve microscopic simulation models and motorway design guidelines (Marczak et al. 2014; Daamen et al. 2010; Schakel et al. 2012; Hill et al. 2015; Marczak and Buisson 2014).

This chapter is structured as follows: section 4.2 gives a summary of the currently available knowledge in the literature regarding turbulence related driving behaviours; section 4.3 presents the method used to answer the research questions; section 4.4 presents the results of the performed analysis; and section 4.5 and 4.6 discuss and summarize the conclusions arising from the analysis.

4.2. Literature review

The goal of the literature review is to summarize the available knowledge regarding turbulence related driving manoeuvres around ramps and their impact on microscopic behaviour, corresponding to the theoretical framework as shown in figure 4.1. To this end, the literature study is structured as follows: first the different manoeuvres that contribute to turbulence are discussed in more detail, followed by the manoeuvre's microscopic aspects in terms of lateral and longitudinal behaviour. This section concludes by discussing the length of the ramp influence area on turbulence.

4.2.1. Manoeuvres

According to the theoretical framework displayed in figure 4.1, different manoeuvres are related to motorway turbulence. These different manoeuvres are graphically explained in figure 4.2.

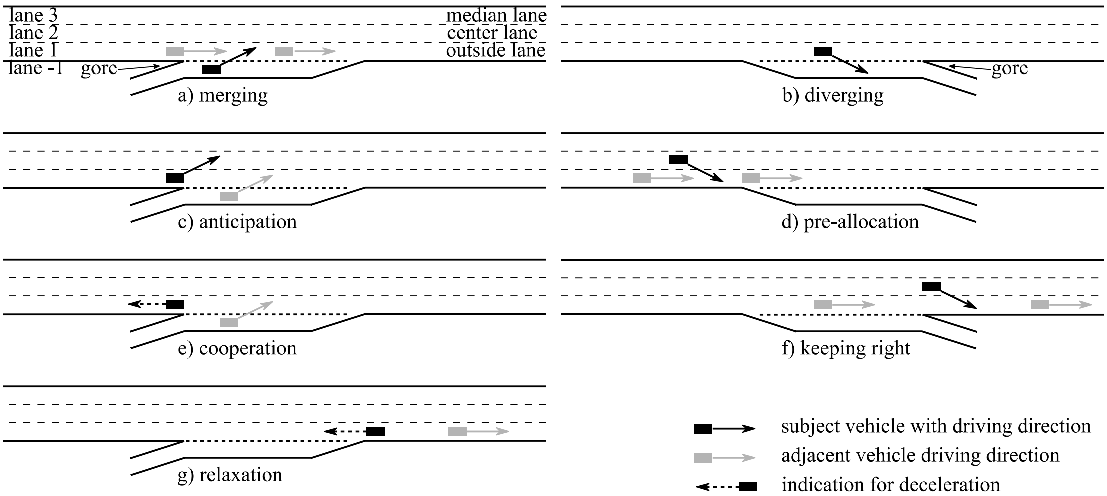


Figure 4.2. Type of manoeuvres around discontinuities.

A merge is performed by a vehicle that drives on the acceleration lane and changes lanes to enter the motorway. Studies on merging in the past 10 years show that merging is a complex combination of merging plan choice, gap acceptance, target gap selection, and acceleration decisions (Choudhury et al. 2009). Merging is also regarded to be a major cause for capacity drops at on-ramps (Leclercq et al. 2016; Chen and Ahn 2018). Furthermore, a substantial proportion of crashes on motorways occur in the vicinity of ramps (Lee and Abdel-Aty 2008, 2009). Many researchers have studied the mechanisms of merging behaviour. Daamen et al. (2010) studied empirical trajectory data and found that at free flow most of the lane changes take place in the first half of the acceleration lane. Calvi and De Blasiis (2011) used a driving simulator and found that the merging length (distance between where a lane change starts and where it ends) increases as the traffic volume increases. The length of the acceleration lane did not show a significant effect on driving behaviour (Calvi and De Blasiis 2011).

A diverging manoeuvre is performed by a vehicle driving on the outside lane and changes lanes to the deceleration lane to exit the motorway. This manoeuvre takes place at off-ramps and weaving segments. Muñoz and Daganzo (2002) found that motorway capacity decreases when more vehicles take the exit. They used empirical loop detector data from a US freeway. Martínez et al. (2011) studied video records and found that the speed on exit lanes is 20km/h lower than on the through going main lanes. El-Basha et al. (2007) used a radar to measure speeds and found that exiting traffic also has a negative effect on the speed of through going traffic. Ahn et al. (2010) studied empirical loop detector data from different off-ramps and found that diverging traffic causes lane-changing manoeuvres which result in deviations in flow compared to the average flow over a longer period of time.

Anticipation is performed when a driver changes lanes towards the median lane to make way for a lane changing vehicle (Kita 1999; Schakel et al. 2012; Cassidy and Rudjanakanoknad 2005). In literature this type of lane change is also referred to as a courtesy lane change. Zheng et al. (2011b) studied NGSIM data (NGSIM 2015) and showed that a lane change, for example due to merging, is a primary trigger for additional lane changes by adjacent vehicles. In this way initial lane changes are found to be responsible for transforming a small raised level of turbulence to substantial turbulence. To the best of our knowledge no other empirical studies regarding anticipation are available.

Pre-allocation is performed by drivers who want to take the next motorway exit and pre-position themselves upstream of the off-ramp by changing lanes towards the outside lane (Toledo et al. 2009; Choudhury 2007). In (Van Beinum et al. 2017) we studied empirical loop detector data from several motorway off-ramps in The Netherlands and found that the lane flow distribution starts to change at about 1,000 m upstream of the off-ramp gore. This change was attributed to pre-allocation and coincides with the location of signposting along the motorway (which are positioned at 1,200 m and 600 m upstream of an off-ramp). To the best of our knowledge no other empirical studies are available that focus on the characteristics of pre-allocation.

In The Netherlands drivers are bound to the right side rule by which they are obliged to change lanes to the outside lane when there is sufficient space to do so (RVV 1990). Overtaking takes place on the inside of the motorway. This will naturally result in situations where faster vehicles drive on the inside lanes and slower vehicles drive on the outside lanes of the motorway (Daganzo 2002a). To the best of our knowledge no empirical studies are available which focus on the implications of keeping right.

A vehicle cooperates when it increases its headway to provide a larger gap for a vehicle that wants to change lanes in front (Kim and Coifman 2013; Choudhury et al. 2009; Hidas 2005). Choudhury et al. (2009) proposed a model which takes lane changing under cooperation into account. The authors used NGSIM data (NGSIM 2015) to validate this model. Although this study showed promising results, further research was recommended to validate the transferability of the model in different traffic states, ranging from very congested to free flow (Choudhury et al. 2009). Zheng et al. (2013) used the same NGSIM trajectory data to calibrate cooperation in the model by Laval and Leclercq (2008). This model was later reformulated and calibrated by Duret et al. (2011), who used the model as a method to systematically identify the impact of cooperation on lane changes. Hill et al. (2015) studied freeway lane change behaviour using trajectory data from an instrumented vehicle and found that drivers are willing to cooperate with merging vehicles. The authors speculate that the same holds true for all lane changing vehicles in uncongested conditions but the results were inconclusive. It was recommended to analyse more data during uncongested conditions.

At ramps vehicles are willing to accept very short headways as they enter or exit the motorway. After the merge the driver will increase its headway to more comfortable values further downstream. This phenomenon is called relaxation (Schakel et al. 2012; Laval and Leclercq 2008; Laval and Daganzo 2006; Duret et al. 2011). Daamen et al. (2010) studied trajectory data from several on-ramps in The Netherlands and observed very short net headways which increase over time. The authors related this to relaxation behaviour. Duret et al. (2011) studied the NGSIM trajectory data and found that after 15 seconds of relaxation an equilibrium was reached. However, due to inferior results, further research on mandatory lane changes in the outside lane was recommended by the authors. Schakel et al. (2012) proposed a lane change model (LMRS) which incorporates relaxation. The model was calibrated using empirical loop detector data from a Dutch two-lane motorway and was proven to be accurate for free flow conditions. The authors recommended that future research should incorporate other locations with different speed limits and more lanes (Schakel et al. 2012).

4.2.2. Mandatory and discretionary lane changes

Merging, diverging, pre-allocating, anticipating and keeping right require lane changes and gap acceptance. In the literature distinction is made between mandatory lane changes (MLC) and discretionary lane changes (DLC) (Minderhoud 1999; Laval and Daganzo 2006; Kesting et al. 2007; Choudhury 2007; Yang and Koutsopoulos 1996; Hill et al. 2015; Pan et al. 2016). A MLC is executed when a driver must change lane due to a strategic route choice. A DLC occurs when a driver seeks for better driving conditions, such as to gain speed (or travel time) advantage. A MLC is expected to be performed in a shorter period of time and with smaller accepted gaps than a DLC (Kusuma et al. 2015). In a field test wherein different participants drove an instrumented vehicle it was found that lane change durations of DLC to the right and to the left do not differ significantly. Also, no significant difference was found between average MLC (merging manoeuvres were excluded) and DLC durations. The authors however recommend to further verify the results using an enriched dataset. Drivers who perform a MLC are willing to accept small gaps and new followers are willing to accept small headways (Schakel et al. 2012; Laval and Leclercq 2008; Laval and Daganzo

2006; Duret et al. 2011; Daamen et al. 2010). This will result in shifting the headway distribution to the left.

4.2.3. Utilization of the weaving segment length

A weaving segment is a motorway discontinuity where an auxiliary lane connects a merge segment (on-ramp) and a diverge segment (off-ramp) (HCM 2010). Marczak et al. (2014) analysed empirical trajectory data from an urban motorway weaving segment in Grenoble, France. They found that in free flow conditions only 60% of the total weaving segment length is used for weaving, which leaves 40% of its length unused. They also found that vehicles changing lane from the acceleration/deceleration lane to the main road accept smaller gaps than vehicles changing lane from the main road to the acceleration/deceleration lane. In the discussion the authors state that the length of a weaving segment might not be of significant relevance for estimating the capacity. However, their results were not compared to weaving segments with different lengths. Kusuma et al. (2015) studied trajectory data from video recordings together with traffic flows and speed from loop detectors in the UK and found that 91% of the traffic decelerates at the beginning of weaving segment to cooperate with the merging and diverging traffic, 48% of the lane changing vehicles change lanes in the first 25% of the weaving segment.

4.2.4. Increased level of turbulence upstream and downstream of the ramp

The literature and design guidelines agree that upstream and downstream of a ramp a raised level of turbulence is present. This area is referred to as the ramp influence area (HCM 2010) and determines the required ramp spacing to avoid traffic operations and traffic safety disturbances. It has been shown that the level of turbulence is expected to increase upstream and to decrease downstream of a ramp. There is however no consistency when it comes to the length of this influence area (Van Beinum et al. 2016). To the best of our knowledge there are only two empirical studies available which indicate the boundaries of the ramp influence area. Kondyli and Elefteriadou (2012) studied instrumented vehicle observations and found that the ramp influence area starts at 110 m upstream and ends at 260 m downstream of the gore of a ramp. (Van Beinum et al. 2017) studied loop detector data from multiple ramps and found that the ramp influence area starts at 200 m (on-ramp) or 900 m (off-ramp) upstream and ends at 900 m (on-ramp) downstream of the ramp gore. it was recommended that in future research the turbulence influence length should be studied using empirical trajectory data of individual vehicles.

4.2.5. Research gaps

Several research gaps were identified in the literature:

- No studies consider the relation between all the turbulence related manoeuvres. There are several studies available which consider one or more manoeuvres but, to the best of our knowledge, there is no literature available which considers all manoeuvres simultaneously. For all the different manoeuvres only the characteristics of merging, diverging and lane changing are well described in literature. The characteristics and mechanisms of pre-allocation, cooperation, anticipation, keep-right and relaxation are yet not well understood, as well as the cohesion between the different manoeuvres. Such understanding is necessary for modelling vehicle interactions realistically.
- There is a debate on weaving segment length. According to the motorway design guidelines the level of turbulence is expected to be dependent on the available length for merging (HCM 2010; Rijkswaterstaat 2017) but empirical studies suggest that the length of a weaving segment might not have a significant influence on road capacity, due to an inefficient use of the total weaving segment length (Marczak et al. 2014). This seems contradicting and requires further research.
- Currently available empirical studies have limitations regarding the available data. Instrumented vehicle studies suffer from a limited number of participants and therefore also limited validity (Hill et al. 2015). Studies using loop detector data fail to capture the behavioural characteristics of drivers at an individual level (e.g. location and duration of lane changes) (Schakel et al. 2012; Van Beinum et al. 2016). The currently available trajectory data captures only a limited length of a motorway (Daamen et al. 2010), and is only available for a limited number of locations with limited range of characteristics, such as available length for lane changes, amount of traffic, legal speed limits and amount of heavy vehicles (e.g. trucks) (Marczak et al. 2014; Duret et al. 2011; NGSIM 2015).

4.3. Method

In this study we have analysed driving behaviour during the different manoeuvres which are related to turbulence. Empirical microscopic data, describing the position (x, y, t) of every vehicle at every time step (trajectories of each individual vehicle) was collected and used for analysis. The different manoeuvres were identified from the data and were assessed on microscopic behaviour.

4.3.1. Data collection

Empirical trajectory data from 14 sites in the Netherlands were used for analysis. The trajectories were collected using a camera mounted underneath a hoovering helicopter, comparable to the method described in (Hoogendoorn et al. 2003), but using a 5120 x 3840 pixel camera and a 15mm Zeiss lens, which enabled us to capture a road stretch of approximately 1,200m - 1,500m from an altitude of approximately 500m. The images were corrected to compensate for the radial distortion that manifests in form of the "barrel" or "fish-eye" effect. The intrinsic characteristics of the lens were calibrated using a method comparable to OpenCV (OpenCV 2018). The image positions in pixels were converted to accurate world positions in meters by relating recognisable objects in the captured images to their locations in Google Maps. The measurements were taken on the 6th of June and the 7th of July 2016, under sunny weather conditions, between 14:00 and 17:00 hours (which is the build up towards the evening peak hour), under free flow conditions, for 30 minutes at each site. The distance of 1,200m - 1,500m coincides with the findings from our earlier study (Van Beinum et al. 2017), where we found that an increased level of turbulence at on-ramps starts at approximately 200m upstream of the ramp gore and ends approximately 900m downstream of the ramp gore. At off-ramps these values are respectively 1,000 m upstream of the ramp gore and approximately 600m downstream of the ramp gore.

The sites were selected by the following criteria: for an on-ramp: no other discontinuity exists within a range of 1,000m upstream and 3,000m downstream; for an off-ramp no other discontinuity exists within a range of 3,000m upstream and 1,000m downstream; and weaving segment length should be between 500m (minimum length according to the Dutch design guidelines (Rijkswaterstaat 2017)) and about 1,200m, so the total length can be measured by the helicopter camera. The following additional characteristics were desired: a) number of through lanes (2 and 3); b) variability in the amount of trucks; c) variability in the traffic flow, and d) legal speed limit (100km/h and 130km/h). An overview of the different sites with their characteristics is given in table 4.1.

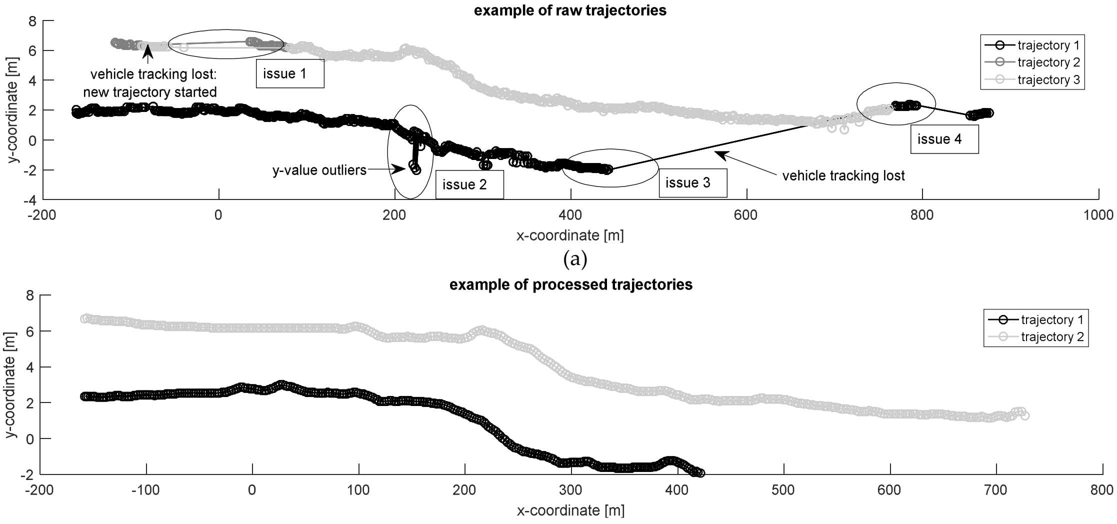
						number of vehicles					
						through					
road	site name GPS coordinates	type	Config.	length* [m]	speed limit [km/h]	flow	F/C	on	off	on/off	number of trucks
A13	Delft 52.014718, 4.373768	off-ramp	3+1	250	100	2.569	0.78	-	270	-	123
A59	Terheijden 51.655155, 4.750176	off-ramp	2+1	250	130	1.599	0.57	-	150	-	200
A16	Zonzeel 51.639134, 4.697074	off-ramp	3+1	210	130	1.943	0.69	-	395	-	444
A13	Delft 52.014498, 4.374516	on-ramp	3+1	300	100	2.654	0.81	323	-	-	168
A59	Terheijden 51.655327, 4.750221	on-ramp	2+1	320	130	1.422	0.51	88	-	-	109
A16	Zonzeel-north 51.651250, 4.688500	on-ramp	3+1	340	130	1.679	0.58	221	-	-	508
A4	Bergen op Zoom-east 51.501793, 4.313943	weaving	2+1	500	120	1.582	0.35	147	148	494	163
A4	Bergen op Zoom-west 51.502537, 4.313162	weaving	2+1	400	120	1.434	0.55	142	85	356	118
A59	Klaverpolder-north 51.696689, 4.645896	weaving	2+1	600	130	1.239	0.55	205	73	33	154
A59	Klaverpolder-south 51.695868, 4.645407	weaving	2+1	500	130	1.760	0.74	131	446	89	274
A16	Princeville-east 51.576286, 4.727040	weaving	3+1	1.000	130	2.396	0.58	107	316	518	629
A16	Princeville-west 51.576906, 4.726322	weaving	3+1	1.100	130	2.082	0.52	272	160	325	410
A15	Ridderkerk-north 51.856599, 4.621377	weaving	3+1	700	130	2.158	0.61	122	110	152	446
A15	Ridderkerk-south 51.856330, 4.620257	weaving	3+1	1000	130	2.868	0.78	107	186	309	555

Table 4.1. Site characteristics; * Length of acceleration lane (on-ramp), deceleration lane (off-ramp) or weaving segment.

4.3.2. Processing raw data

The trajectory data originates from video footage (12 fps), which were processed with automated vehicle recognition software to *x*, *y*, *t* - coordinates, which represent the centre of the vehicle at a specific time. The raw data was processed to reduce the noise due to measurement errors and inaccuracies. Figure 4.3(a) shows 4 different issues in the data that were encountered. The automatic vehicle recognition and vehicle following software sometimes loses track of the vehicle due to objects overhead (e.g. a viaduct). When the vehicle is recognized again, it was sometimes recognized as a new vehicle (issue 1), as a different, wrong, vehicle (issue 3) or as the same, correct, vehicle further downstream (issue 4). Also unrealistic x- and -y values were measured (issue 2). These unrealistic values are caused by shadows besides the vehicle, that were sometimes recognized as part of the vehicle, or by vehicles driving closely next to each other that were recognized as one vehicle.

These issues in the data where repaired as follows. First unrealistic x- and y-values were filtered from the dataset. Unrealistic x-values are values where vehicles are moving backwards and unrealistic y-values are the outliers. This solves issue 2. Also overlapping x and y-values for equal time entries were removed. After the filtering process all trajectories where cut into parts. Cuts were applied when the trajectory data has a gap. This solves issue 3. After cutting, the trajectories were merged again by using an iterative search process. Two trajectories were merged into one when 1) the trajectory to merge with, starts at a short distance from where the subject trajectory ends and 2) when the speed difference between the end of the subject trajectory and the start of the potential trajectory is small. This search is repeated for increasing distances and for increasing speed differences. This solves issue 1 and 4. Finally all missing data points in the trajectories were interpolated and the trajectories were smoothed using a polynomial regression filter (Toledo, Koutsopoulos, and Ahmed 2007). Figure 4.3(b) shows the trajectories after processing.



(a)

(b)

Figure 4.3. Example of raw (a) and processed trajectories (b).

4.3.3. Identification of manoeuvres

The different manoeuvres were identified in the dataset by using the criteria shown in table 4.2. For each individual vehicle that performs a specific manoeuvre, microscopic characteristics were stored in a database for further analysis, being: lane change location, lane change direction, accepted gap, headway and speed.

manoeuvre	origin	dest.	lane change	manoeuvre location	extra criteria
merging	lane -1*	lane 1	to inside	at acceleration lane	only entering traffic
diverging	lane 1	lane -1	to outside	at deceleration lane	only exiting traffic
pre-allocating	lane 2, 3	lane 1	to outside	upstream of off-ramp	only exiting traffic
cooperation	lane 1	lane 1	none	upstream and at ramp	cooperating vehicle has same leader in a 10 seconds period before a merging or pre-allocating vehicle moves in front
anticipation	lane 1	lane 2, 3	to inside	upstream and at ramp	merging or pre-allocating vehicle in front
relaxation	lane 1	lane 1	none	downstream of on-ramp	1) only entering traffic 2) vehicle has same leader in a 10 seconds period after it has merged
keeping right	lane 2, 3	lane 1,2	to outside	whole segment	-

Table 4.2. Manoeuvre Identification Criteria; * The lane coding correspondents with the lane coding in figure 4.2.

Not all lane changes towards the left could be categorized to a specific manoeuvre class. For example a lane change where a vehicle overtakes another vehicle to improve its driving conditions, without being triggered by a merging or pre-allocation vehicle that moves in front. These lane changes were labelled as other (left).

4.3.4. Data analysis

The location and intensity of lane changes were investigated for merging, diverging, pre-allocation, anticipation, keeping right and other (left). To do so the number of lane changes where determined for 25 m bins.

Merging and diverging only takes place at the acceleration and deceleration lane. Some entering vehicles make additional lane changes to the inside of the motorway. These are labelled as secondary merges. Secondary merges take place downstream of the ramp and contribute directly to the increased level of turbulence that is caused by entering traffic. However, the further downstream of the ramp a merged vehicle will get, the less a secondary merge is related to the primary merge and the more it will be related to a discretionary lane change to improve driving conditions. For the analysis we assume that lane changes related to secondary merges no longer contribute to the raised level of turbulence when the intensity of secondary merges gets below 2 lane changes per 25 m.

Pre-allocation takes place upstream of the ramp and is expected to be influenced by the position of post signs, which are placed at 1.200 m and 600m upstream of the studied ramps. The remaining pre-allocating lane changes are expected to take place just prior to the ramp.

For lane changes that involve keeping right and lane changes towards the inside (left side) of the motorway, which could not be attributed to a specific manoeuvre, it was assumed that these are always present in the traffic stream and are not directly caused by entering or exiting traffic. However, these lane changes can be triggered by entering or exiting traffic. For these lane changes the average intensity outside the ramp influence area is of interest. For the analysis the ramp influence area was, for practical reasons, assumed to be restricted to an area that starts 200 m upstream of the start of the ramp and ends 200m downstream of the end of the ramp. The average number of lane changes outside the influence area was used to identify the locations where the number of lane changes is above average. An overview of the aspects that were analysed for each manoeuvre is given in table 4.3.

Both traffic flow and the available length for changing lanes are expected to have an impact on: 1) lane change location and intensity, 2) the size of accepted gaps for MLC and DLC and 3) the need for anticipation, cooperation and relaxation. The impact of the available length for lane changes was studied by comparing results from different weaving segments with different lengths. The impact of traffic flow was studied by comparing the results of different on-ramps, off-ramps and weaving segments with different flows.

Cooperation and anticipation were studied by comparing the headway and speed that were measured prior to the manoeuvre and after the manoeuvre. The following moments were chosen: 1) for cooperation at 10 s before the moment a vehicle merges and at the moment of the merge and 2) for relaxation at the moment of merging and 10 s after the merge. For relaxation only the on-ramp data was studied, because relaxation is expected most at locations where vehicles merge. For cooperation also the influence of weaving segment length was studied. The 10s period was chosen based on the area that is covered by the video images. This ranges from approximately 300 m upstream of the gore to approximately 600 m downstream of the gore. When assuming that merging vehicles change lanes near the gore and drive with a speed of approximately 30 m/s (108 km/h), it is possible to investigate headways in a period of 10 s before the merging area until 20 s after the merge area.

analysis	**aspect**	**ramp type**
Location and frequency of lane changes		
merge and diverge	location where lane changes take place	on-ramp off-ramp
	the percentage of total number of LC that involve merging or diverging	
Pre-allocation	percentage of diverging vehicles that pre-allocate	off-ramp
	percentage of diverging vehicles that pre-allocate at 600m upstream, where the sign post is.	
	percentage of diverging traffic that is already driving on the outside lane at the beginning of the measured area	
anticipation	anticipation as percentage of total number of LC	on-ramp
	location of first anticipation LC	
secondary merge	percentage of merging vehicles that are secondary merges	on-ramp
	location where intensity of LC gets below 2LC/25m	
keep right and uncategorised left	average intensity of LC outside ramp area	on-ramp off-ramp
	location where intensity of LC gets above average intensity of LC upstream of ramp	
	location where intensity of LC gets below average intensity of LC downstream of ramp	
Impact of weaving segment length and traffic flow		
merge and diverge	cumulative distribution of number of LC over the total available length for merging and diverging for different weavings segment lengths and different traffic flows	on-ramp off-ramp weaving segment
cooperation	difference in headway and speed distribution between the moment a vehicle changes lanes in front and becomes a new leader, and 10 seconds before that LC	on-ramp weaving segment
relaxation	difference in headway and speed distribution between the moment the subject vehicle merges and 10 seconds after that merge	on-ramp
difference between MLC and DLC for merge, secondary merge, diverge, keep right	distribution of accepted gaps for different	on-ramp off-ramp weaving segment

Table 4.3. Overview of analysis.

4.4. Results

The goal of this section is to present the analysis results that are used to answer the research questions. To this end this section is structured as follows: In the first part the results regarding the contribution of the different manoeuvres to a raised level of turbulence and the location where the raised level of turbulence starts and ends are shown in terms of location and frequency of lane changes. In the second part the results regarding the impact of the amount of traffic and the motorway's design on the level of turbulence are shown in terms of utilization of the available length for merging and diverging and gap acceptance.

4.4.1. Location and frequency of lane changes

The lane change locations and number of lane changes are displayed in figure 4.4. The results if the analysis are summarised in table 4.4 on page 81.

The results show that the majority of the lane changes occur at the acceleration lane or deceleration lane. This effect is stronger for off-ramps than for on-ramps, which indicates that the ramp influence area for on-ramps is larger than for off-ramps. Of all the merging vehicles about a third of the vehicles make additional lane changes towards the left (secondary merges). The location where the intensity of secondary merges is reduced to an intensity of less than 2 lane changes per 25 m appears to be related to the traffic flow. The location with the highest flow (Delft) gives the longest distance (575 m).

Most of the diverging vehicles change lanes directly after the start of the deceleration lane. On average 96% of the vehicles change lanes in the first half of the deceleration lane. Diverging vehicles appear to pre-allocate at a relatively long distance upstream of the off-ramp. More than 85% of the diverging vehicles are already driving on the outside lane at when entering the measured area. At the off-ramp of Terheijden an increased number of pre-allocation lane changes is found at 600m upstream of the off-ramp gore. In total 6% of the diverging vehicles pre-allocate at this position. A second location with an increased number of pre-allocation related lane changes is found at 400m upstream of the gore (Zonzeel).

The first lane change identified as anticipation was recorded at 100 m upstream of the on-ramp and on average 4% of all lane changes was identified as anticipation. The lane change location seems not to be effected by traffic flow.

Lane changes identified as keeping right and uncategorised lane changes to the left are present over the whole length of the measured motorway segments. Outside the assumed 200 m ramp influence area the average number of keep right lane changes are relatively constant. However, the average is a little lower for the site with a low traffic flow (Terheijden). The amount of keeping right related lane changes increases within the ramp influence area. This is especially the case for the off-ramps. The number of keeping right lane changes seems to be related to the number of exiting vehicles: a higher number of exiting vehicles corresponds to a higher number of keeping right lane changes. The distance over which the average number of keeping right lane changes is above average, is relatively constant for on-ramps and off-ramps but its location differs. At on-ramps the area with an increased average is measured further downstream than at off-ramps. The same holds for the uncategorised lane changes to the left. Again the distance over which average number of lane changes is increased is comparable for on-ramps and off-ramps but the locations differs. For on-ramps the area is measured further downstream than for off-ramps.

	on-ramp			**off-ramp**		
	Delft	**Terheijden**	**Zonzeel**	**Delft**	**Terheijden**	**Zonzeel**
Flow/Capacity ratio	0.81	0.51	0.58	0.78	0.57	0.69
merge as percentage of total number of LC	55%	33%	41%	–	–	–
percentage merges which are secondary merges	26%	32%	41%	–	–	–
downstream location where number of sec. merge < 2 LC/25m	475m	425m	575m	–	–	–
diverge as percentage of total number of LC	–	–	–	47%	61%	58%
percentage of diverging veh. that are already in lane 1 at start	–	–	–	96%	86%	91%
percentage of diverging veh. which pre-allocate at -600m	–	–	–	–	6%	–
anticipation as percentage of total number of LC	9%	6%	4%	–	–	–
location of first anticipation LC	-25m	-75m	-100m	–	–	–
Average number of keep right LC/25m outside 200m zone	3.0	2.9	3.2	2.9	1.6	2.7
Average number of keep right LC/25m at acc. lane	7.0	3.8	3.4	11.9	3.5	5.9
first loc. where number of keep right LC/25m is above average	-425m	-300m	-250m	-475m	-600m	-500m
last loc. where number of keep right LC/25m is above average	525m	550m	500m	375m	250m	325m
Average number of uncategorised left LC/25m outside 200m zone	3.4	4.5	7.8	3.1	2.1	5.0
Average number of uncategorised left LC/25m at acc. lane	8.3	6.4	13.1	10.0	3.9	10.1
first loc. where number. of uncategorised left LC/25m is above avg.	-400m	-200m	-300m	-500m	-675m	-475m
last loc. where number of uncategorised left LC/25m is above avg.	525m	675m	575m	450m	275m	625m

Table 4.4. Analysis results of lane change location and intensity.

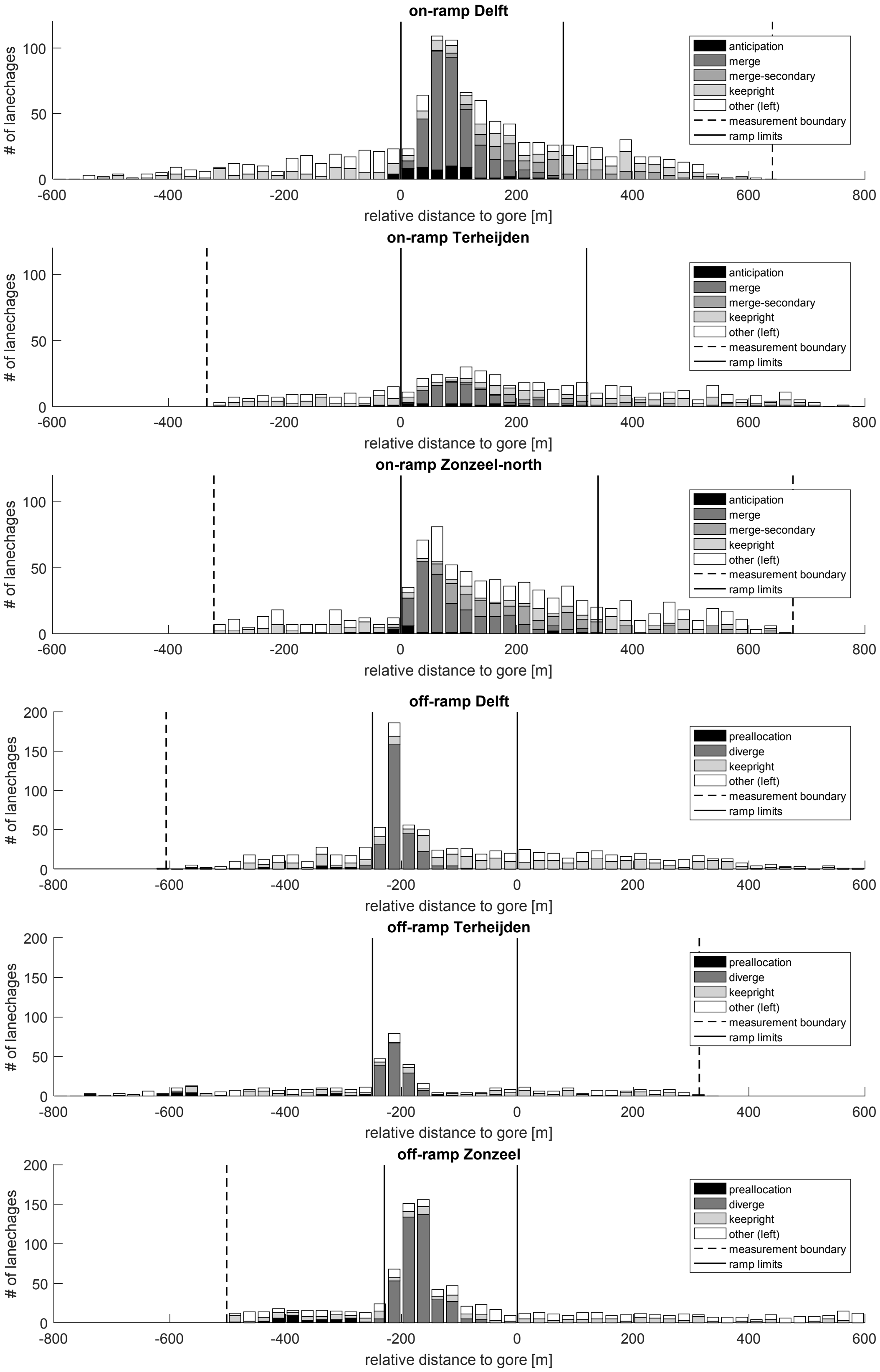


Figure 4.4. Lane change locations near on-ramps and off-ramps.

4.4.2. Impact of weaving segment length and traffic flow

Utilization of the available length for merging and diverging

Most of merging and diverging lane changes were performed in the first part of an acceleration lane, deceleration lane or weaving segment. Figure 4.4 shows that most lane changes are performed in the first 25% of the lane. The corresponding percentages are displayed in table 4.5. The figure shows distributions with comparable shapes for a scenario with a low traffic flow. However, a two sample Kolmogorov Smirnov (KS) test showed that the difference between the distributions is significant. In the scenario with a high traffic flow the distribution shapes start to deviate at F(X) = 0.5. For both a high and a low traffic flow on the motorway the use of a long weaving segment by merging vehicles is comparable (KS-test: n1 = 107, n2 = 122, p = 0.624).

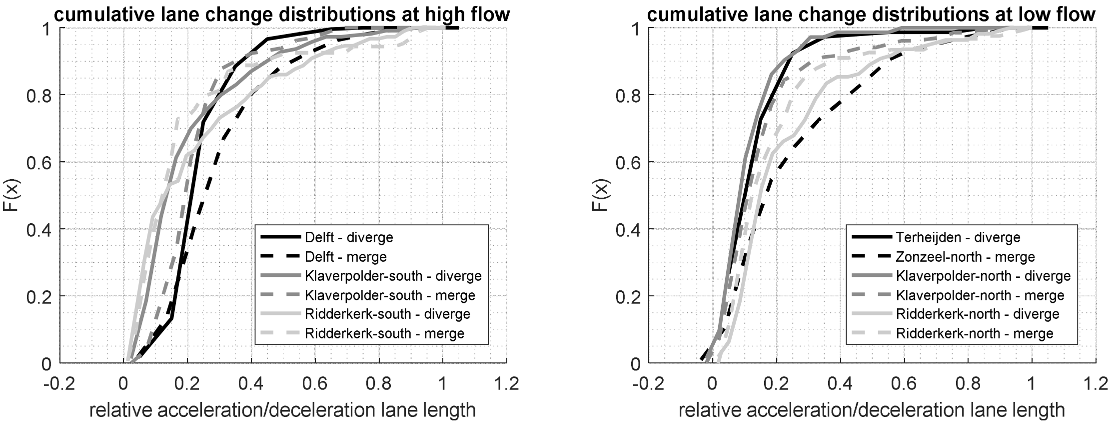


Figure 4.5. Use of acceleration and deceleration lane under different conditions.

	percentage of lane changes performed in first 25% of the lane	
	high traffic flow (0.74 ≤ F/C ≤ 0.81)	**low traffic flow (0.55 ≤ F/C ≤ 0.61)**
off-ramp - diverge	80%	95%
on-ramp - merge	65%	68%
short weaving - diverge	80%	95%
short weaving - merge	85%	90%
long weaving - diverge	73%	74%
long weaving - merge	80%	86%

Table 4.5. Utilization of the available length for weaving.

In figure 4.6 headway and speed distributions are compared. The first line represents the distribution at the moment another vehicle merges in front (t = 0 s). The second line shows the distribution 10 seconds prior to this moment (t = -10 s). This comparison is done for both sites with a relative high traffic flow and sites with a relative low traffic flow. Table 4.6 shows the descriptive statistics of the headway progression and the results of a two sample KS-test. The results show no cooperative behaviour. Both the headway and speed distributions do not significantly differ at t = 0 s and t = -10 s, regardless the flow or the length of the weaving segment.

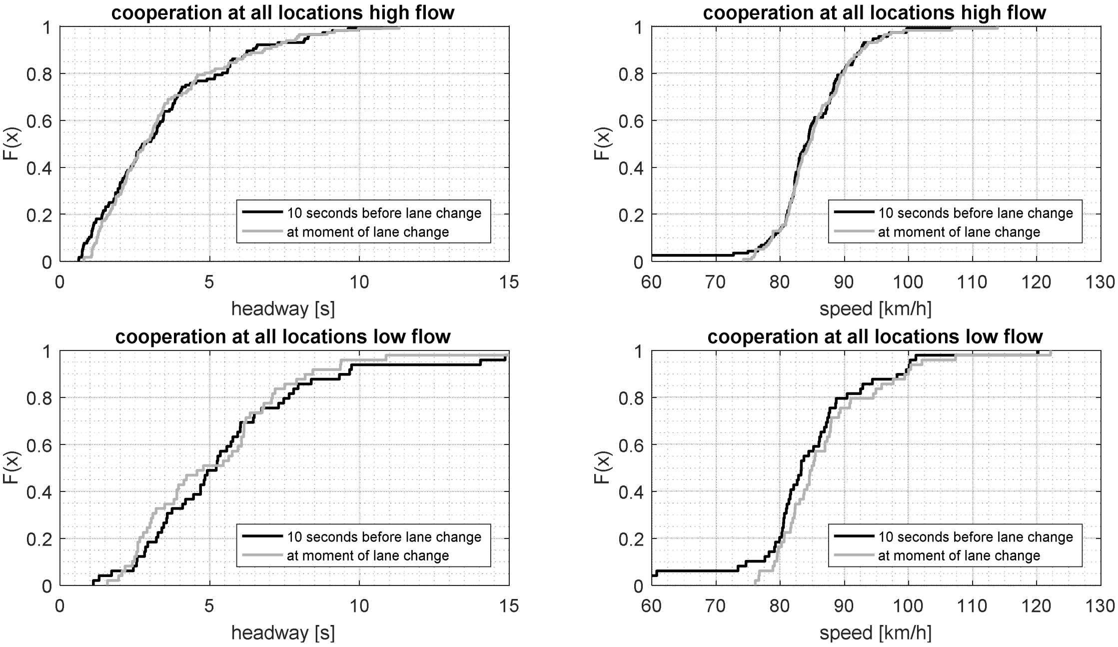


Figure 4.6. Headway and speed progression of cooperating vehicles.

site		n	mean t=0s [sec]	mean t=10s [sec]	std. t=-10s [sec]	std. t=0s [sec]	p-value KS-test
headway	on-ramp Zonzeel-north	31	6.1	5.5	2.9	3.0	**0.559**
	weaving Ridderkerk-north	6	4.4	5.0	3.2	3.1	**0.810**
	weaving Klaverpolder-north	12	5.1	4.7	3.7	2.4	**1.000**
	all locations - low flow	49	5.6	5.3	3.2	2.9	**0.665**
	on-ramp Delft	97	3.3	3.2	2.2	2.1	**0.778**
	weaving Ridderkerk-south	5	4.3	4.7	2.9	3.4	**1.000**
	weaving Klaverpolder-south	14	3.7	4.4	2.5	2.4	**0.862**
	all locations - high flow	116	3.4	3.4	2.2	2.2	**0.541**
speed	on-ramp Zonzeel-north	31	83.2	85.3	10.9	6.9	**0.944**
	weaving Ridderkerk-north	6	81.0	84.4	5.2	3.1	**0.318**
	weaving Klaverpolder-north	12	87.8	94.0	16.2	11.7	**0.786**
	all locations - low flow	49	84.1	87.3	11.9	8.8	**0.494**
	on-ramp Delft	97	84.2	85.5	9.1	5.9	**0.883**
	weaving Ridderkerk-south	5	86.0	84.1	4.1	5.5	**1.000**
	weaving Klaverpolder-south	14	83.8	85.8	12.4	8.1	**0.541**
	all locations - high flow	116	84.2	85.5	9.4	6.1	**0.938**

Table 4.6. Descriptive statistics of headway progression of cooperating vehicles.

The different headway and speed distributions for relaxation at on-ramps are displayed in figure 4.7. The black line represents the distribution at the moment the subject vehicle merges from the acceleration lane to lane 1 (t = 0 s). The grey line shows the distribution 10 seconds after to this moment (t = 10 s). The descriptive statistics for the headway progression are shown in table 4.7, as well as the results of a two sample KS-test.

The results shown that the headways show a slight increase after t = 0 s for all 3 on-ramps. However, only for the on-ramp of Delft the difference is significant. The measured mean speeds also show an increase but this difference is not significant.

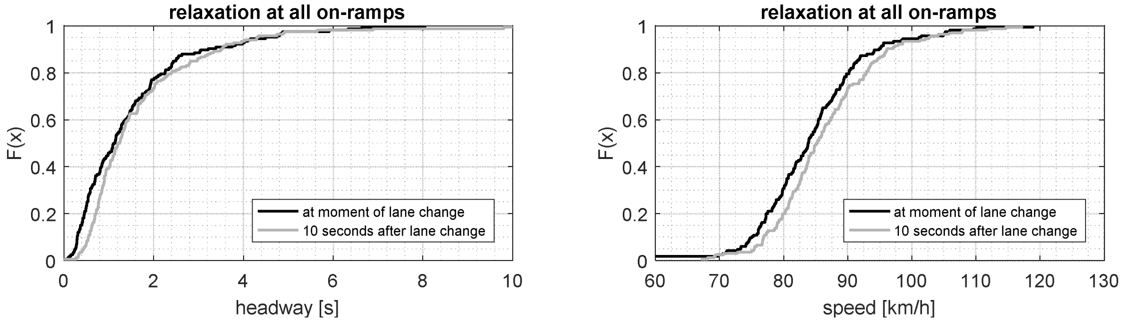


Figure 4.7. Headway and speed progression under relaxation.

site		n	mean t=0s [sec]	mean t=10s [sec]	std. t=0s [sec]	std. t=10s [sec]	p-value KS-test
headway	on-ramp Delft	115	1.2	1.4	1.0	0.9	0.005
	on-ramp Terheijden	22	2.4	2.7	2.1	2.5	**1.000**
	on-ramp Zonzeel-north	29	2.0	2.1	1.7	1.9	**0.996**
	all on-ramps	166	1.5	1.7	1.4	1.5	0.008
speed	on-ramp Delft	115	83.3	86.0	7.8	6.8	**0.054**
	on-ramp Terheijden	22	90.1	93.1	17.6	14.3	**0.821**
	on-ramp Zonzeel-north	29	82.9	83.1	5.9	6.2	**0.996**
	all on-ramps	166	84.1	86.5	9.6	8.5	**0.099**

Table 4.7. Descriptive statistics of headway progression of relaxation.

Gap acceptance for merging at different designs and speeds

Figure 4.8 displays the cumulative distribution functions of accepted gaps (net headways) during merging, secondary merging, diverging and keeping right. Four scenarios are displayed: gap acceptance at long weaving segments, under high and low flow, and gap acceptance at short weaving segments under high and low traffic flow conditions. The descriptive statistics for these distributions are shown in table 4.8. For each scenario the accepted gaps of MLC (merge and diverge) and DLC (secondary merge and keeping right) are compared. The results of the comparison is shown in table 4.9. To give an indication of the impact of the weaving segment length the distribution of accepted gaps of merging traffic at on on-ramp is taken as a reference. The accepted gap distributions show that gap acceptance at a long weaving segment, under low traffic flow conditions, is comparable to merging at an on-ramp at low traffic flow conditions. The mean accepted gap is between 5.5 and 7.5 seconds. For the other scenarios in figure 4.8 the shapes of the distributions seem to be similar, but the results of the KS-test do not support this for most cases. In the scenario with a long weaving segment and high traffic flow conditions, the difference might be explained by the high volume of trucks in the weaving segment "Ridderkerk-South" and the low volume of trucks at the on-ramp of "Delft". For the scenario with a long weaving segment length and high traffic flow conditions and the scenario with a short weaving segment and low traffic flow conditions, the accepted gap distribution for diverging stands out. This can be explained by the amount of entering and exiting traffic, as shown in table 4.1. In the long weaving segment "Ridderkerk - south" the amount of entering traffic is low (416 vehicles), which explains a relatively large average accepted gap. In the short weaving segment "Bergen op Zoom - east" the entering flow is high (641 vehicle), which explains a relatively small average accepted gap. When comparing merging (MLC) and secondary merging (DLC) the results show that on average smaller gaps are accepted for merging. The only exception is the scenario with the short weaving segment and the low traffic flow conditions. Here the average accepted gap for secondary merging is smaller, but for merging and secondary merging the average accepted gap is relatively large due to the small amount of traffic.

The results of a cross comparison between weaving segments with comparable lengths and flows are shown in table 4.10. The KS-test results show that the accepted gap distributions at long weaving segments are reasonably comparable for both high and low traffic flow conditions. The same holds for gap acceptance when weaving under high traffic flow conditions. The distributions for both the long and short weaving segment are comparable at high flow conditions. Except for the accepted gap distribution for diverging.

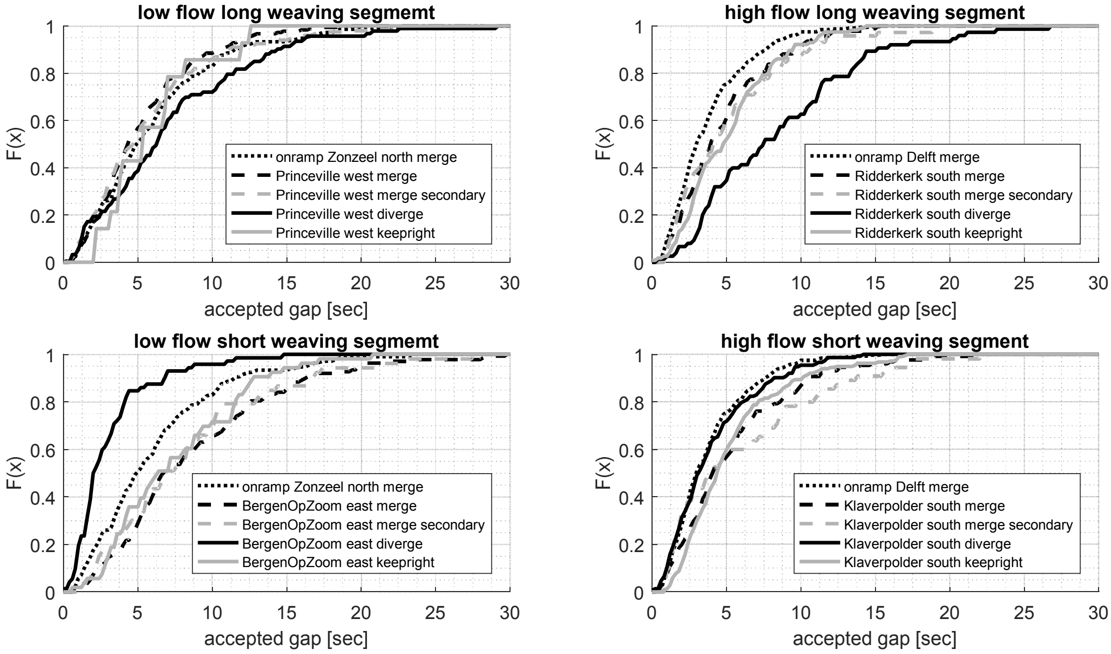


Figure 4.8. Comparison of MLC and DLC under different conditions.

site and manoeuvre	n	mean	std.	site and manoeuvre	n	mean	std.
low flow and long weaving segment				**high flow and long weaving segment**			
onramp Zonzeel-north merge	212	6.36	5.02	onramp Delft merge	322	3.95	2.68
Princeville-west merge	183	5.46	3.59	Ridderkerk-south merge	95	4.78	3.26
Princeville-west merge secondary	201	6.05	5.05	Ridderkerk-south merge secondary	72	5.34	4.05
Princeville-west diverge	93	7.40	5.48	Ridderkerk-south diverge	75	8.69	5.61
Princeville-west keeping right	15	5.66	3.51	Ridderkerk-south keeping right	115	5.31	3.09
low flow and short weaving segment				**high flow and short weaving segment**			
onramp Zonzeel-north merge	212	6.36	5.02	onramp Delft merge	322	3.95	2.68
Bergen op Zoom-east merge	139	9.06	6.22	Klaverpolder-south merge	130	5.55	4.15
Bergen op Zoom-east merge secondary	54	8.88	6.47	Klaverpolder-south merge secondary	55	6.13	5.28
Bergen op Zoom-east diverge	72	3.22	2.74	Klaverpolder-south diverge	153	4.15	2.99
Bergen op Zoom-east keeping right	53	7.68	4.51	Klaverpolder-south keeping right	217	5.40	3.51

Table 4.8. Descriptive statistics of accepted gap distributions.

		scenario 1	**length [m]**	**F/C**	**n**	**scenario 2**	**length [m]**	**F/C**	**n**	**p**
long weaving segment length	**low flow**	onramp Zonzeel-north merge	340	0.58	212	Princeville-west merge	1100	0.52	183	**0.259**
		onramp Zonzeel-north merge	340	0.58	212	Princeville-west merge sec.	1100	0.52	201	**0.303**
		onramp Zonzeel-north merge	340	0.58	212	Princeville-west diverge	1100	0.52	93	**0.221**
		onramp Zonzeel-north merge	340	0.58	212	Princeville-west keeping right	1100	0.52	15	**0.987**
		Princeville-west merge	1100	0.52	183	Princeville-west merge sec.	1100	0.52	201	**0.661**
		Princeville-west diverge	1100	0.52	93	Princeville-west keeping right	1100	0.52	15	**0.643**
	high flow	onramp Delft merge	300	0.81	322	Ridderkerk-south merge	1000	0.78	95	0.038
		onramp Delft merge	300	0.81	322	Ridderkerk-south merge sec.	1000	0.78	72	0.015
		onramp Delft merge	300	0.81	322	Ridderkerk-south diverge	1000	0.78	75	0.000
		onramp Delft merge	300	0.81	322	Ridderkerk-south keeping right	1000	0.78	115	0.000
		Ridderkerk-south merge	1000	0.78	95	Ridderkerk-south merge sec.	1000	0.78	72	**0.922**
		Ridderkerk-south diverge	1000	0.78	75	Ridderkerk-south keeping right	1000	0.78	115	0.000
short weaving segment length	**low flow**	onramp Zonzeel-north merge	340	0.58	212	Bergen op Zoom-east merge	500	0.35	139	0.000
		onramp Zonzeel-north merge	340	0.58	212	Bergen op Zoom-east merge sec.	500	0.35	54	0.013
		onramp Zonzeel-north merge	340	0.58	212	Bergen op Zoom-east diverge	500	0.35	72	0.000
		onramp Zonzeel-north merge	340	0.58	212	Bergen op Zoom-east keeping right	500	0.35	53	**0.086**
		Bergen op Zoom-east merge	500	0.35	139	Bergen op Zoom-east merge sec.	500	0.35	54	**0.723**
		Bergen op Zoom-east diverge	500	0.35	72	Bergen op Zoom-east keeping right	500	0.35	53	0.000
	high flow	onramp Delft merge	300	0.81	322	Klaverpolder-south merge	500	0.74	130	0.001
		onramp Delft merge	300	0.81	322	Klaverpolder-south merge sec.	500	0.74	55	0.005
		onramp Delft merge	300	0.81	322	Klaverpolder-south diverge	500	0.74	153	**0.914**
		onramp Delft merge	300	0.81	322	Klaverpolder-south keeping right	500	0.74	217	0.000
		Klaverpolder-south merge	500	0.74	130	Klaverpolder-south merge sec.	500	0.74	55	**0.300**
		Klaverpolder-south diverge	500	0.74	153	Klaverpolder-south keeping right	500	0.74	217	0.001

Table 4.9. Results statistical comparison gap acceptance; comparison of weaving segment length.

		scenario 1	**length [m]**	**F/C**	**n**	**scenario 2**	**length [m]**	**F/C**	**n**	**p**
weaving segment length	**long**	Princeville-west merge	1100	0.52	183	Ridderkerk-south merge	1000	0.78	95	**0.410**
		Princeville-west merge sec.	1100	0.52	201	Ridderkerk-south merge sec.	1000	0.78	72	**0.710**
		Princeville-west diverge	1100	0.52	93	Ridderkerk-south diverge	1000	0.78	75	**0.125**
		Princeville-west keeping right	1100	0.52	15	Ridderkerk-south keeping right	1000	0.78	115	**0.858**
	short	Bergen op Zoom-east merge	500	0.35	139	Klaverpolder-south merge	500	0.74	130	0.000
		Bergen op Zoom-east merge sec.	500	0.35	54	Klaverpolder-south merge sec.	500	0.74	55	0.017
		Bergen op Zoom-east diverge	500	0.35	72	Klaverpolder-south diverge	500	0.74	153	0.016
		Bergen op Zoom-east keeping right	500	0.35	53	Klaverpolder-south keeping right	500	0.74	217	0.002
flow	**low**	Princeville-west merge	1100	0.52	183	Bergen op Zoom-east merge	500	0.35	139	0.000
		Princeville-west merge sec.	1100	0.52	201	Bergen op Zoom-east merge sec.	500	0.35	54	0.005
		Princeville-west diverge	1100	0.52	93	Bergen op Zoom-east diverge	500	0.35	72	0.000
		Princeville-west keeping right	1100	0.52	15	Bergen op Zoom-east keeping right	500	0.35	53	**0.232**
	high	Ridderkerk-south merge	1000	0.78	95	Klaverpolder-south merge	500	0.74	130	**0.486**
		Ridderkerk-south merge sec.	1000	0.78	72	Klaverpolder-south merge sec.	500	0.74	55	**0.610**
		Ridderkerk-south diverge	1000	0.78	75	Klaverpolder-south diverge	500	0.74	153	0.000
		Ridderkerk-south keeping right	1000	0.78	115	Klaverpolder-south keeping right	500	0.74	217	**0.518**

Table 4.10. Results statistical comparison gap acceptance; cross comparison of weaving segment length and traffic flow.

4.5. Discussion

The level of turbulence is defined as the frequency and intensity of individual changes in speed, headways, and lanes (i.e. lane-changes) (Van Beinum et al. 2016). The results show that the largest contribution to turbulence is given by the intensity of lane changes. Only small changes in headway and speed were found for both cooperation and relaxation. For changes in speed, the differences were found to be not significant. For changes in headway, only the change in headway during relaxation under high traffic flow conditions was found to be significant. Nevertheless, it is expected that the effects of cooperation, anticipation and relaxation will increase as the traffic flow increases, since these manoeuvres are more likely to occur in (near) saturated or congested traffic.

In this chapter, we found that the frequency of lane changes was found to be highest around ramps: 50% of all lane changes in the vicinity of ramps take place at the acceleration and deceleration lane, which is only 20-25% of the measured length of motorway. Pre-allocation and anticipation were found to be of little influence for turbulence. The intensity of these lane changes is low and mainly take place at a close distance from the ramp. This suggests that the ramp influence area is smaller than currently perceived in the different guidelines (Rijkswaterstaat 2017; HCM 2010). This is especially the case for off-ramps where only pre-allocating vehicles provide a little increase in the level of turbulence. For on-ramps mainly secondary lane changes create turbulence downstream of the ramp. These secondary lane changes might also explain the increased intensity of keeping right lane changes downstream of the on-ramp.

Not all measured lane changes can directly be linked to entering or exiting traffic. Lane changes to the inside and outside of the motorway, which are not triggered by entering or exiting vehicles nearby, are present over the whole measured area with an average of lane changes per 25 m that ranges between 2 and 8. This indicates that turbulence is always present in traffic, which is consistent with (HCM 2010). However, it was found that the rate of these lane changes increases in the vicinity of ramps.

A higher traffic volume results in a higher level of turbulence. Shorter gaps are accepted for MLC under high traffic flow conditions which results in small initial headways which gradually increase over time (relaxation). A longer weaving segment length has a positive effect on the level of turbulence. Drivers make use of a longer distance to select a suitable gap which results in larger accepted gaps for MLC. This is in line with the findings of (Calvi and De Blasiis 2011). However when a weaving segment gets longer this effect gets smaller, since only the first part of the weaving segment is used. More than 85% of the lane changes for merging and diverging are performed in the first 50% of the weaving segment length. This coincides with previous findings (Daamen et al. 2010; Marczak et al. 2014). Weaving segment lengths longer than 1,000m are not expected to provide a significant additional benefit.

4.6. Conclusions

This study focusses on driving behaviour near motorway ramps (on-ramps, off-ramps and weaving segments). Different manoeuvres are identified that are performed by drivers that either enter the motorway, exit the motorway or anticipate / cooperate with entering or exiting vehicles. These manoeuvres create an increased level of turbulence that starts upstream of the ramp, is at its highest at the ramp and decreases downstream of the ramp. The study shows that the increased level of turbulence, in free flow conditions, is mainly characterised by increased numbers of lane changes. Changes in speed and headway are limited. Only for relaxation a significant change was found under high traffic flow conditions. Most of the lane changes are attributed to merging and diverging and take place at the acceleration lane or deceleration lane. Further upstream and downstream the intensity of lane changes is much less. Especially for off-ramps, where only pre-allocation was shown to be of influence. Pre-allocation related lane changes are small in number and seem to be correlated to the location of signposting. At on-ramps anticipation generates lane changes upstream of the ramp but only at a maximum distance of 25 m - 100 m. Downstream of the on-ramp secondary lane changes are performed. 26%-41% of the merging vehicles perform additional lane changes towards the median lane after they have merges. These lane changes are performed until about 475 m - 575 m downstream of the ramp.

The findings related to the start and end of turbulence are shown in table 4.11 and are compared to previous studies. The prescribed upstream values in the HCM are slightly larger than found in our study. This coincides with the findings of (Kondyli and Elefteriadou 2012). The downstream values are comparable. The prescribed values for on-ramps in the Dutch design guidelines (Rijkswaterstaat 2017) are reasonably consistent with our findings.

For off-ramps the upstream value is slightly higher when the impact of the sign post is not taken into account.

on-ramp		off-ramp		source
upstream [m]	downstream [m]	upstream [m]	downstream [m]	
25-100	475-575	400-600*	200-375	this study
200	900	1,000	-	(Van Beinum et al. 2017)
110	260	-	-	(Kondyli and Elefteriadou 2012)
460	460	460	460	(HCM 2010)
150	750	750	150	(Rijkswaterstaat 2017)

Table 4.11. Ramp influence areas; * location of sign post.

The use of the available road length by merging and diverging vehicles is rather constant. Most vehicles make only use of the first part of the acceleration lane or deceleration lane, regardless of the traffic flow or the available length (which ranged between 210 m - 250 m for off-ramps and 300 m - 340 m for off-ramps). Comparable behaviour is observed at weaving segments (with lengths ranging from 400 m - 1,100 m). Both entering and exiting vehicles make use of only the first part of the weaving segment, which results in an accumulation of lane changes in the first part and only a few lane changes in the last part of the weaving segment. This corresponds to findings in other studies (Marczak et al. 2014; Kusuma et al. 2015).

Based on the analysis of our dataset, both road design and traffic flow have shown to affect the use of the acceleration lane and deceleration lane. When the length of a weaving segment is increased, more length is used for merging. Road design and traffic flow seem to hardly affect gap acceptance. We found significant difference in the mean accepted gaps between low and high traffic flow at short weaving segments, but not at long weaving segments. For long weaving segments similar accepted gap distributions were found for both high flow and low flow traffic conditions. At short weaving segments a significant difference was found between the two distributions. Therefore, the results are not conclusive.

Our findings give an interesting insight into the characteristics of the different manoeuvres that contribute to turbulence. It shows where turbulence starts and ends, but more importantly: it shows how the different manoeuvres are performed and how these are affected by motorway design and traffic flow. This study is based on a large dataset of trajectories from individual vehicles driving in the vicinity of ramps. This information is essential for gaining more understanding on driving behaviour which can be used for improving our microscopic simulation models and for improving our design guidelines. It is recommended to use this data to improve the modelling of the different manoeuvres and the interaction between vehicles that perform these manoeuvres. Some of the studied manoeuvres have been given much attention in literature, such as merging and diverging, but for other manoeuvres much less research has been performed. Examples of manoeuvres that require further research are: pre-allocation, secondary merges and keeping right. Moreover it is recommended to further investigate the variability in behaviour among drivers (e.g. the level of risk different drivers are willing to take) and its impact on traffic flow characteristics and safety. Our final recommendation is to put more effort in investigating the impact of road (design) characteristics on driving behaviour. For example the impact of horizontal alignment, vertical alignment, number of lanes and lane width on lane change behaviour.

5. Microscopic modelling of turbulence

Abstract

In the current motorway design practice microscopic simulation is used to assess the traffic safety and capacity implications of design variants. Many different simulation packages are available, and many researchers invested effort in improving and calibrating models that describe driving behaviour. Based on a multi criteria analysis two simulation software packages (VISSIM and MOTUS) were selected and calibrated using a recently collected set of rich empirical trajectory data from an on-ramp, an off-ramp and 2 weaving segments in The Netherlands. The results show that both packages are yet unable to simulate turbulent traffic around motorway ramps realistically, in terms of lane change locations and headway distribution. This is a drawback when assessing traffic operations for specific designs. Vehicle interaction, in terms of gap acceptance, was found to be simulated reasonably accurate. This is an advantage when assessing traffic safety of a specific design.

5.1. Introduction

Traditionally the design of a motorway is based on design guidelines, such as the Highway Capacity Manual (HCM 2010) and the 'AASHTO Green Book' in the USA, (AASHTO 2011), the 'Richtlinien für die Anlage von Autobahnen (RAA)' (RAA 2008) in Germany, the 'Design Manual for Roads and Bridges (DMRB 1994)' in Great Brittan and 'Richtlijnen voor het Ontwerp van Autosnelwegen (ROA)' (Rijkswaterstaat 2017) in The Netherlands. These guidelines provide standard 'one size fits all' solutions with standardized dimensions that guarantee consistency in road geometry and provide safe motorways with a sufficient level of service (Rijkswaterstaat 1992).

Ramp-spacing (the distance between consecutive ramps) and weaving segment length are two important design elements that influence the longitudinal design of motorways. A weaving segment is the case wherein the acceleration lane of an on-ramp is connected to the deceleration lane of an off-ramp by one (or more) auxiliary lane(s). The weaving segment length is the length of the auxiliary lane.

Different approaches are used for the determination of the required ramp spacing and weaving segment length in the different design guidelines. A common general concept of these approaches, is that the applied length must be sufficient to cope with the raised level of turbulence, that is created by traffic that enters or exits the motorway (Van Beinum et al. 2016). The raised level of turbulence is referred to as an increased intensity of individual changes in speed, headways, and lane-changes, over a certain period of time, compared to that at a continuous segment of road under comparable traffic conditions (Van Beinum et al. 2016). Turbulence has a negative impact on traffic safety and traffic operations (Abdel-Aty, Uddin, et al. 2005; Golob et al. 2004; HCM 2010; Kondyli and Elefteriadou 2012; Lee et al. 2003b, 2003a; Chen and Ahn 2018).

In densely populated areas, such as many areas in The Netherlands, the solution that is prescribed by the guideline, can sometimes not be realized due to a lack of physical space. In such cases, deviation from the guidelines is considered. However, the quantitative implications of such deviations for traffic safety and operations of such deviations are not provided by the design guidelines. For these special 'fit for purpose' designs, often microscopic simulation models are used as a supporting design tool as an addition to the guidelines. These are useful tools (Zheng 2014) for simulating, analysing and quantifying traffic flow phenomena for different designs (Garber and Fontaine 1999; Wang et al. 2014; Martínez et al. 2011). However, these models need to be predictively valid to ensure that the correct implications for traffic safety and operations are derived. The currently available microscopic simulation software packages have limitations in terms of their predictive validity (Choudhury 2007; Daamen et al. 2010). It is possible to calibrate the driving behaviour models that are implemented in a simulation software package, when empirical data of individual vehicle movements are available. However, the availability of this type of data is limited in both quantity and quality (Van Beinum et al. 2018). But even after calibration simulated driving behaviour differs from behaviour found in field data. Examples are gap acceptance (Daamen et al. 2010) and lane change locations (Choudhury 2007). This lack of accuracy is a challenge when a microscopic simulation model is to be used for evaluating design variants for its effect on turbulence.

Microscopic simulation software packages are based on mathematical models to simulate the longitudinal and lateral driver behaviour. Despite the huge improvements in microscopic simulation software packages' interface and visualization, the advancement in its traffic behaviour performance is at a much slower pace. For example, the most recent car following model in VISSIM dates back to 1991 (PTV 2017) and AIMSUN uses a car-following model based on the model developed by Gipps (1981). However, much research is done in the last 10 years and different new mathematical models are proposed in the literature, such as (Hamdar et al. 2015; Wan et al. 2014; Schakel et al. 2013; Schakel et al. 2012; Chong et al. 2013; Choudhury et al. 2009; Sun and Elefteriadou 2010; Toledo, Koutsopoulos, and Ben-Akiva 2007) which are not (yet) incorporated in the widely used commercial microscopic simulation software packages.

The first objective of this chapter is to investigate whether currently available microscopic simulation software packages and recently proposed mathematical models are capable to simulate turbulence in the vicinity of ramps realistically. The second objective is to investigate whether the recently proposed mathematical models give a better representation of driving behaviour around ramps and at weaving segments compared to the models that are already implemented in the existing microscopic simulation software packages.

To this end the authors derived a set of criteria that a suitable driver behaviour model in theory should fulfil for the purpose of simulating turbulence. Based on this set of criteria the authors have selected a commonly used microscopic simulation software package, a recently proposed longitudinal behaviour model and a recently proposed lateral behaviour model. Both the software package and the models were calibrated based on trajectory data that were collected at different on-ramps (1 site), off-ramps (1 site) and weaving segments (2 sites) in The Netherlands (Van Beinum et al. 2018). After calibration the performance of the software package and the models were evaluated by comparing the simulated trajectory data with the empirical trajectory data.

The remaining of this chapter is structured as follows. In the literature review section (section 2) an overview is given of the characteristics of driving behaviour around ramps and the characteristics of existing mathematical models. Based on this review, the most suitable mathematical models are selected for both the longitudinal and lateral behaviour. This is followed by the Research Method (section 3), which describes the collected empirical trajectory data, the calibration procedure for the microscopic simulation models and the evaluation procedure. The results section (section 4) presents the outcomes of the calibration and evaluation. The chapter concludes with a discussion section (section 5), followed by conclusions and recommendations for future research (section 6).

5.2. Review of micro simulation models

This review section, is structured as follows. First, the criteria and functionalities that a suitable simulation model for simulating turbulence should fulfil are defined. Second, an overview is given of the mathematical models that are incorporated in the currently available microscopic simulation software packages. The overview shows how these models have progressed with time to the current state of the art. The third and final part of this section presents a critical review and a summary whether the state of the art models fulfil the different criteria and functionalities defined in the first section. This summary results in the selection of the most suitable longitudinal and lateral driver behaviour models that are later subjected to further analysis quantitative evaluation utilizing the empirical data.

5.2.1. Model criteria for simulating turbulence

Turbulence is the result of multiple manoeuvres which are executed by drivers in the vicinity of ramps (Van Beinum et al. 2016). These manoeuvres involve both lateral and longitudinal driving behaviour and has an impact on the macroscopic characteristics of the traffic stream. This concept is shown in the theoretical framework as shown in figure 5.1.

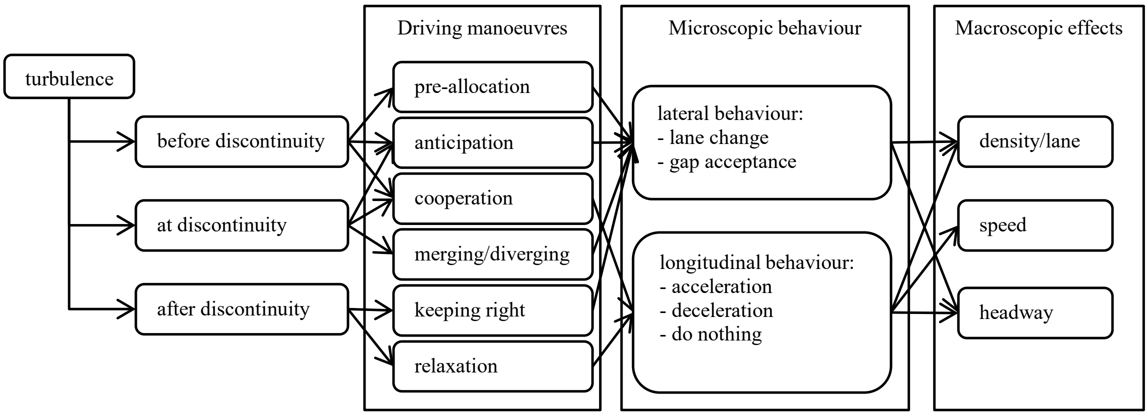


Figure 5.1. Theoretical framework for turbulence (Van Beinum et al. 2016).

In (Van Beinum et al. 2018) the authors have found that the largest contribution to turbulence around ramps stems from lateral behaviour: i.e., the intensity of lane changes. It was also shown that the contribution of the longitudinal behaviour to turbulence is small: only small changes in headways and speeds were found for both cooperation and relaxation manoeuvres.

Driving manoeuvres

The manoeuvres that involve a lane change, and are performed to enter or exit a motorway, or as a reaction to entering or exiting vehicles are displayed in figure 5.2. A detailed description of the characteristics of these manoeuvres is given in (Van Beinum et al. 2018).

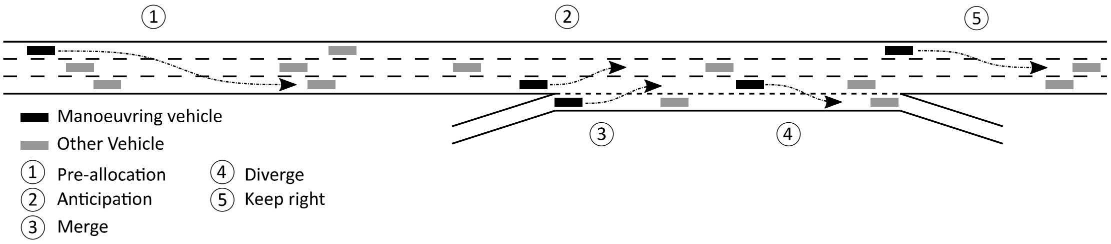


Figure 5.2. Characteristics of manoeuvres that involve a lane change.

It was shown in the literature that drivers that exit the motorway (*4*) tend to pre-allocate (*1*) themselves on the outside lane upstream of the deceleration lane (Van Beinum et al. 2018; Choudhury 2007; Toledo, Koutsopoulos, and Ben-Akiva 2007; Van Beinum et al. 2016). Drivers that enter the motorway (*3*) select specific gaps in which they merge into (Daamen et al. 2010). Drivers anticipate the potential changes in traffic ahead (such as: merging vehicle from an on-ramp, or pre-allocating vehicle), and consequently change their driving lane towards the inside of the motorway, possibly to avoid short headways (*2*) (Cassidy and Rudjanakanoknad 2005; Van Beinum et al. 2018). In The Netherlands drivers are bound to the right side rule by which they are obliged to change lanes to the outside lane (*5*) when there is sufficient space to do so (RVV 1990). Overtaking takes place on the inside of the motorway.
The decisions that drivers make when performing the necessary manoeuvres to enter or exit a motorway are based on a specific plan (Choudhury 2007) and affect the location of the lane change.

Microscopic behaviour

Drivers that perform a lane change often have to merge into a gap between two other vehicles on the desired adjacent lane. The size of the accepted gap and the lane change duration are dependent on the urge of the driver to change lanes (Van Beinum et al. 2018; Kusuma et al. 2015). Drivers who want to pre-allocate before diverging or who select a suitable gap to merge into, are expected to adapt their speed and align with their selected gap. This phenomenon is called synchronisation (Schakel et al. 2012). In some situations, the nearby vehicles cooperate with the driver who desires to make a lane change, by creating a gap (Kim and Coifman 2013; Choudhury et al. 2009; Hidas 2005; Hill et al. 2015). Due to the combination of changing lanes and speed adaption, synchronisation is an example in which lateral and longitudinal behaviour are integrated (Toledo, Koutsopoulos, and Ben-Akiva 2007). Drivers that have merged into a small gap tend to gradually increase their headway further downstream (Van Beinum et al. 2018; Daamen et al. 2010; Duret et al. 2011). This phenomenon is called relaxation. The acceleration (and deceleration) values are limited by vehicle capabilities and the extent into which drivers are willing to use their vehicle's capabilities or the level of comfort they desire. This range is expected to be between –3 and 2m/s2 and the maximum rate of acceleration reduces for increasing speeds (Schakel 2015).

Macroscopic effects

Drivers have certain desired speeds. On a motorway, slower vehicles (such as trucks) usually drive on the outside lane of the motorway, while faster vehicles drive on the inside lane of the motorway, where they are more able to reach their desired speeds (Daganzo 2002a, 2002b). These preferences cause a natural distribution of traffic over the lanes, resulting in different traffic densities per motorway lane. Previous studies have shown that the distribution over the different motorway lanes is significantly different for on-ramps and basic continuous motorway sections. Upstream of an on-ramp the fraction of flow on the median lane (the lane in the vicinity of the motorway median) gets higher due to anticipatory behaviour. As a consequence, the fraction of flow on the outside lane gets lower. Upstream of an off-ramp the fraction of flow on the outside lane is expected to be higher due to drivers that pre-allocate. The fraction of flow in the centre lane (in case there are three lanes) hardly changes (Carter et al. 1999; Van Beinum et al. 2017; Knoop et al. 2010; HCM 2010; Amin and Banks 2005).

General model criteria

There are two general criteria that a model is preferred to fulfil. The first pertains to the number of parameters that need to be calibrated and their physical meaning. A small number of parameters is preferred, and it is also preferred that these parameters represent measurable traffic phenomena. A large number of parameters, i.e. more complex models, may potentially makes it possible to take more elements of driving behaviour into account, but the simulation results may be difficult to relate to specific parameter values, and it might lead to overfitting problems. The second last requirement is that a model is preferred to be open source, such that its effects are comprehensible.

Overview of criteria and functionalities

Based on the different manoeuvres that are found to be present around motorway ramps and weaving segments, the criteria for a microscopic simulation model that is suitable for simulating turbulence, are defined in table 5.1.

no.	category	criteria and functionalities
1	manoeuvres	the locations of lateral movements around ramps and in weaving segments are based on latent tactical plans by the driver, that incorporate pre-allocation and gap selection.
2		the lateral movement is anticipative.
3		the lateral movements are influenced by the rule to keep right.
4	microscopic behaviour	the desire to change lanes increases as the available length for changing lanes decreases.
5		the longitudinal/lateral interactions include cooperation and synchronization.
6		the longitudinal/lateral interactions include relaxation.
7		maximum acceleration and deceleration related to vehicle limitations.
8	macroscopic effects	desired speeds for each vehicle are distributed realistically.
9		lane selection is based on the desired speed.
10	general model criteria	the number of model parameters for calibration is preferably small.
11		model is open source, so that simulated behaviour can be explained.

Table 5.1. Overview of criteria and functionalities.

5.2.2. Available and widely used microscopic simulation models

Known examples of microscopic simulation software packages which are widely used in research are AIMSUN (Young et al. 2014), CORSIM (Sun and Kondyli 2010), MITSIM (Sun and Elefteriadou 2010; Choudhury et al. 2009; Toledo, Koutsopoulos, and Ben-Akiva 2007), MOTUS (Schakel 2015), PARAMICS (Dijkstra 2011) and VISSIM (Chih-Sheng and Nichols 2015). Each of these packages makes use of an integrated longitudinal and lateral behaviour model. In this section, an overview is given of the different models that are used in the different microscopic simulation software packages. The considered software packages and the driver behaviour models that are implemented in these packages are displayed in figure 5.3. A description of the development of each model and its main characteristics are given below.

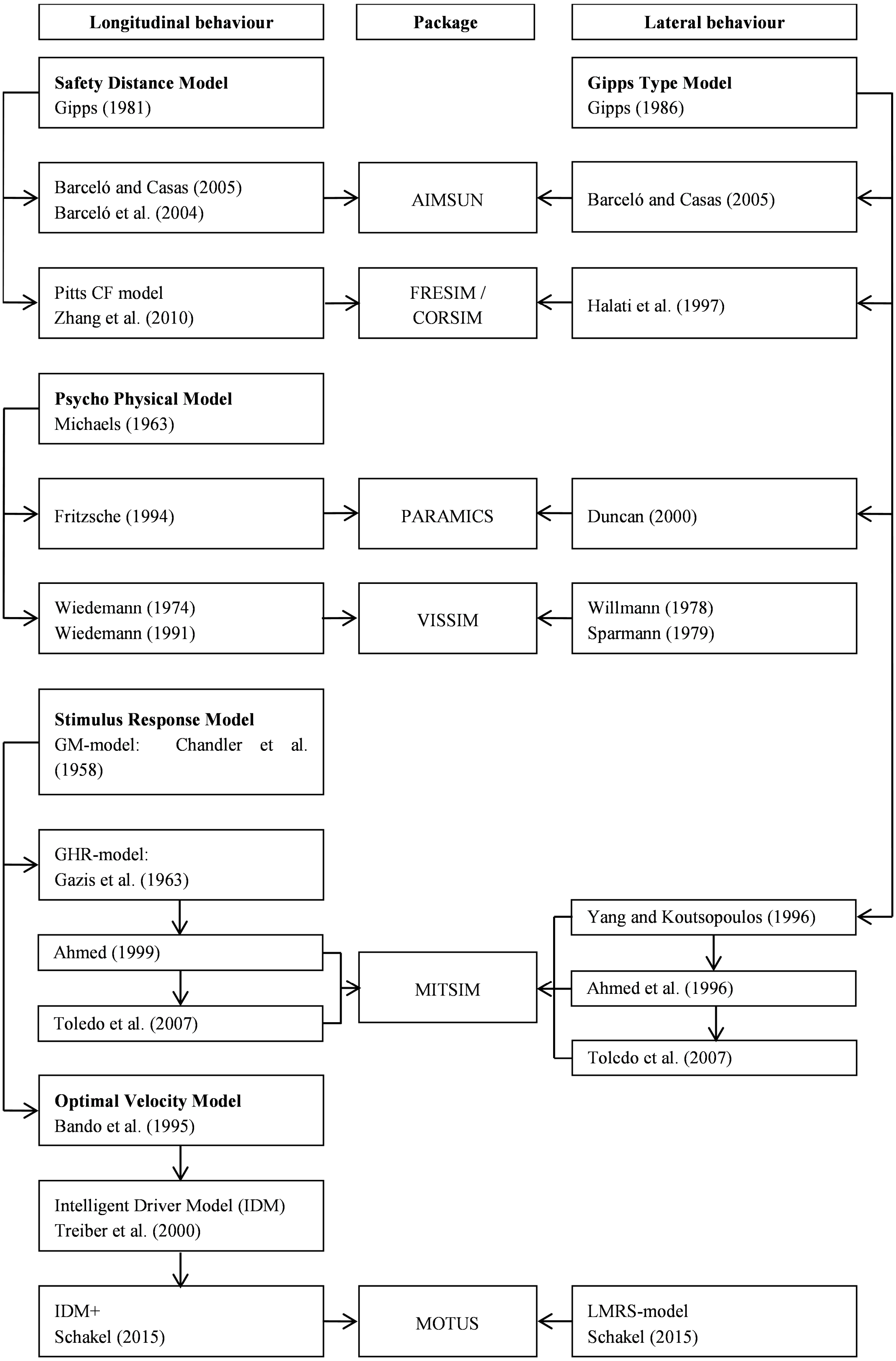


Figure 5.3. Overview of models used in microscopic simulation software packages.

AIMSUN

The main aspects of AIMSUN are described by Barceló et al. (2004). However, the mathematical explanation of the implemented behavioural models are not provided. Also, AIMSUN is not open source.

The AIMSUN car following is based on the safety distance model that was developed by Gipps (Gipps 1981). In this model the desired speed is stochastically set for each vehicle, is dependent on the lane in which the vehicle drives and can vary within the network. The desired speed is affected by the lane type of the adjacent lane (i.e. deceleration lane) and the average speed of a certain number of vehicles driving on that lane. A minimum and maximum acceleration is set for each vehicle and is affected by the grade of the road (Barceló and Casas 2005; Barceló et al. 2004). The use of the Gipps model has some general drawbacks: the parameters of the models were not estimated rigorously and the reaction time was set arbitrarily for all drivers (Ahmed 1999). Furthermore, a following vehicle reacts on the actions of its leader directly (Toledo 2003), and therefore, anticipation is not taken into account. Also synchronisation and relaxation are not taken into account.

The lateral behaviour model in AIMSUN is a further evolution of the Gipps lane change model (Gipps 1986). In this model, the decision to change lane depends on three criteria: 1) is it possible to change lanes?; 2) is it necessary to change lanes?; 3) is it desirable to change lanes? The necessity to change lanes depends on route decisions and the speed and queue lengths in the current lane (Barceló and Casas 2005). For lane changes due to route decisions three consecutive zones are defined upstream of the lane change decision point. The desire to change lanes increases as the vehicle progresses through the zones. When a vehicle is driving below its desired speed, it tries to overtake the preceding vehicle, and when it is driving at its desired speed, it tends to move to the slower lane (keep right). To make sure that lane changes are performed in time and a vehicle does not miss its turn, a look ahead process is added to the lane change model. In this process vehicles are given knowledge of available gaps for various next turning movements from which it can choose, instead of only one (latent plan).

CORSIM

The main aspects of CORSIM are described by Halati et al. (1997) and Holm et al. (2007). However, not all the behavioural models (Holm et al. 2007). CORSIM is not open source and is therefore labelled as a ‘black box’. The CORSIM car following model is an improved version of the Gipps car following model (Gipps 1981; Zhang et al. 2010). In CORSIM each vehicle has a stochastically assigned desired free-flow speed on a particular link that is equal to the facility free-flow speed adjusted by a multiplier unique to the driver type (Holm et al. 2007). Furthermore it is assumed that a following vehicle will maintain a desired headway between itself and its leader, which depends on the speed at which the vehicle is traveling. Relaxation is not incorporated.

The CORSIM lateral model is an improved version of the Gipps model (Gipps 1986; Zhang et al. 2010). A vehicle that follows a leader below its desired speed gains a desire to change lanes to achieve a higher speed (Holm et al. 2007). When this vehicle can choose between two adjacent lanes, the lane with the highest headway to its new potential leader is chosen as the target lane (Zhang et al. 2010). The right side rule and anticipation are not incorporated. For route choice related lane changes, a risk factor is computed for each potential lane change. Vehicles will accept a higher risk (deceleration) as the vehicle approaches the latest opportunity to perform the lane change (Toledo 2003; Holm et al. 2007). No path planning is implemented in CORSIM as only the nearest vehicles are taken into consideration in the decision making process (Holm et al. 2007).

MITSIM

MITSIM is developed at the ITS program at Massachusetts Institute of Technology, MIT (MIT 2018). Because MITSIM is open source, different longitudinal and lateral behaviour models have been implemented in the past (Ahmed 1999; Toledo, Koutsopoulos, and Ben-Akiva 2007; Choudhury 2007).

The basic longitudinal model in MITSIM is an extended version of the GHR-model (Yang and Koutsopoulos 1996), by Gazis et al. (1963). This extended model includes a general acceleration model in which the driver is assigned to one of three regimes, based on time headway: emergency, car following and free-flow. Also relaxation and cooperation were implemented. Ahmed (1999) proposed improvements for the car following and free-flow regimes and implemented it in MITSIM. The car following component of this model is a generalization of the GM model (Gazis et al. 1961), that adds heterogeneity among drivers by allowing non-linearity in the stimulus term and different reaction times. In the free-flow regime the driver tries to attain its desired speed.

The lateral behaviour model which is incorporated in MITSIM is based on the Gipps model (Gipps 1986). The location of route choice related lane changes depends on a predefined distance from the latest possible lane change opportunity. As a vehicle gets closer to a critical distance, probability that a lane change is started increases, and accepted gaps become smaller

(Yang and Koutsopoulos 1996). Ahmed et al. (1996) and Ahmed (1999) developed a general lane change model framework that captures both MLC and DLC situations, and implemented it in MITSIM. The model allows different gap acceptance parameters for DLC and MLC situations and also cooperative behaviour was implemented (Ahmed 1999). No specific path planning was incorporated.

Toledo (2003) developed an integrated driving behaviour model, wherein acceleration is affected by gap selection, and implemented it in MITSIM. When a driver needs to change lanes, a target gap is selected on the target lane. The driver will then accelerate or decelerate to reach the target gap. This is an example of synchronization and latent path planning by the driver. The acceleration model is based on (Ahmed 1999) and is divided into a car following regime, where the driver reacts to the leader relative speed, and a free flow regime, where the driver tries to attain a desired speed. The integrated driving behaviour model has a high number of parameters (71), which makes calibration difficult.

MOTUS

MOTUS is an open-source microscopic traffic simulation package developed by Delft University of Technology (MOTUS; Schakel 2015).

The longitudinal model in MOTUS is the IDM+ model (Schakel 2015), and is based on the intelligent driver model (IDM) by Treiber et al. (2000). In this model a driver responds to its leader by a stimulus which is based on the difference between its current speed and its desired speed. An 'intelligent' dynamic term is implemented that reduces or increases the acceleration.

The lateral behaviour model in MOTUS is the Lane change Model with Relaxation and Synchronization (LMRS) Schakel (2015). In this model acceleration is used in the gap acceptance process, comparable to MOBIL lane change model (Kesting et al. 2007), but with smaller maximum deceleration rates and extended with the relaxation component. In this model it was hypothesized that drivers have an underlying lane change desire and the occurrence of synchronization or relaxation is based on the level of desire. Consequently, lane changes are not classified by the reasons for which they are performed (i.e. MLC or DLC) but rather the way in which they are performed, i.e. with or without synchronization and/or cooperation. IDM+ and LMRS have thirteen parameters for calibration.

PARAMICS

The main aspects of PARAMICS are described by Duncan (2000) and Fritzsche (1994). In these papers the longitudinal behaviour is described. The lateral behaviour, however, is not described. Furthermore, PARAMICS is not open source, and is therefore labelled as a 'black box'.

The PARAMICS car following model was developed by Fritzsche (1994), and is based on the psycho physical model by Michaels (1963). In this model it is assumed that the lead vehicle has a constant speed and that the potential follower catches up with a constant relative speed. Speed adjustments made by the following vehicle take place at an acceleration rate, which is limited to realistic values and constant in time. Each vehicle has a desired headway, which is affected by a stochastically assigned driver aggressiveness and a driver awareness. A high aggression value will cause drivers to accept a smaller headway. Similarly, a high awareness value will affect the use of a longer headway to allow other vehicles to merge in front (cooperation).

A minor description of the implemented gap acceptance model is given by (Duncan 2000), who clarifies that a lane change is only performed when the gap between successive vehicles on the target lane is large enough.

The number of model parameters is however small (Fritzsche 1994), which makes the model relatively easy to calibrate.

VISSIM

The main aspects of VISSIM are described in the VISSIM user manual (PTV 2017). Not all behaviour is explained by the provided documentation and VISSIM is not open source, which makes VISSIM a 'black box'.

The VISSIM car following model is a psycho physical developed by (Wiedemann 1974, 1991). In this model the acceleration of a vehicle is assumed to be constant between action points, while at the action points, drivers perceive a change in the situation that requires adaptation of the acceleration. Each vehicle has a stochastically assigned desired free flow speed and a maximum acceleration and deceleration rate.

The VISSIM lane change model is based on the work of Willmann (1978) and Sparmann (1979) and the basic principles are described by Fellendorf and Vortisch (2010). In VISSIM it is possible to activate the right-side rule, which makes slower vehicles to change lanes towards the outside of the motorway when possible. Vehicles that cannot drive at their desired speed move to the inside of the motorway when possible to overtake slow vehicles in front. The lane change location for route choice related lane changes are affected by 2 variables that need to be adjusted in the simulated network: 1) the lane change distance, where a vehicle starts the procedure to change lanes, and 2) the emergency stop distance, where the subject vehicle comes to a complete stop in case no lane change is possible. No specific path planning is implemented in VISSIM. While executing a lane change a driver is willing to force a lag vehicle on the desired lane to decelerate. Furthermore, synchronisation and cooperation are incorporated (Fellendorf and Vortisch 2010).

The number of behavioural parameters that are used for the car-following and lane-changing part is more than 50, which is rather high. This means that the model may be hard to calibrate and validate.

5.2.3. Fulfilment of the defined criteria

Driving around ramps is highly complex due to the different manoeuvres and behaviours that need to be performed, such as pre-allocation, anticipation, synchronization, gap selection, gap acceptance, acceleration and deceleration. The different manoeuvres are recognized in the literature and identified by the empirical data. A microscopic simulation software package that is used to assess the capacity and traffic safety aspects of a road design should be able to simulate these manoeuvres realistically. These software packages are regarded to be powerful tools but they also have their limitations. Recently more realistic driving behaviour models are proposed (Ahmed 1999; Toledo, Koutsopoulos, and Ben-Akiva 2007; Schakel et al. 2012) and implemented in experimental setups like MITSIM and MOTUS. The capabilities and limitations of the assessed microscopic simulation packages, following the criteria defined in section 2.1, are summarized in table 5.2.

For the investigated commercial microscopic simulation packages it is shown that CORSIM fulfils only 4 criteria and much of the desired information regarding the working of PARAMICS is unavailable. These two models were therefore not selected. AIMSUN differs from VISSIM on the criteria 1, 5, 6 and 10. Since lane changes are the main source for turbulence, it is preferred that the lane change process is modelled correctly, therefore the authors chose to prefer the ability of synchronisation and relaxation above latent tactical plans and a lower number of parameters. This points VISSIM out as the most appropriate commercial microscopic simulation package for this study.

MITSIM (Toledo, Koutsopoulos, and Ben-Akiva 2007) and MOTUS are the recently proposed models that were compared. The integrated model of Toledo, Koutsopoulos, and Ben-Akiva (2007) is quite advanced and covers many elements of driving behaviour, but the model uses a large quantity of parameters, which makes simulation results more difficult to relate to specific model parameter settings. MOTUS is therefore pointed out as most appropriate recently proposed model for this study.

5.3. Research method

The microscopic simulation package VISSIM (PTV 2017) and the recently developed model MOTUS (the longitudinal behaviour model IDM+ and the lateral behaviour model LMRS) (Schakel 2015), are preferred for modelling driving behaviour around ramps. To this end VISSIM and MOTUS were calibrated using empirical trajectory data from The Netherlands. After calibration, VISSIM and MOTUS were used to generate simulated trajectory data that were compared to the empirical trajectory data. Based on this comparison it was assessed to what extent the simulated behaviour corresponds to the actual behaviour in the field.

The remainder of this section is structured as follows. First a brief description of the empirical data is given. Second, the calibration procedure is described, and the third part describes how the simulated and empirical trajectories are compared.

5.3.1. Empirical data: Trajectory data recorded from a helicopter

For this study a selection of the empirical trajectory data that was collected at 16 different locations in The Netherlands (Van Beinum 2018) was used. From this dataset the on-ramp, off-ramp, short weaving segment and long weaving segment with the highest traffic flow were selected for calibration and evaluation of VISSIM and MOTUS. An overview of the selected data is shown in table 5.3. A more detailed description of the data characteristics is given in (Van Beinum et al. 2018). The selected locations have a F/C ratio between 0.74 and 0.81, which is regarded to be reasonably high. It is expected that in this F/C ratio range entering and exiting traffic will have a significant effect on turbulence.

criteria	**AIMSUN**	**CORSIM**	**PARAMICS**	**VISSIM**	**MITSIM**			**MOTUS**
	(Barceló and Casas 2005)	(Holm et al. 2007)	(Duncan 2000)	(PTV 2017)	(Yang and Koutsopoulos 1996)	(Ahmed 1999)	(Toledo, Koutsopoulos, and Ben-Akiva 2007)	(Schakel et al. 2012)
1. latent tactical plans	yes	no	--*	no	no	no	yes	no
2. anticipation	no	no	--	no	no	no	no	no
3. keep right	yes	no	--	yes	no	no	yes	yes
4. LC desire	yes	yes	--	yes	yes	yes	yes	yes
5. synchronization	no	no	no	yes	no	no	yes	yes
6. relaxation	no	no	yes	yes	yes	yes	yes	yes
7. acceleration	yes	--	yes	yes	yes	yes	yes	yes
8. desired speed	yes	yes	yes	yes	yes	yes	yes	yes
9. lane selection	yes	yes	--	yes	yes	yes	yes	yes
10. number of parameters	yes	yes	yes	no	no	no	no	yes
11. open source	no	no	no	no	yes	yes	yes	yes

Table 5.2. Overview of microscopic simulation software package criteria; * "--" means that no information was found on this aspect in the literature.

						number of vehicles [veh]					
						through					
road	**site name** **GPS coordinates**	**type**	**config.**	length* **[m]**	**speed limit [km/h]**	**flow**	**F/C**	**on**	**off**	**on/off**	**number of trucks [veh]**
A13	Delft 52.014718, 4.373768	off-ramp	3+1	250	100	2,569	0.78	-	270	-	123
A13	Delft 52.014498, 4.374516	on-ramp	3+1	300	100	2,654	0.81	323	-	-	168
A59	Klaverpolder-south 51.695868, 4.645407	weaving	2+1	500	130	1,760	0.74	131	446	89	274
A15	Ridderkerk-south 51.856330, 4.620257	weaving	3+1	1000	130	2,868	0.78	107	186	309	555

Table 5.3. Overview of Empirical Data; * Length of acceleration lane (on-ramp), deceleration lane (off-ramp) or weaving segment.

5.3.2. Calibration

The model parameters of both VISSIM and MOTUS were calibrated. Because the driver behaviour models in VISSIM and MOTUS are rather deterministic, a root-mean-square error (RMSE) minimization was applied to compare the model result to the observed values. The general form of the RMSE error term is given in equation (1).

$$\varepsilon_i = \beta_i \cdot \sqrt{\frac{\sum_{t=1}^{T} \left(\hat{y}_t - y_t\right)^2}{T}} \qquad (1)$$

Where β_n are weight factors in the error term. These weight factors were used to even out the differences in error for the different indicators. The weight factors were calculated using equation (2). Where $\varepsilon_{i,initial}$ is the calculated error for indicator *n* when using the initial model parameters.

$$\beta_i = \frac{1}{\varepsilon_{i,initial}} \qquad (2)$$

Since turbulence is represented by the intensity and location of lane changes, changes in speed and changes in headway, the calibration focusses on minimizing the error for lane change locations, headway distribution (on each lane) and gap acceptance. VISSIM and MOTUS use different approaches to simulate driving behaviour. The most relevant differences, regarding simulating the behaviour that causes turbulence, are:
1) VISSIM derives lane change locations for route choice related lane changes based on specific parameters that can be adjusted in the network. MOTUS does not have such a model parameter and suggests that lane change location is the result of the way that a lane change is performed (based on relaxation and synchronisation). 2) VISSIM uses the 'slow lane rule' that makes slower vehicles move towards the slower lane, which results in segregation of fast and slow driving vehicles over the lanes. However, slower vehicles will only change lanes when a suitable gap is available and is therefore closely related to the headway distribution and gap acceptance. Within MOTUS this behaviour is integrated by default.

Because of the differences between VISSIM and MOTUS, the elements that define the error are implemented differently in the RMSE equations used for calibration.

In VISSIM lane change locations are affected by the headway distribution on the target lane and gap acceptance. To acquire realistic results it is necessary that traffic is distributed realistically over the lanes, with fast driving vehicles driving on the inside and slow driving vehicles on the outside. This can be measured by the mean headway per lane, which represents the amount of traffic on that lane, and the mean speed and the standard deviation of the speed on each lane. The size of the accepted gaps is measured by the mean accepted gap. The simulation error in VISSIM was therefore calculated at the ramp area for: 1) the mean and standard deviation of speed distribution on each lane, 2) the mean of the headway distribution on each lane and 3) the mean and standard deviation of the accepted gap distribution on all lanes. The general RMSE equation that was used for the calibration of VISSIM is displayed in equation (3).

$$\varepsilon_i = \beta_i \cdot \sum_{n=1}^{N} \sqrt{\left(\hat{y}_t - y_t\right)^2} \tag{3}$$

Where n is the lane number and N the total number of lanes. The measures for y are shown in table 5.4.

In MOTUS the lane change locations are affected by driving behaviour (headway distribution, and gap acceptance and desire), instead of a specific parameter in the network. For the calibration of lane change locations, the RMSE is calculated over the whole length of the simulated motorway, separately for space bins of 10 meters each. This is done separately for time headways and lane changes; both lane changes to the left and lane changes to the right. Since a headway distribution is in general not normally distributed, the error for time headways is based on the 25th, 50th and 75th percentile of the headway distribution and is calculated for each lane. Finally two error terms are made for the mean and standard deviation of the accepted gaps. The general RMSE equation that was used for the calibration of MOTUS is displayed in equation (4).

$$\varepsilon_i = \beta_i \cdot \sqrt{\frac{\sum_{x=1}^{X} \left(\hat{y} - y\right)^2}{X}} \tag{4}$$

Where x is the space bin and X the total number of space bins. The measures for y are given in table 5.4.

model	term *i*	measure	value	lane
VISSIM	1	speed	mean	all
	2	speed	std.	all
	3	headway	mean	all
	4	accepted gap	mean	all
	5	accepted gap	std.	all
MOTUS	1	headway	25th percentile	lane 1
	2	headway	25th percentile	lane 2
	3	headway	25th percentile	lane 3
	4	headway	50th percentile	lane 1
	5	headway	50th percentile	lane 2
	6	headway	50th percentile	lane 3
	7	headway	75th percentile	lane 1
	8	headway	75th percentile	lane 2
	9	headway	75th percentile	lane 3
	10	lane change location	to the left	all
	11	lane change location	to the right	all
	12	accepted gap	mean	all
	13	accepted gap	std.	all

Table 5.4. Elements in error term for calibration.

Selection of model parameters to calibrate

Driving behaviour in VISSIM is described by 59 parameters. 39 of these parameters affect driving behaviour on motorways (PTV 2017) and 18 of these are relevant for simulating turbulence in free-flow traffic conditions. MOTUS has a total of 20 parameters. 7 parameters can be set as fixed values, 2 parameters are dependent of other parameters, 6 parameters apply for free flow conditions and 5 parameters only apply for congested conditions (Schakel et al. 2012), which is outside the scope of this study. Two of the free flow parameters: the mean and standard deviation of the desired speed are retrieved from the empirical data and are set as fixed values. 2 of the parameters that apply for a congested traffic state also affect lane change behaviour in high but free flow conditions: the average minimum time headway and the relaxation time. In total 6 parameters remain for calibration.

Sensitivity analysis

To further reduce the number of parameters for calibration a one-at-a-Time sensitivity analysis (Lownes and Machemehl 2006; Mathew and Radhakrishnan 2010; Punzo et al. 2015) was performed to select the parameters with the biggest influence on the RMSE. For both VISSIM and MOTUS a sensitivity analysis was performed, where each relevant model parameter was changed in different steps over a certain range based on a realistic upper and lower bound. While changing the considered parameter, the other parameter values remained unchanged at the default values. For VISSIM 18 parameters and for MOTUS 6 parameters were evaluated based on the resulting RMSE, based on the simulated and empirical trajectory data. This was done for each site separately. The parameters that were selected for calibration are shown in table 5.5.

	parameter	**unit**	**parameter description**
VISSIM	*maximum look ahead distance*	m	defines the distance that the driver can detect another vehicle
	number of observed vehicles	-	affects how well a vehicle can predict another vehicle's move
	CC0	m	default distance between stopped cars
	CC1	s	the driver dependent part of the time headway
	CC2	m	extra distance the driver keeps with the leading vehicle
	CC3	s	start of the deceleration process, when a slower leading vehicle is detected
	CC4	m/s	negative speed difference during the following process
	CC5	m/s	positive speed difference during the following process
	CC6	1/(m • s)	influence of distance on speed oscillation while in following process
	CC7	m/s^2	actual acceleration value during the oscillation process
	CC8	m/s^2	desired acceleration when starting from standstill
	CC9	m/s^2	desired acceleration at 80 km/h
	slow lane rule	-	if is selected, vehicles are only allowed to overtake on the left side
	max deceleration (Trailing veh.)	m/s^2	maximum deceleration of a trailing vehicle under cooperation
	minimum headway (front/rear)	m	minimum distance between two vehicles that must be available after a lane change
	free driving time	s	minimum front gap on the target lane for a vehicle to switch to the slower lane
	safety distance reduction factor	-	"aggressiveness" of lane changing behaviour
	cooperative lane change	-	if checked, vehicles in the target lane may make room for the lane changing vehicle
MOTUS	T_{min}	s	average minimum time headway
	τ	s	relaxation time
	x_0	m	anticipation distance
	t_0	s	remaining time at which desire to change lanes starts
	d_{free}	-	free lane change desire
	v_{gain}	km/h	speed gain at which full desire is experienced

Table 5.5. Parameters selected for calibration.

Optimization algorithm

For each model, an optimization technique was chosen that fits the number of parameters to be calibrated. For VISSIM a stepwise approach was followed for calibration. Within each step 60 sets of parameters were generated using a Latin Hypercube Algorithm (LHA) (Park and Qi 2005; McKay et al. 1979). Each parameter set was run with 10 different random seeds, so a total of 600 simulations per individual ramp. This process was automated by connecting Matlab to the VISSIM COM interface. A Matlab algorithm was used to change the model parameters in VISSIM. After the first step of 600 simulations the performance of the parameter sets was evaluated and the 10 best performing parameter sets were selected. These 10 sets were used to define a new range for the parameters in the LHA to generate 60 new parameter sets. These sets were then used in an additional calibration step. The performance of the best performing parameter set from the second round of simulations was compared with the performance of the best performing set from the first round, to conclude if the calibration results has improved. When the result did improve, a new round of simulations was performed, otherwise the best performing parameter set until that point was considered as the optimal one. This method requires a considerable amount of manual labour, therefore, the calibration was done only for the on-ramp (merging traffic) and the off-ramp (diverging traffic). The parameters for weaving segments (combination of merging and diverging traffic) were derived from the on-ramp and off-ramp model parameters by taking the mean value of the two. For MOTUS the model parameter values were set iteratively and probabilistically by using the simulated annealing (SA) optimization technique (Aarts and Korst 1988). This technique was automated by using Matlab. For MOTUS the model parameters for on-ramp, off-ramp and weaving segments were calibrated separately.

5.3.3. Comparison of Simulated and Empirical trajectory data

The performance of VISSIM and MOTUS was analysed by comparing generated trajectory data by the model to empirically collected trajectory data. The following driving behaviour characteristics are compared: 1) distribution of lane change locations for MLC and DLC, 2) the headway distribution for each lane, and 3) the accepted gap distribution. The different distributions are compared using the two sample Kolmogorov Smirnov test (KS-test).

5.4. Results

5.4.1. Sensitivity analysis results

In figure 5.4 an example is given of the sensitivity analysis results for MOTUS at the off-ramp of Delft. The figure shows that the impact of parameter τ is very limited. For parameter v_{gain} it shows that the impact is limited below and above a certain threshold. The parameters T_{min}, x_0, t_0, and d_{free} have most impact and are selected for calibration. The parameters τ and v_{gain} were set as fixed parameters with the default parameter setting. The sensitivity analysis for VISSIM was done in a similar way. To limit the size of this chapter, the detailed description of these results are not included in this chapter. Based on the results of the sensitivity analysis, the number of parameters to calibrate was reduced to 15 for VISSIM and 4 for MOTUS. The calibrated parameters are shown in table 5.6.

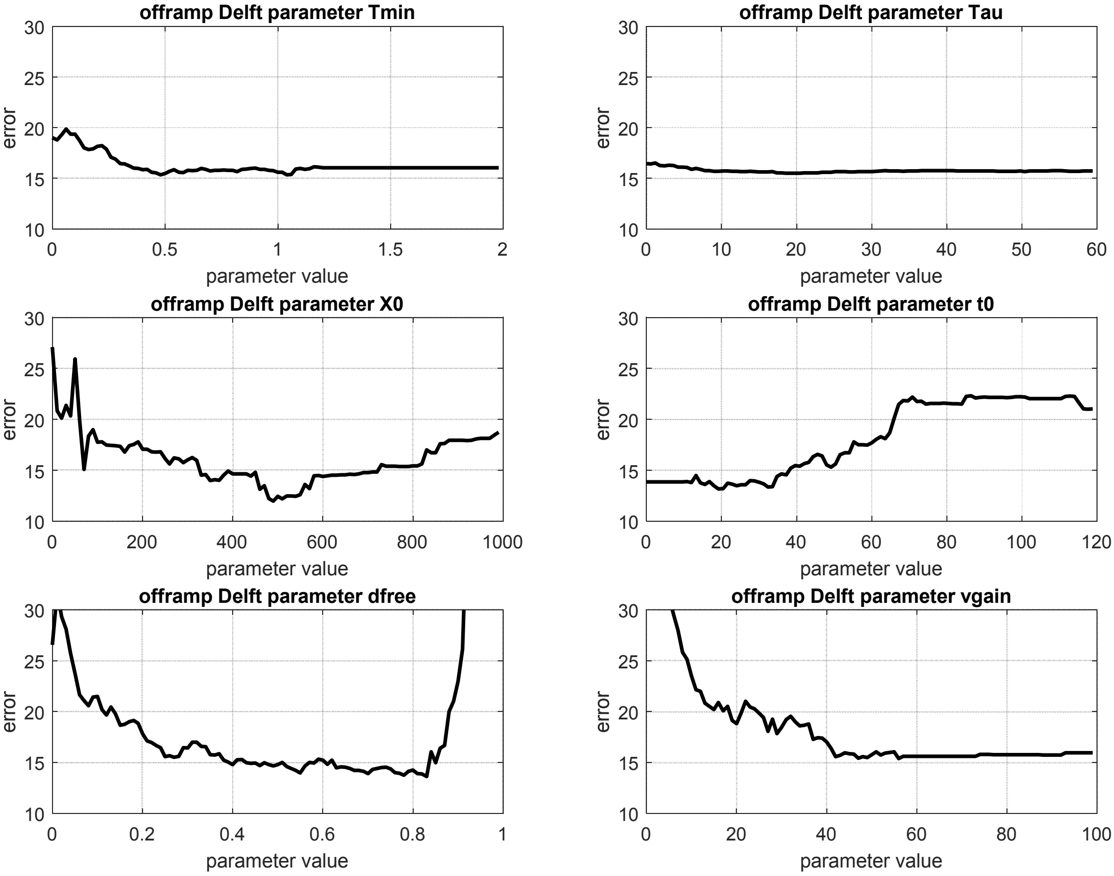


Figure 5.4. Results of the sensitivity analysis.

	parameter	**initial value**	**on-ramp Delft**	**off-ramp Delft**	**weave-short Klaverpolder-s**	**weave-long Ridderkerk-s**
VISSIM	RMSE - default parameters		39.55	26.26	28.59	40.04
	RMSE - calibrated parameters		26.50	22.03	23.27	30.77
	maximum look ahead distance	250	286.37	239.95	263.16	263.16
	number of observed vehicles	2	7	8	8	8
	CC0	1.5	2.64	2.03	2.335	2.335
	CC1	0.9	0.5	0.5	0.5	0.5
	CC2	4	3.67	4.25	3.91	3.91
	CC3	-8	-8.19	-11.54	-9.87	-9.87
	CC4	-0.35	-1.33	-1.08	-1.21	-1.21
	CC5	0.35	0.8	1.21	1.00	1.00
	CC7	0.25	0.34	0.2	0.24	0.24
	slow lane rule	false	slow lane rule	slow lane rule	slow lane rule	slow lane rule
	max deceleration (trailing veh.)	-3	-1.77	-2.91	-2.35	-2.35
	minimum headway (front/rear)	0.50	1.32	0.35	0.83	0.83
	free driving time	40	9.75	18.01	13.88	13.88
	safety distance reduction factor	0.60	0.41	0.47	0.43	0.43
	cooperative lane change	false	true	true	true	true
MOTUS	RMSE - default parameters		14.03	22.12	18.05	14.79
	RMSE - calibrated parameters		12.95	19.81	17.05	12.89
	T_{min}	0.56	0.87	0.48	0.4	0.71
	x_0	295	321	253	274	309
	t_0	43	32	51	26	49
	d_{free}	0.365	0.460	0.283	0.203	0.411

Table 5.6. Overview of calibrated model parameters.

5.4.2. Calibration results

For VISSIM the model parameters calibration was done for both the on-ramp and the off-ramp and the parameters for the weaving segments were derived by taking the mean value for the on-ramp and the off-ramp values. For MOTUS each site was calibrated separately. The calibrated parameter values are displayed in table 5.6. The calibration results show that the RMSE decreases after calibration for all sites, for both VISSIM and MOTUS. This indicates that the calibrated model parameters improve the model's results.

5.4.3. Evaluation Results

The calibrated models in VISSIM and MOTUS were used to generate a set of trajectory data. This set of trajectory data was compared to the empirical trajectory data and the trajectory data that was generated by VISSIM and MOTUS, using the default parameters. The comparison was done for 1) the distribution of lane change locations, 2) the headway distributions on the different motorway lanes and 3) the distribution of accepted gaps, for both lane changes to the right and to the left.

Spatial distribution of lane changes

The results for the distribution of lane change locations are shown in figure 5.5. In this figure the total number or lane changes is displayed and it shows that VISSIM generally overestimates the number of lane changes. MOTUS on the other hand underestimates the number of lane changes. When looking at the lane change location it shows that VISSIM locates the lane changes at the on-ramp (merging) too far upstream, while MOTUS locates these lane changes too far downstream. For the off-ramp (diverging) VISSIM locates the lane changes quite accurate, while MOTUS locates it too far downstream.

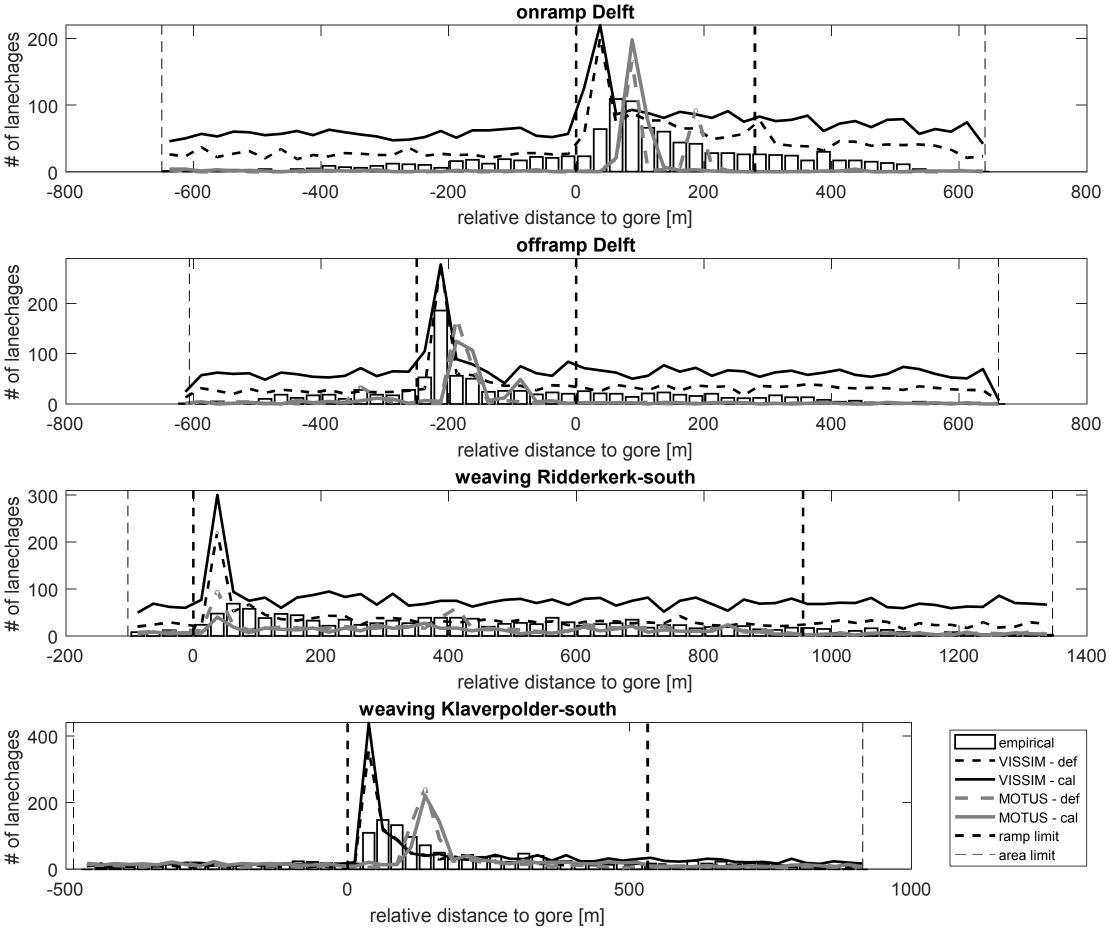


Figure 5.5. Comparison of lane change locations.

These findings are tested statistically; the results are presented in table 5.7. In this table a separation is made between lane changes toward the left and to the right. For both VISSIM and MOTUS, the distribution of lane change locations was compared to the empirical data by performing a 2 sample Kolmogorov-Smirnov test (KS-test). The results of these tests are depicted by the p-values.

The table shows that the distribution of lane change location as simulated by both VISSIM and MOTUS differ significantly from the locations as shown in the empirical data. Only for lane changes to the right at the weaving segment of Ridderkerk the difference was not statistically significant. However, the significance is not very strong (p=0.058).

Time headway distribution

The cumulative density functions of the time headway distributions for both the empirical data, the VISSIM data and the MOTUS data are shown in figure 5.6. The statistics that correspond with this figure are shown in table

5.8. For all distributions the simulated distributions differ significantly from the empirical data. The only exception is on-ramp Delft, lane 1, where the results show that the similarity between the simulated headway distribution at the on-ramp by VISSIM and the empirical data is significant.

When looking at the shape of the distributions it shows that VISSIM simulates the headway distribution on lane 1 (the utter right lane) and lane 2 (2nd lane from the right) reasonably well. At lane 3 the simulated distribution by VISSIM does not correspond to the empirical distribution. MOTUS shows a different shape of the distribution. There is a steep line at a headway of approximately 2 seconds. This can be explained by the vehicles that are constrained by a leading vehicle and are driving with a desired headway, which is equal for all drivers.

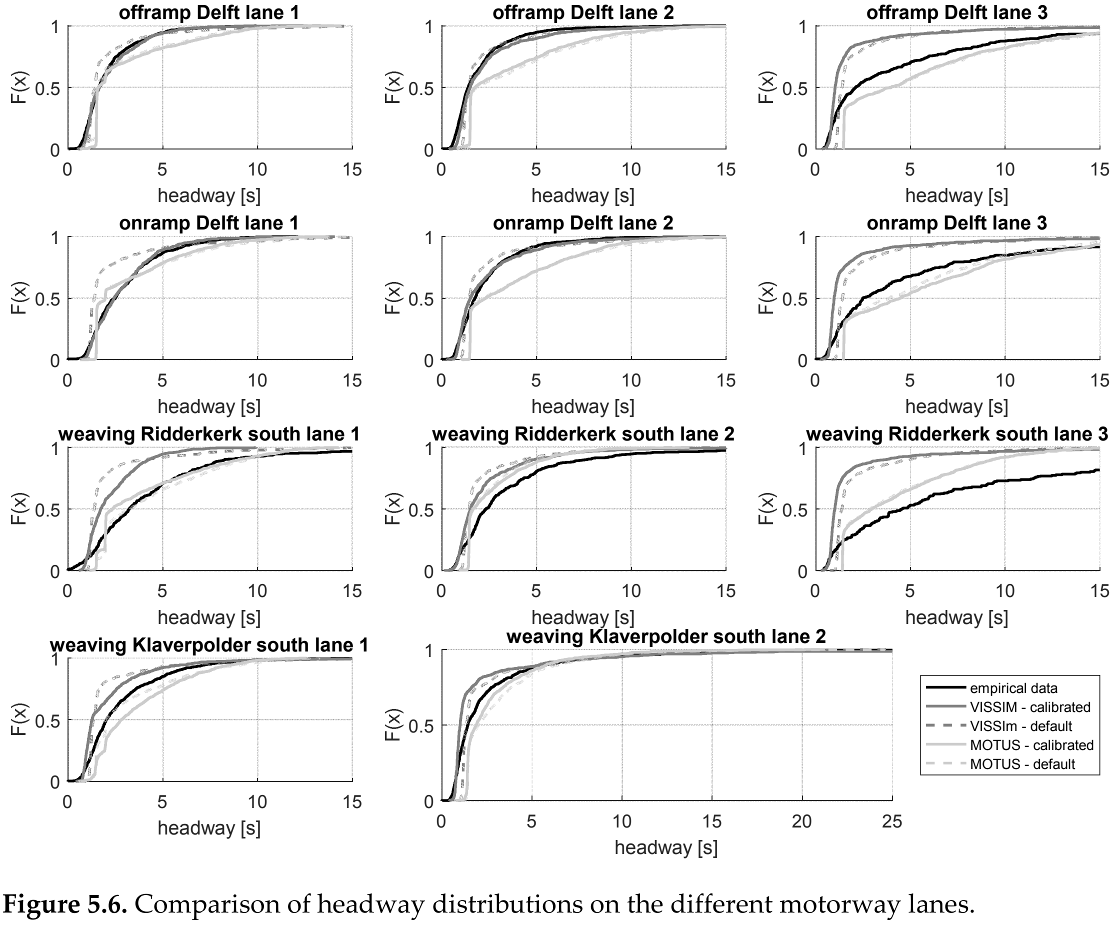


Figure 5.6. Comparison of headway distributions on the different motorway lanes.

site	LC direction	n			p-value KS-test	
		empirical	VISSIM	MOTUS	VISSIM	MOTUS
off-ramp Delft	right	661	1,924	410	0	0
off-ramp Delft	left	297	1,489	0	0	0
on-ramp Delft	right	269	1,483	55	0	0
on-ramp Delft	left	768	2,142	300	0	0
weaving Ridderkerk-south	right	692	2,202	389	0	0.058
weaving Ridderkerk-south	left	604	2,205	227	0	0
weaving Klaverpolder-south	right	997	1,151	830	0	0
weaving Klaverpolder-south	left	430	725	400	0	0

Table 5.7. Lane change location statistics.

		mean			n			p-value KS-test	
site	lane	empirical	VISSIM	MOTUS	empirical	VISSIM	MOTUS	VISSIM	MOTUS
off-ramp Delft	lane 1	2.12	2.23	3.03	882	806	1,089	0.039	0
off-ramp Delft	lane 2	1.99	2.37	3.58	936	760	922	0	0
off-ramp Delft	lane 3	4.69	2	5.59	396	899	589	0	0
on-ramp Delft	lane 1	2.96	2.92	3.27	629	616	1,008	0.480	0
on-ramp Delft	lane 2	2.33	2.42	3.79	798	744	870	0	0
on-ramp Delft	lane 3	5.17	2.02	5.98	356	892	551	0	0
weaving Ridderkerk-south	lane 1	4.7	2.28	4.06	376	787	812	0	0
weaving Ridderkerk-south	lane 2	3.82	2.39	2.7	466	752	1,223	0	0
weaving Ridderkerk-south	lane 3	8.41	1.97	4.32	203	914	761	0	0
weaving Klaverpolder-south	lane 1	2.84	2.22	3.71	625	810	888	0	0
weaving Klaverpolder-south	lane 2	2.66	2.38	2.93	668	751	1,127	0	0

Table 5.8. Headway distribution statistics.

site	LC dir.	n			mean			std.			p-value KS-test	
		emp.	VIS	MOT	emp.	VIS	MOT	emp.	VIS	MOT	VIS	MOT
off-ramp Delft	right	318	1,250	81	3.51	3.59	4.57	1.86	1.82	2.72	**0.563**	0.003
on-ramp Delft	left	459	597	279	3.67	3.3	4.05	2.18	2.13	2.62	0	0.001
weaving Ridderkerk-south	right	157	1,368	146	4.79	3.68	6.43	2.37	1.9	2.39	0	0
weaving Ridderkerk-south	left	154	290	102	4.15	3.46	5.22	2.42	2.32	2.35	0.008	0.001
weaving Klaverpolder-south	right	417	613	380	3.95	4.12	5.87	2.19	2.24	2.57	**0.562**	0
weaving Klaverpolder-south	left	172	221	152	4.15	3.39	5.43	2.52	2.26	2.51	0.008	0

Table 5.9. Accepted gap statistics, for gaps smaller than 10 sec.

Accepted gap distribution

Figure 5.7 shows the distribution of accepted gaps, smaller than 10 seconds. The statistics are shown in table 5.9. The results show that most accepted gap distributions by VISSIM differ significantly from the empirical data. The only examples are the distributions for lane changes to the right at the off-ramp and the short weaving segment of Klaverpolder. When looking at the shape of the distributions, VISSIM shows to simulate gap acceptance quite reasonable. MOTUS also shows comparable shapes for gap acceptance at the on-ramp and off-ramp. For the weaving segments, MOTUS simulates distributions with a different shape.

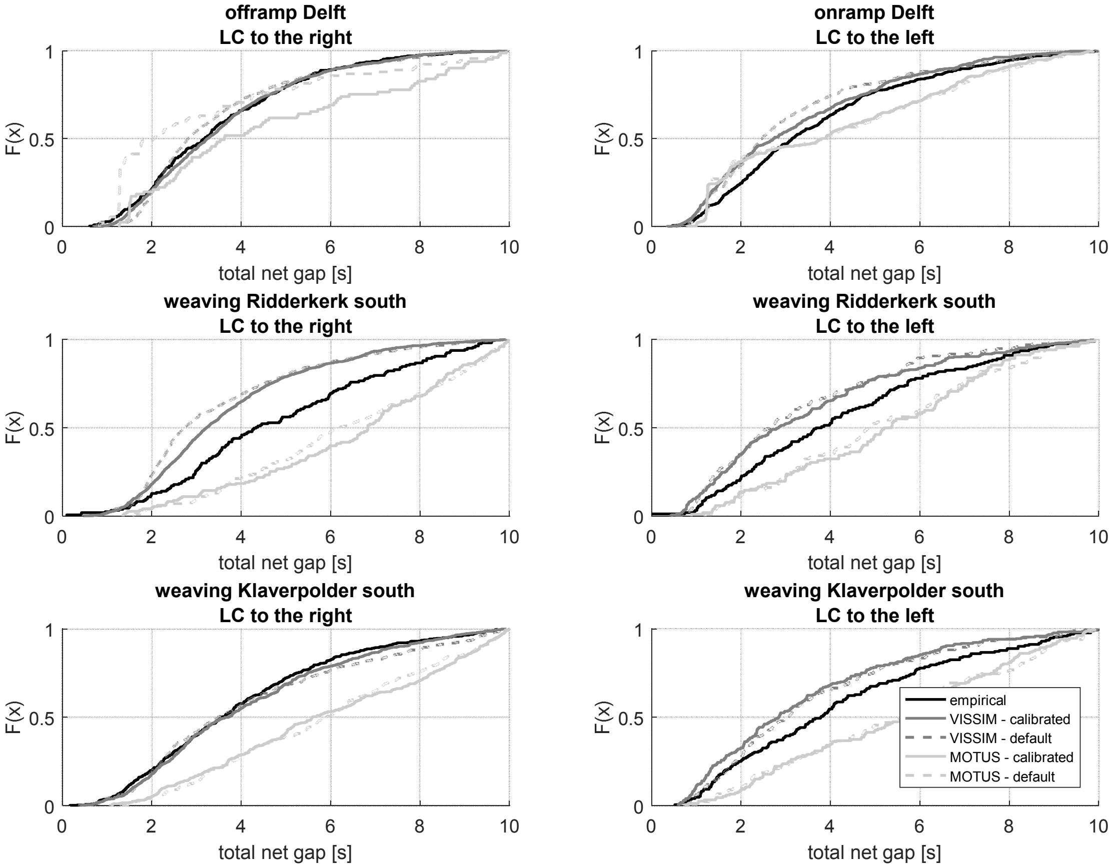


Figure 5.7. Distribution of accepted gaps, smaller than 10 sec.

5.5. Discussion

For this study the authors have selected and calibrated two simulation models: a commonly used commercial microscopic simulation software package (VISSIM) and a recently developed (research) simulation model (MOTUS). The calibration was successful by means of a reduction of the RMSE after calibration. However, from an overall point of view the simulated driving behaviour was proven to be unrealistic for the most important element of turbulence: the location and intensity of lane changes. VISSIM gives an overestimation in the number of lane changes and MOTUS gives an underestimation. Both models apparently fail to simulate lane change patterns realistically. Where vehicles in VISSIM change lanes too frequent, vehicles in MOTUS rather stay in their lane. For VISSIM this behaviour also leads to a second problem: an overestimation for the amount of traffic on the left lane, as is depicted by the small mean headway. The simulation results will probably improve when the lane change incentive is modelled more realistically. Based on these findings, both VISSIM and MOTUS seem unsuitable for assessing the implications on traffic operation for specific motorway designs that deviate from the guidelines.

When looking at the results on vehicle interaction, both VISSIM and MOTUS show reasonable results in terms of gap acceptance. For both lane changes to the right at the off-ramp and lane changes to the left at on-ramps the accepted gap distributions show similar shapes. For the weaving segments the shapes of the distributions are less similar. For VISSIM this might be explained by the calibration technique, where the parameter settings for the weaving segments were derived from the calibration results for on-ramps and off-ramps. A specific calibration of these weaving segments will probably improve the VISSIM results. Based on these findings VISSIM and MOTUS seem suitable for assessing traffic safety, since traffic safety studies based on surrogate safety measures (Tarko 2012) mainly consider vehicle interaction.

A final observation is that the behaviour as shown in the empirical data often lies between the results as generated by VISSIM and MOTUS. An average of these results might fit the observed results better. Therefore, a combined use of the two models might partly compensate each model's limitations and would probably give more realistic results. This pleads for the use of mixed models.

5.6. Conclusions and outlook

This study shows that both VISSIM and MOTUS fail to simulate turbulence related driving behaviour accurately. Especially the most relevant aspect of turbulence: the location and intensity of lane changes, are not simulated realistically. VISSIM over estimates the number of lane changes and MOTUS underestimates the number of lane changes. Also, the locations where lane changes take place are not simulated accurately. The results regarding gap acceptance and headway distribution show a reasonable similarity between simulated and empirical data. However, this similarity is only statistically significant for a limited number of cases.

Both VISSIM and MOTUS have their strengths and weaknesses. The biggest weakness of VISSIM is the overestimation of lane changes and the unrealistic distribution of traffic over the different motorway lanes. MOTUS is performing better on these aspects. The biggest strength of VISSIM is the way car following is modelled. Traffic that is driving in a car following regime is driving with a similar headway distribution as found in the empirical data. MOTUS on the other hand simulates car following more deterministic than reality. The biggest strength of MOTUS is the way drivers choose the lane to drive in. Gap acceptance on the other hand is a weakness of MOTUS: the simulated accepted gaps are larger than in reality.

In recent years much effort is put in improving driving behaviour models, but our results show that further improvements are necessary. The authors therefore recommend focussing further research on modelling the different manoeuvres that lead to lane changes. Improvements of the LMRS model in MOTUS are being developed in OpenTrafficSim (Van Lint et al. 2016) which are promising for improving simulation of turbulence. These improvements include social interactions between traffic participants, for example resulting in more lane changes and a more realistic headways distribution during car following; precisely the weaknesses of LMRS as found in this work. Other developments in OpenTrafficSim concern human factors, such as dynamic reaction time, situational awareness, perception errors, anticipation and behavioural adaptation due to the driving task being too demanding, including adaptation of speed and headway. Without simulation frameworks and models for this, safety in complex situations with turbulence is difficult to ascertain, especially for road designs that deviate from design guidelines.

6. Microscopic simulation and traffic safety

Abstract
In the recent years microscopic traffic simulation software is used to assess the impact of a road design variants on capacity and traffic safety. Despite a long history of developing driving behaviour models, the use of microscopic simulation software for traffic safety assessment has been subject of debate. It is expected that these packages, even after calibration, simulate traffic safety related driver behavioural aspects inaccurately. A quantitative indication of this inaccuracy is however lacking, as well as suitable empirical data for model calibration and comparison. In this study a large quantity of high quality empirical trajectory data, that were collected at an on-ramp, an off-ramp and 2 weaving segments on motorways in The Netherlands, was used to calibrate a microscopic simulation model (VISSIM), and to investigate to what extent a microscopic simulation model is able to reproduce the number and severity of traffic conflicts. The results show that the number of simulated traffic conflicts are overestimated, due to an overestimated number of lane changes and an unrealistic distribution of traffic over the different lanes. The severity of the conflicts was shown to be reasonably accurate, but not significantly comparable.

6.1. Introduction

Crashes on motorway ramps and interchanges are an important issue of motorway safety, since most crashes occur in the vicinity of ramps (NCHRP 2012; Khorashadi 1998; Lunenfeld 1993). Crashes on motorway ramps are related to high speeds, variation of speed (Lee et al. 2002; Lee et al. 2003b; Abdel-Aty, Pande, et al. 2005), high density (Lee et al. 2002) and an increased number of lane changes (Golob et al. 2004). Lane changes, changes in speed and changes in the headway distribution are referred to as “turbulence” (Fitzpatrick et al. 2011; Van Beinum et al. 2016).

Most lane changes occur at on-ramps, off-ramps and weaving segments, and are executed by drivers who want to enter or exit the motorway (Van Beinum et al. 2018). These merging or diverging lane changes also trigger other nearby drivers to change lanes to the inside of the motorway, to avoid the slower traffic on the outside lane near the ramps. Therefore, an increased level of turbulence is present in the vicinity of ramps. The level of turbulence increases upstream of the ramp and decreases downstream of the ramp (Kondyli and Elefteriadou 2012; Van Beinum et al. 2017). Furthermore, the level of turbulence is affected by a road’s design (HCM 2010). Sufficient length for weaving is required to offer merging and diverging vehicles the opportunity to change lanes safely and without affecting roadway capacity negatively (Fitzpatrick et al. 2011; HCM 2010). It is expected that the level of turbulence will intensify when the available length gets shorter (Van Beinum et al. 2016).

However, the desired weaving segment lengths as prescribed in the guidelines are not always feasible within the available physical space. In such cases it is tempting to accept a shorter length than desired. However, the implications for traffic safety of deviating from the guidelines are not fully understood (Van Beinum et al. 2016).

For these special ‘fit for purpose’ designs, often microscopic simulation models are used as a supporting design tool in addition to the guidelines, to model and evaluate different designs before being built. The use of microscopic simulation was shown to be a promising tool for assessing traffic safety implications of different motorway designs e.g. Choi and Oh (2016); Li et al. (2016); Yao et al. (2017). Furthermore, Young et al. (2014) reviewed the developments in the area of road safety simulation models and concluded that ‘traffic simulation models have potential in measuring the level of conflict on parts of the network using surrogate safety measures’. And it was shown that the surrogate safety measures (SSM) of traffic conflicts correlated well with crash statistics (Young et al. 2014). But despite the promising results, the use of microscopic simulation software for traffic safety is on debate: different previous studies have shown that simulated driving behaviour differs from behaviour found in field data, such as gap acceptance (Daamen et al. 2010) and lane change locations (Choudhury 2007).

To ensure the valid use of microsimulation for traffic safety, it is key that: 1) the simulation models represent the microscopic behaviour of drivers realistically (Young et al. 2014), and 2) behaviour is related to risk. These requirements reach beyond the (original) objective of many microscopic simulation packages, which is generally to represent the macroscopic flow characteristics sufficiently accurate. Microscopic simulation packages such as VISSIM (PTV 2017), PARAMICS (Duncan 2000) and AIMSUN (Barceló and Casas 2005), provide the possibility to calibrate or change model parameters to better represent the dynamics of traffic behaviour.

One of the limitations for accurate calibration of the model parameters is the availability of high quality empirical trajectory data. This data is argued to be essential for calibrating and developing models to describe driving behaviour realistically. Collecting empirical trajectory data, however, is time consuming and costly.

The aim of this study

The objective of this study is twofold: 1) to identify if the number and severity of conflicts, as simulated by a commonly used microscopic simulation software package for traffic safety assessments (VISSIM (PTV 2017)), are comparable to the field-measured conflicts at motorway weaving segments, and 2) to improve the level of realism of the simulated driving behaviour by calibrating the model parameters.

For this study we have used empirical trajectory data that were collected on four different ramps: an on-ramp, an off-ramp and two weaving sections on motorways in The Netherlands.

6.2. Literature review

6.2.1. Overview of safety related driving behaviours around ramps

According to the Highway Capacity Manual (HCM 2010), three types of segments are found on motorways: 1) merge and diverge segments, which are the on-ramps and off-ramps where traffic enters or exits the ongoing motorway; 2) weaving segments, which are segments where an on-ramp is closely followed by an off-ramp and the two are connected by one or more continuous auxiliary lanes, and 3) basic motorway segments, which are all segments that are not merge, diverge, or weaving segments. At merge, diverge and weaving segments, an auxiliary lane provides a room for merging traffic to accelerate (acceleration lane), for diverging traffic to decelerate before reaching a downstream curve or intersection (deceleration lane). In the case of a weaving segment the auxiliary lane accommodates both accelerating and decelerating vehicles.

Relevant manoeuvres at ramps

The increased level of turbulence in the vicinity of ramps is caused by drivers that perform manoeuvres to enter or exit the motorway. The following manoeuvres are performed in the vicinity of ramps: merging, diverging, pre-allocation, cooperation, anticipation keeping right and relaxation (Van Beinum et al. 2018). The different manoeuvres are graphically displayed in figure 6.1. A more detailed overview and description of these manoeuvres is given in (Van Beinum et al. 2016, 2018).

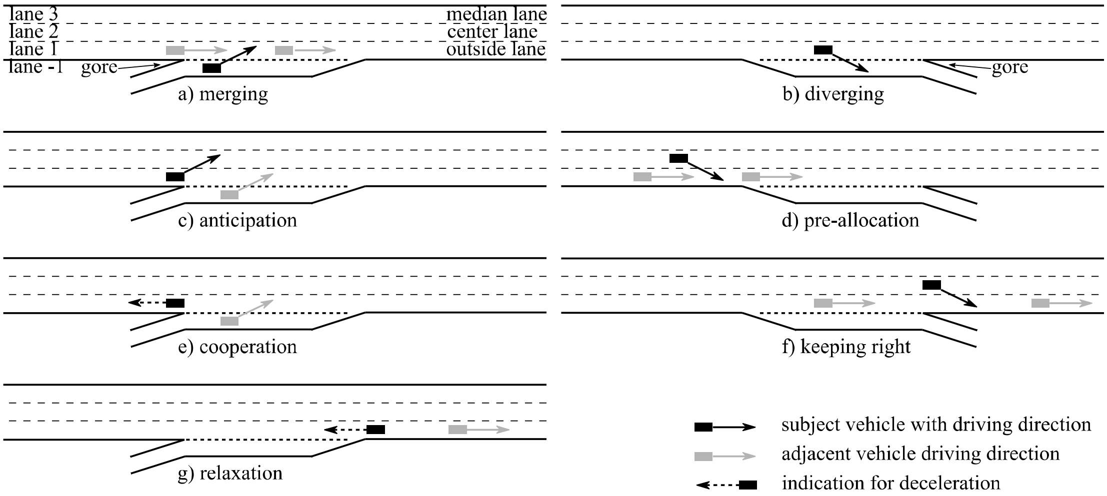


Figure 6.1. Manoeuvres in the vicinity of ramps.

Most turbulence is created by merging and diverging traffic (Van Beinum et al. 2018). These manoeuvres involve lane changing and often trigger additional lane changes by surrounding ongoing drivers on the motorway, who anticipate on the entering and exiting vehicles (Van Beinum et al. 2018; Choudhury 2007). A lane change is a complex manoeuvre involving different actions that need to be performed by a driver. First a driver selects a gap to merge into and then accelerates or decelerates to align its vehicle with that gap (change in speed) (Schakel et al. 2012; Toledo, Koutsopoulos, and Ben-Akiva 2007). Once the gap is accepted and the vehicle is aligned, the driver merges into the gap (lane change). When the accepted gap is small, the lane changing driver might force its new follower to adjust its speed to increase the gap (changed headway distribution) (Choudhury et al. 2009; Hidas 2005). The combination of changes in speed, changes in driving lanes, and small headways affect the frequency of crashes (HCM 2010; Golob et al. 2004; Lee et al. 2002).

6.2.2. Traffic safety: crashes and traffic conflicts

Traditionally, the safety of roads is assessed by studying crash statistics; the frequency of crashes is the most direct way to quantify traffic safety (Tarko et al. 2009; Lord and Mannering 2010). However, the use of crash statistic has some limitations: 1) only available for existing roads and existing situations (Dijkstra 2011); 2) accidents are rare events, making it troublesome to base traffic safety analyses at individual sites on accidents only (Laureshyn et al. 2010); 3) crash data are not always sufficient due to small sample sizes (Tarko et al. 2009; Laureshyn et al. 2010) and accounting for longer time period to increase the number of serious crashes per road length, is complicated because over the years different confounding factors can influence the frequency and severity of crashes; 4) not all crashes are reported and the level of underreporting depends on the accident's severity and types of road users involved (Laureshyn et al. 2010; Anastasopoulos et al. 2008; Archer 2005) and 5) the lack of details to improve our understanding of crash failure mechanism and especially the driver crash avoidance behaviour (Tarko et al. 2009).

In recent years researchers studied a more pro-active approach that intend to overcome the crash data quality issues and also takes into account near-crashes. An alternative method was proposed, in which the traditional crash statistics could be complemented with a surrogate measures of safety (Laureshyn et al. 2010; Tarko et al. 2009). These measures rely on traffic conflict techniques (Zheng et al. 2014b) and are commonly referred to as SSM and aim to quantify the dangerousness of a traffic conflict in a meaningful way, by measuring the characteristics of the interaction between different drivers (De Ceunynck 2017). An example definition of traffic conflict is given by (Svensson 1998): "A conflict is an observational situation in which two or more road users approach each other in space and time to such an extent that a collision is imminent if their movements remain unchanged". In this view a collision can be explained by a number of factors that led to it (Reason et al. 2006). For near collisions this implies that a successful interaction between two drivers might have led to a collision if a number of factors had been different. Conflicts and crashes therefore, belong to the same process, just with a different degree of outcome severity (Hydén 1987) and collisions represent a logical continuation of serious conflicts.

6.2.3. Traffic conflict techniques

The traffic conflict, as used in this study, is based on temporal (and (or) spatial) proximity of two adjacent vehicles. The severity of traffic conflicts is identified by the proximity in time and (or) space (referring to the conflict measures) (Zheng et al. 2014b). The general concept is that when the interaction between drivers takes place within a limited amount of space/time and with high speed differences, drivers make (more) mistakes and accident risks increase (Laureshyn et al. 2010). Different measures are proposed by many different researchers; for an overview of the different available measures several studies are available (De Ceunynck 2017; Mahmud et al. 2017; Young et al. 2014; Zheng et al. 2014b; Archer 2005). In this chapter we limit ourselves to two relevant measures for traffic conflicts in the vicinity of ramps: the Time To Collision (TTC) (Hayward 1972) and the Post-Encroachment Time (PET) (Kraay and Van der Horst 1985).

The TTC represents the: "the time required for two vehicles to collide if they continue at their present speeds and on the same path" (Hayward 1972). Different thresholds are mentioned in literature: a threshold of 1.5 s has been used to determine if a severe conflict will take place (Hydén 1987; Shahdah et al. 2014) and a threshold of 3.5 s for drivers without an automatic cruise control system and 2.6 s for drivers with driving support (Hogema and Janssen 1996). Although different thresholds are mentioned, a general rule is applicable: the higher a TTC-value, the more safe the situation is (Minderhoud and Bovy 2001; Bevrani and Chung 2012).

The TTC of a vehicle (*i*) at a certain time instant (*t*) with respect to a leading vehicle (*i*-1) can be calculated by equation (5), where: *v* denotes the speed, *x* the longitudinal position, and *l* the vehicle length.

$$TTC_i = \frac{x_{i-1}(t) - x_i(t) - l_i}{v_i(t) - v_{i-1}(t)} \forall v_i(t) > v_{i-1}(t) \tag{5}$$

A further variation of the Time-to-Collision concept is Post-Encroachment Time (PET). This measure is used to measure situations in which two road-users that are not on a collision course, pass over a common spatial point or area with a temporal difference that is below a predetermined threshold (Archer 2005). When considering a lane change manoeuvre PET is defined as the time interval between the moment that the leading vehicle entirely leaves the encroachment line and the following vehicle arrives at the encroachment line Zheng et al. (2014a). The encroachment line is a visual line perpendicular to the lane marking. PET is usually used supplementary to TTC when crossing vehicle trajectories are involved. Different thresholds are proposed for PET: 1 sec (Kraay and Van der Horst 1985) and 1.5 sec (Archer 2005). In figure 6.2 the concept of the PET to a vehicle in front is shown for a vehicle that changes lanes towards the right. The PET of a vehicle (*i*) at the time of lane change (*t*) with respect to a leading vehicle (*i*-1) can be calculated by equation (6), where: *v* denotes the speed, x_e is the longitudinal position of the encroachment line and *x* is the longitudinal position.

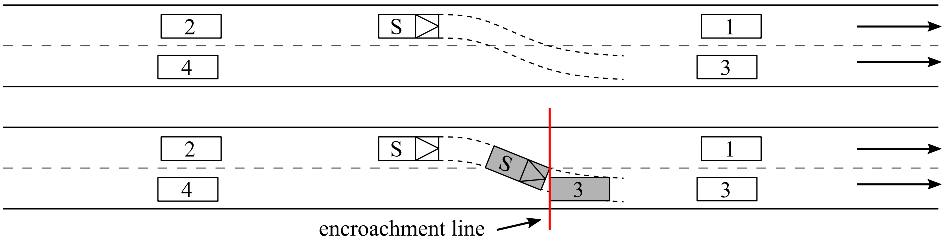


Figure 6.2. measurement concept (Zheng et al. 2014a).

$$PET_i = \frac{x_e(t) - x_i(t)}{v_i(t)} - \frac{x_e(t) - x_{i-1}(t)}{v_{i-1}(t)} \tag{6}$$

6.2.4. Traffic conflict measure calculation

Since traffic conflict measures describe vehicle interactions, these measures are preferably derived from trajectory data that describe the movement (*x*, *y*) of individual vehicles in time (*t*). Trajectory data can be collected in field measurements, but this is time consuming and costly (Archer 2005; Louah et al. 2011) and can only be collected on existing roads. Furthermore, measurement inaccuracies can be problematic as a small measurement error in (*x*,*y*) within a short time difference (*t*), can lead to large deviations when calculating speed and acceleration.

An alternative is to generate trajectories with micro simulation models (Bevrani and Chung 2012; Astarita et al. 2012). Several recent studies have used different microscopic simulation packages to generate trajectory data for safety analysis, with promising results. Examples of software packages that are used for safety analysis are: VISSIM (Fan et al. 2013; Habtemichael and De Picado Santos 2013; Habtemichael and de Picado Santos 2014; Yao et al. 2017) and PARAMICS (Dijkstra 2011; Lee et al. 2004) and AIMSUN (Goh et al. 2013). However, these packages are designed to simulate 'collision free'

traffic, which is a potential problem for traffic safety related studies (Bevrani and Chung 2012; Dijkstra et al. 2010; Xin et al. 2008). When studying traffic conflicts, a realistic representation of driving behaviour and interaction between vehicles is essential. Within the available software packages it is possible to change or calibrate driving behaviour model parameters to improve the level of realism of the simulated driving behaviour. In previous studies different types of empirical data were used for calibration, such as: traffic flows and (average) vehicle speeds (Habtemichael and de Picado Santos 2014; Habtemichael and De Picado Santos 2013; Choi and Oh 2016), loop detectors (Nezamuddin et al. 2011), a radar gun and video footage (Fan et al. 2013) and empirical trajectory data (Park et al. 2018; Li et al. 2016).
Previous studies have shown that the available software packages provide a flexible enough platform for the modelling of safety (Young et al. 2014). Some examples are provided hereafter. Habtemichael and De Picado Santos (2013) used VISSIM to evaluate the safety and operational benefits of a variable speed limit on a 12-km stretch of motorway around Lisbon, Portugal. Their results are in agreement with previously performed studies, but contradicts the findings of several other studies that used PARAMICS instead of VISSIM. Habtemichael and de Picado Santos (2014) used VISSIM to evaluate the safety implications of aggressive driving on a 7 km stretch of motorway around Lisbon, Portugal. They found that microscopic traffic simulation can be used for safety analysis of motorway traffic and that traffic conflicts can be used as a surrogates for crashes and near-crashes. Yao et al. (2017) used VISSIM to analyse the influence of ramp spacing, lane number of mainline, traffic volume, weaving ratio and percentage of heavy vehicles on safety performance of auxiliary lanes in motorway weaving segments. They found that adding auxiliary lanes can significantly reduce the ratio of traffic conflicts in weaving segments and the analysed factors have great influence on safety impacts of auxiliary lanes. Fan et al. (2013) identified if the consistency between the simulated and the field-measured traffic conflicts could be improved by calibrating a VISSIM simulation model. They found that calibration of VISSIM improved the consistence considerably. Furthermore they found that there was a reasonable consistency between the simulated and the observed traffic conflicts.

6.2.5. Summary

Lane changes are the main source of turbulence near motorway ramps and weaving segments (Van Beinum et al. 2018; Choudhury 2007), and hazardous situations that can lead to crashes are more likely to occur in turbulent traffic (HCM 2010; Golob et al. 2004; Lee et al. 2002). To study the impact of turbulence on traffic safety empirically, either crash data is needed for direct analysis or empirical trajectory data is needed to study traffic conflicts that result from the lane-change manoeuvres performed by drivers. Both crash data and empirical trajectory data have availability and quality issues, which limit the possibilities to study traffic safety implications of turbulence. The alternative: the use of microscopic simulation software, was successfully used in previous studies to evaluate traffic safety around motorway ramps by using traffic conflict techniques (Li et al. 2016; Fan et al. 2013; Saleem et al. 2014). In a number of cases it was found that the simulation-based traffic conflicts significantly correlate with crash statistics (Gettman et al. 2008; Young et al. 2014). Despite the promising results additional effort in calibrating VISSIM and collecting additional empirical trajectory data was recommended (Fan et al. 2013; Park et al. 2018; Young et al. 2014). Therefore additional research, based on empirical trajectory data, is needed to determine to what extent microscopic simulation software packages, like VISSIM, can: 1) be calibrated to reproduce realistic driving behaviour around motorway ramps, and 2) reproduce the number and severity of traffic conflicts that occur in reality.

6.3. Method

General description

In this study a microscopic simulation software package (VISSIM) was calibrated based on empirical trajectory data, that was collected at 4 different ramps in The Netherlands. VISSIM was selected since it is one of the most commonly used microscopic simulation software packages for assessing traffic safety aspects of motorway designs. The calibrated VISSIM model was used to generate trajectory data for traffic that is driving under similar conditions (road design and traffic characteristics) as was present during the field measurements. The simulated trajectory data was then compared to empirical trajectory data, by: 1) the number of conflicts and 2) the distributions of minimum TTC and PET values for each identified pair of conflicting vehicles. An overview of the method is displayed in figure 6.3.

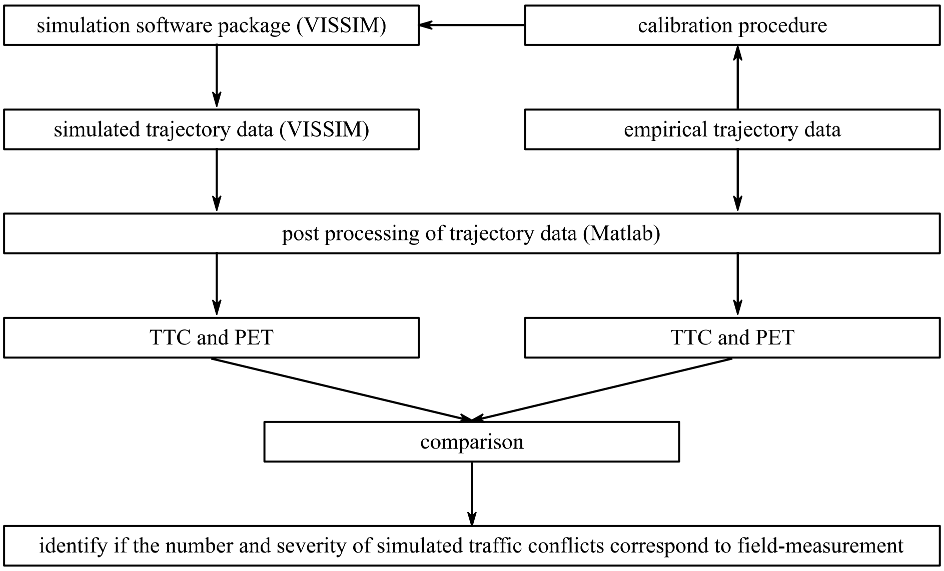


Figure 6.3. Overview of the followed procedure.

6.3.1. Empirical data

The empirical trajectory data that was used for this study is a selection of the empirical trajectory data that was collected at 16 different locations in the Netherlands (Van Beinum 2018). From this dataset the on-ramp, off-ramp, short weaving segment and long weaving segment with the highest traffic flow were selected. These locations have a F/C ratio between 0.74 and 0.81, which is regarded to be reasonably high. It is expected that in this F/C ratio range entering and exiting traffic will have a significant effect on turbulence. An overview of the data characteristics is shown in table 6.1. on page 135.

The trajectories were collected using a camera mounted underneath a hoovering helicopter, comparable to the method described in (Hoogendoorn et al. 2003), but using a 5120 x 3840 pixel camera and a 15mm Zeiss lens, which enabled us to capture a road stretch of approximately 1,200m - 1,500m from an altitude of approximately 500m. The data was smoothed (Toledo, Koutsopoulos, and Ahmed 2007) to reduce the measurement noise. A detailed description of the data and its characteristics are given in Van Beinum et al. (2018).

Road	**Site name** **GPS coordinates**	**type**	**Config.**	**length* [m]**	**speed limit [km/h]**	**number of vehicles**					**number of trucks**
						through					
						flow	**F/C**	**on**	**off**	**on/off**	
A13	Delft 52.014718, 4.373768	off-ramp	3+1	250	100	2,569	0.78	-	270	-	123
A13	Delft 52.014498, 4.374516	on-ramp	3+1	300	100	2,654	0.81	323	-	-	168
A59	Klaverpolder-south 51.695868, 4.645407	weaving	2+1	500	130	1,760	0.74	131	446	89	274
A15	Ridderkerk-south 51.856330, 4.620257	weaving	3+1	1000	130	2,868	0.78	107	186	309	555

Table 6.1. Overview of Empirical Data. * Length of acceleration lane (on-ramp), deceleration lane (off-ramp) or weaving segment.

6.3.2. Changing and calibrating the VISSIM model parameters

The model parameters in VISSIM were adjusted in two steps: 1) changing the model parameters related to traffic conditions and 2) calibrating driving behaviour model parameters. In the first step the following input parameters were changed: traffic flows, study area boundaries, roadway speed distribution and roadways geometry characteristics. Traffic flows and speed distributions were extracted from the empirical data. The road geometry characteristics (number of lanes and ramp length) were based on aerial photography as was taken during the field measurements (Van Beinum 2018).

RMSE minimization

The driving behaviour model parameters in VISSIM were calibrated by applying a root-mean-square error (RMSE) minimization of the model result compared to the observed values. The general form of the RMSE error term is given in (7).

$$\varepsilon_i = \beta_i \cdot \sqrt{\frac{\sum_{t=1}^{T} (\hat{y}_t - y_t)^2}{T}} \tag{7}$$

Where β_n are weight factors in the error term. These weight factors were used to even out the differences in error for the different elements. The weight factors were calculated using formula (8). Where $\varepsilon_{i,initial}$ is the calculated error for element n when using the initial model parameters

$$\beta_i = \frac{1}{\varepsilon_{i,initial}} \tag{8}$$

To acquire realistic lane change behaviour, it is necessary that traffic is distributed realistically over the lanes. It is expected that each vehicle has a desired speed and selects the desired lane accordingly (Toledo, Koutsopoulos, and Ben-Akiva 2007), with fast driving vehicles driving on the left (inside) and slow driving vehicles on the right (outside). This behaviour results in different speed distributions on the different lanes, and realistic speed differences between vehicles in different lanes. The simulation error in VISSIM was therefore calculated at the ramp area for: 1) the mean speed ($\overline{V}$) and the standard deviation of speeds (σ_V) on each lane (n), 2) the mean headway ($\overline{T}$) on each lane and 3) the mean accepted gap ($\overline{S}$) the standard deviation of the accepted gaps (σ_S). The RMSE equation as used in this study is displayed in equation (9).

$$\begin{aligned}\varepsilon = {} & \beta_1 \cdot \sum_{n=1}^{N} \sqrt{\left(\overline{V}_{lane_n}^{real} - \overline{V}_{lane_n}^{sim}\right)^2} + \beta_2 \cdot \sum_{n=1}^{N} \sqrt{\left(\sigma_{V,lane_n}^{real} - \sigma_{V,lane_n}^{sim}\right)^2} + \beta_3 \cdot \sum_{n=1}^{N} \sqrt{\left(\overline{T}_{lane_n}^{real} - \overline{T}_{lane_n}^{sim}\right)^2} + \\ & \beta_4 \cdot \sqrt{\left(\overline{S}_{lane_n}^{real} - \overline{S}_{lane_n}^{sim}\right)^2} + \beta_5 \cdot \sqrt{\left(\sigma_{S,lane_n}^{real} - \sigma_{S,lane_n}^{sim}\right)^2}\end{aligned} \qquad (9)$$

Selection of model parameters to calibrate

Driving behaviour in VISSIM is described by 59 parameters. 39 of these parameters affect driving behaviour on motorways (PTV 2017). To reduce the number of parameters for calibration a one-at-Time sensitivity analysis (Lownes and Machemehl 2006; Mathew and Radhakrishnan 2010; Punzo et al. 2015) was performed to select the parameters regarding free-flow traffic conditions, with the biggest influence on the RMSE. This was done by changing each relevant model parameter in different steps, over a certain range, based on a realistic upper and lower bound. While changing the considered parameter, the other parameter values remained unchanged at the default values. Finally 15 parameters were selected for calibration. The description of these parameters is displayed in table 6.2.

Parameter	unit	Parameter description
Maximum look ahead distance	m	Defines the distance that the driver can detect another vehicle
Number of observed vehicles	-	Affects how well a vehicle can predict another vehicle's move
CC0	m	Default distance between stopped cars
CC1	s	The driver dependent part of the time headway
CC2	m	Extra distance the driver keeps with the leading vehicle
CC3	s	Start of the deceleration process, when a slower leading vehicle is detected
CC4	m/s	Negative speed difference during the following process
CC5	m/s	Positive speed difference during the following process
CC7	m/s²	Actual acceleration value during the oscillation process
Slow lane rule	-	If is selected, vehicles are only allowed to overtake on the left side
Max deceleration (Trailing veh.)	m/s²	Maximum deceleration of a trailing vehicle under cooperation
Minimum headway (front/rear)	m	Minimum distance between two vehicles that must be available after a lane change
Free driving time	s	Minimum front gap on the target lane for a vehicle to switch to the slower lane
Safety distance reduction factor	-	"Aggressiveness" of lane changing behaviour
Cooperative lane change	-	If checked, vehicles in the target lane may make room for the lane changing vehicle

Table 6.2. Parameters selected for evaluation.

Calibration of model parameters

A stepwise approach was followed for the calibration of VISSIM's driver behaviour model parameters. Within each step 60 sets of parameters were generated using a Latin Hypercube Algorithm (LHA) (Park and Qi 2005; McKay et al. 1979). Each parameter set was run with 10 different random seeds, so a total of 600 simulations per individual ramp. This process was automated by connecting Matlab to the VISSIM COM interface. After the first step of 600 simulations the performance of the parameter sets was evaluated and the 10 best performing parameter sets were selected. These 10 sets were used to define a new range for the parameters using the LHA to generate 60 new parameter sets. These sets were then used in an additional calibration step. The performance of the best performing parameter set from the second round of simulations was compared with the performance of the best performing set from the first round, to conclude if the calibration results has improved. When the result did improve, a new round of simulations was performed, otherwise the best performing parameter set until that point was considered as the optimal one. This method requires a considerable amount of manual labour, therefore the calibration was done only for the on-ramp (merging traffic) and the off-ramp (diverging traffic). The parameters for weaving segments were derived from the on-ramp and off-ramp model parameters by taking the mean value of the two. Since the lane changing manoeuvres that are performed at weaving segments are mostly merging and diverging, it is expected that the average value of the calibrated parameter settings for on-ramps and off-ramps, are a valid approximation for the parameter settings at weaving segments.

6.3.3. Comparison of empirical and simulated trajectory data

For both the empirical trajectory data and the simulated trajectory data, that were generated by the calibrated VISSIM models, TTC and PET were derived for each lane change. TTC and PET are calculated following the concept as shown in figure 6.4. In this concept the subject vehicle is changing lanes to the right, from lane 2 to lane 1. At a certain time (*t*) the centre of subject vehicle crosses the lane dividing marking. This moment was regarded to be the time of the lane change (TOL). The centre of a vehicle was taken as the reference point, because the centre is also the reference point of a vehicle in the empirical trajectory data. Furthermore, taking the centre as a reference, eliminates possible measurement errors in the approximated vehicle length and width. Therefore, this is method regarded to be the most accurate way to pinpoint a lane change location.

At TOL, 4 adjacent vehicles are taken into account: the leader on the current lane (vehicle 1), the follower on the current lane (vehicle 2), the new leader on the target lane (vehicle 3) and the new follower on the target lane (vehicle 4). The case where the follower on the current lane (vehicle 2) approaches the subject vehicle is expected to be irrelevant for the calculation of TTC, since its headway increases after the subject vehicle changes lanes.

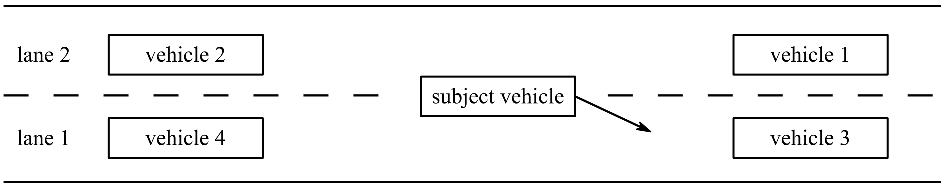


Figure 6.4 Example of lane changing vehicle.

For the considered vehicles the PET and TTC were calculated, by following the rules as displayed in table 6.3. Furthermore, PET was only calculated on TOL; TTC was calculated for a time period of 10 seconds (after TOL for vehicles 3 and 4, and before TOL for vehicle 1). PET and TTC are calculated by equation (10) and (11).

vehicle	PET	TTC
vehicle 1	time for subject vehicle to reach position of vehicle 1	front of subject vehicle to rear of vehicle 1
vehicle 2	time for vehicle 2 to reach position of subject vehicle	not calculated
vehicle 3	time for subject vehicle to reach position of vehicle 3	front of subject vehicle to rear of vehicle 3
vehicle 4	time for vehicle 4 to reach position of subject vehicle	front of vehicle 4 to rear of subject vehicle

Table 6.3. Scenario's for the calculation of PET and TTC.

$$PET = \frac{x_{follow,front} - x_{lead,rear}}{v_{follow}} \tag{10}$$

$$TTC = \frac{x_{follow,front} - x_{lead,rear}}{v_{follow} - v_{lead}} \tag{11}$$

In these equations $x_{follow,front}$ and $x_{lead,rear}$ represent the longitudinal position of respectively the front of the following vehicle and the rear of the leading vehicle. v_{follow} and v_{lead} represent the speed of respectively the following and leading vehicles.

The calculated PET and TTC values were stored into a database. The interaction between the vehicles was labelled as a conflict when either the minimum PET or the minimum TTC value is below the threshold values maxPET and maxTTC. For this study the following thresholds are used: maxPET = 1 seconds and maxTTC = 5 seconds. These threshold values are different from what is commonly used: 1,5 s for TTC (Hayward 1972) and 5 s for PET (Hydén 1987). The main reason for this is that most studies consider (un)signalised intersections where traffic is driving in opposite directions (head-on approach). In this case it is logical to take a maxPET that is higher than maxTTC. Since motorway traffic is driving in the same direction, it makes more sense to set maxPET lower than maxTTC. To rule out a bias related to the selected threshold values, the impact of these values on the number of conflicts was tested. Besides the used thresholds of maxTTC = 5 s and maxPET = 1 s, also the commonly used values of respectively 1.5 s and 5 s, and the intermediate values of respectively 2.5 s and 2.5 s were evaluated.

Since both PET and TTC are based on headway and speed, these quantities need to be accurately reproduced by the calibrated simulation software package, especially at the location where most lane changes take place: on lane 1 (where most vehicles change lanes to and from) in the vicinity of the ramp. And since this study focusses on traffic conflicts, lane changes with small accepted gaps and high speed differences are most relevant.

6.4. Results

6.4.1. Calibration results

The results of the calibration are shown in table 6.4 while a graphical representation of a selection of the results is given in figure 6.5. The calibrated parameter values are shown in table 6.5. For creating the distribution of accepted gaps, all lane changes where the subject vehicle merges into a gap between a new leader and a new follower were taken into account. For the speed and headway distributions the measurements were taken at specific cross section. For the off-ramp the cross section wat located at 10 m downstream of the off-ramp nose; just after the location where all diverging lane changes take place. For the on-ramp the cross section was located 10 m upstream of the on-ramp nose, just before the location where all merging lane changes take place. For the weaving segment the cross section was located 150 m downstream of the first weaving segment nose, after most merging and diverging lane changes have taken place.

measure		site	n			mean			std.			P-value KS-test
			empirical	VISSIM		empirical	VISSIM		empirical	VISSIM		VISSIM
				calibrated	default		calibrated	default		calibrated	default	calibrated
acc. gaps [sec]	**LC right**	off-ramp Delft	324	1,290	777	3.66	3.98	4.03	2.12	3.19	3.40	**0.463**
		weaving Klaverpolder-s	195	1,430	792	6.57	4.25	4.20	4.53	3.61	3.44	0
		weaving Ridderkerk-s	448	831	667	4.58	7.67	8.03	3.19	7.62	7.01	0
	LC left	on-ramp Delft	478	646	598	4.02	4.33	5.19	2.75	4.88	6.31	0.003
		weaving Klaverpolder-s	173	301	212	5.07	3.83	4.32	3.60	3.08	4.04	0.001
		weaving Ridderkerk-s	206	259	220	5.77	5.98	5.16	4.56	8.23	5.12	0.009
time headway [sec]	**lane 1**	off-ramp Delft	664	645	719	2.80	2.77	2.50	1.86	1.97	2.64	0.046
		on-ramp Delft	622	611	749	2.99	2.94	2.40	2.08	1.88	2.80	**0.429**
		weaving Klaverpolder-s	463	699	751	3.85	2.57	2.39	2.97	1.51	2.37	0
		weaving Ridderkerk-s	460	556	605	3.85	3.23	2.97	3.30	2.97	3.58	0.001
	lane 2	off-ramp Delft	938	710	746	1.99	2.53	2.41	1.80	2.93	2.40	0.004
		on-ramp Delft	862	755	776	2.16	2.38	2.32	1.66	2.40	2.39	**0.055**
		weaving Klaverpolder-s	602	761	837	2.96	2.36	2.15	2.48	2.24	1.92	0
		weaving Ridderkerk-s	591	687	623	3.01	2.61	2.88	3.77	4.40	3.26	0
	lane 3	off-ramp Delft	401	856	756	4.63	2.10	2.38	6.72	3.95	2.62	0
		on-ramp Delft	404	888	775	4.56	1.96	2.32	5.70	3.20	2.67	0
		weaving Ridderkerk-s	304	955	814	5.85	1.88	2.21	6.70	2.96	2.32	0
speed [km/h]	**lane 1**	off-ramp Delft	665	646	720	91.20	82.50	90.15	7.39	13.10	15.27	0
		on-ramp Delft	623	612	750	88.61	84.73	84.76	7.55	9.87	13.38	0
		weaving Klaverpolder-s	464	700	752	88.21	82.12	83.85	9.49	10.95	13.04	0
		weaving Ridderkerk-s	461	557	606	97.97	84.35	87.15	14.93	12.08	13.58	0
	lane 2	off-ramp Delft	939	711	747	100.80	88.03	87.22	6.54	17.87	12.58	0
		on-ramp Delft	863	756	777	98.30	91.12	87.89	6.13	14.02	11.30	0
		weaving Klaverpolder-s	603	762	838	101.97	86.94	86.43	7.95	13.91	10.35	0
		weaving Ridderkerk-s	592	688	624	116.01	93.94	87.34	10.06	13.52	8.90	0
	lane 3	off-ramp Delft	402	857	757	111.30	95.01	86.07	8.59	18.18	13.18	0
		on-ramp Delft	405	889	776	109.12	96.20	87.32	9.31	17.35	9.98	0
		weaving Ridderkerk-so	305	956	815	113.45	91.87	85.43	8.70	16.36	9.64	0

Table 6.4. Calibration result statistics.

parameter	**initial value**	**on-ramp Delft**	**off-ramp Delft**	**weave-short Klaverpolder-s**	**weave-long Ridderkerk-s**
RMSE - default parameters		39.55	26.26	28.59	40.04
RMSE - calibrated parameters		26.50	22.03	23.27	30.77
maximum look ahead distance	250	286.37	239.95	263.16	263.16
number of observed vehicles	2	7	8	8	8
CC0	1.5	2.64	2.03	2.335	2.335
CC1	0.9	0.5	0.5	0.5	0.5
CC2	4	3.67	4.25	3.91	3.91
CC3	-8	-8.19	-11.54	-9.87	-9.87
CC4	-0.35	-1.33	-1.08	-1.21	-1.21
CC5	0.35	0.8	1.21	1.00	1.00
CC7	0.25	0.34	0.2	0.24	0.24
slow lane rule	false	slow lane rule	slow lane rule	slow lane rule	slow lane rule
max deceleration (Trailing veh.)	-3	-1.77	-2.91	-2.35	-2.35
minimum headway (front/rear)	0.50	1.32	0.35	0.83	0.83
free driving time	40	9.75	18.01	13.88	13.88
safety distance reduction factor	0.60	0.41	0.47	0.43	0.43
cooperative lane change	false	true	true	true	true

Table 6.5. Overview of calibrated model parameters.

The results show that the calibration has improved the results in terms of accepted gap distribution, the headway distribution on lane 1 and the speed distributions on lane 2 and 3. On the other hand the results have deteriorated for the headway distribution on lane 2 and 3, and the speed distribution on lane 1. The mean and std. of the simulated accepted gap distributions correspond to the empirical values. For the off-ramp at Delft the distributions do not differ significantly. For the headway distributions the differences are bigger. The empirical data shows a mean headway of 2.8-3.8 s on lane 1, whereas the simulated data shows slightly lower values: 2.8-3.2 s. On lane 2 the values are 2.0-3.0s versus 2.4-2.6, and on lane 3: 4.6-5.9 versus 1.9-2.1. This shows that VISSIM overestimates the number of vehicles that drives on lane 3, the most left lane. This is also supported by the differences in the speed distributions, where VISSIM shows considerable lower mean speeds on lane 2 and 3. It seems that vehicles with a relatively low desired speed hinder vehicles with a higher desired speed.

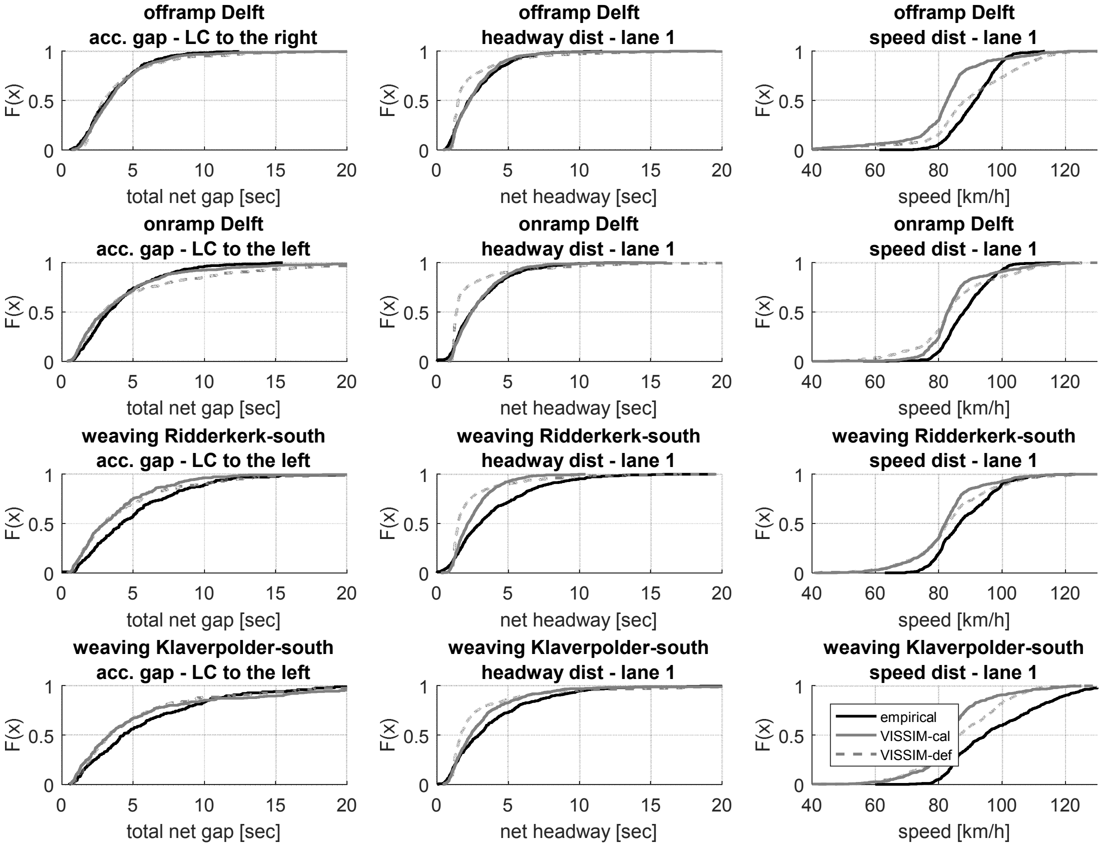


Figure 6.5. Calibration results.

6.4.2. Comparison SSM - VISSIM/Empirical

For each lane change the TTC over a range of 10 s and the PET were calculated to identify conflicts. An example of the calculated TTC for an anticipating vehicle (changing lanes from lane 1 to lane 2) from the empirical dataset is shown in figure 6.6. The vehicle numbers correspond to the system as presented in figure 6.4 on page 139. The lines represent TTC values ≥ 0 s. The TTC becomes negative when the leading vehicle has a higher speed than its follower. These cases are left out of the figure. The displayed lines are reasonably smooth. This is best shown in the graph displaying the TTC with vehicle 1. The peaks however are quite high. This can be partly explained by the short time interval (0.1 s) between data points in the trajectory data, which increases the impact of small speed differences.

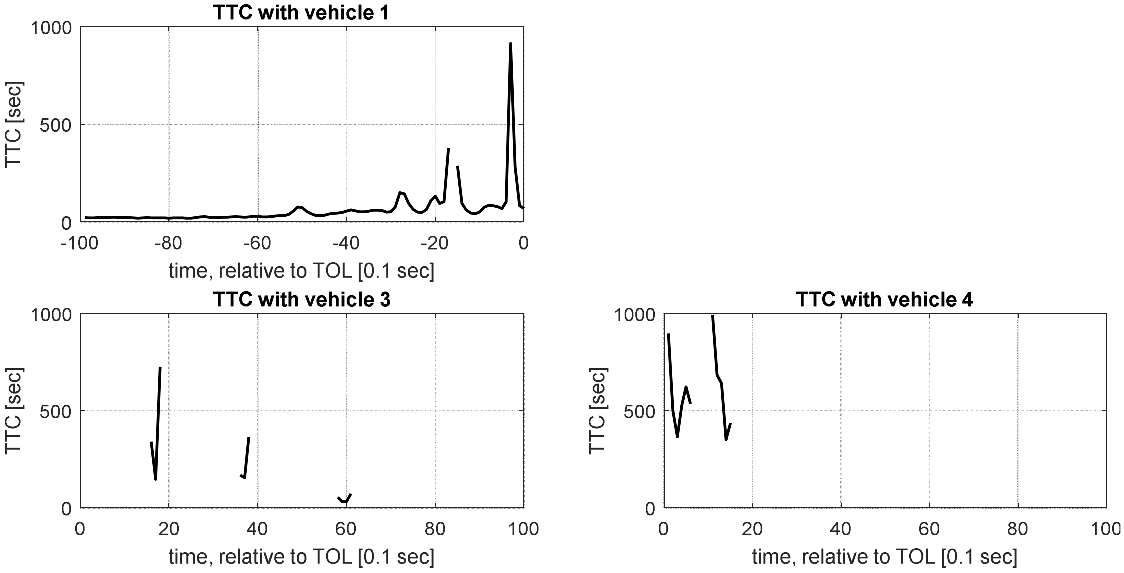


Figure 6.6. Example of TTC distributions of an anticipating vehicle.

TTC distribution

The cumulative distributions of the simulated and the observed TTC and PET values are displayed in figure 6.7. The descriptive statistics are shown in table 6.6, as well as the results of a two sample Kolmogorov-Smirnov test (KS-test) in which the distribution from the simulated data is compared to the distribution from the empirical data. The results show that the TTC distributions derived from the simulated data and the empirical data have comparable shapes, but differ significantly. It also shows that the simulated number of lane changes is approximately 3 times higher than occurred during the field measurements.

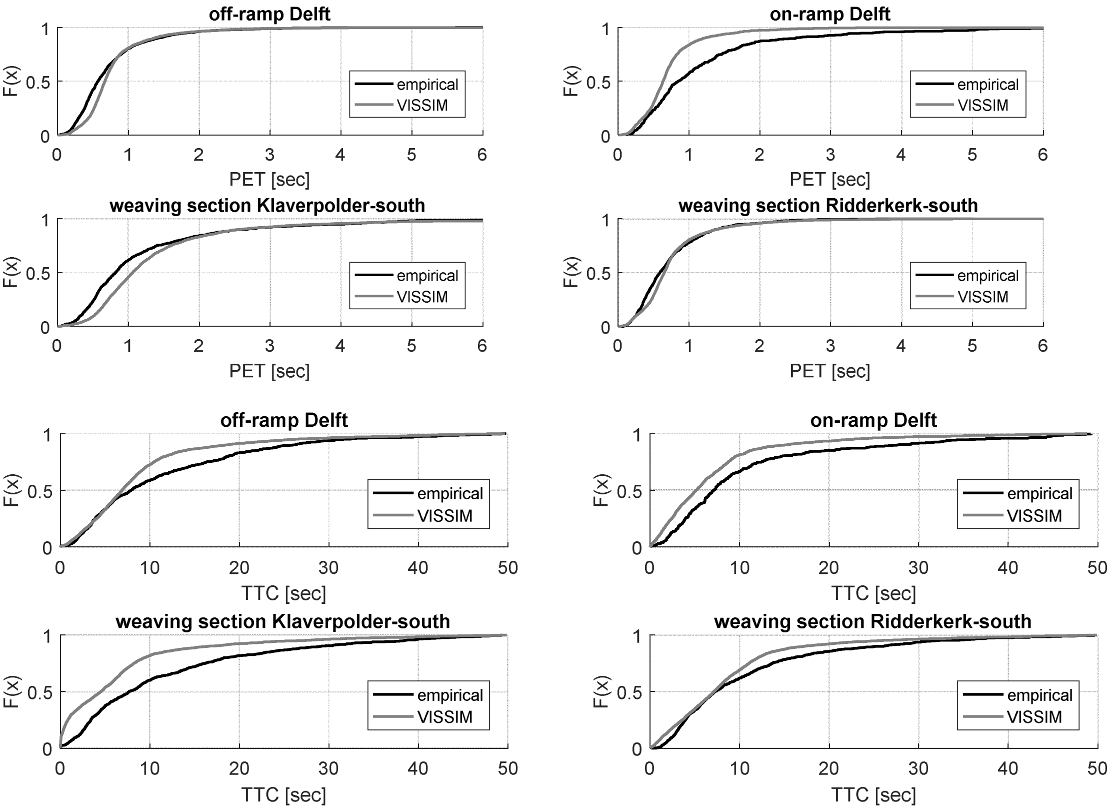


Figure 6.7. TTC and PET distribution

Number of traffic conflicts

The number of traffic conflicts that was derived from the calculated TTC and PET values, based on the different threshold values, are displayed in table 6.7. The results show that the number of conflicts in VISSIM are considerably higher than those measured in the empirical data. The threshold values have a considerable impact on the number of identified conflicts, which is to be expected. The relative difference between the number of simulated conflicts and the number of identified conflicts in the empirical data is however rather constant, which indicates difference between VISSIM and the empirical data is not explained by the threshold values. The difference is explained by the overestimation of the number of lane changes by VISSIM.

	site	**n**		**mean**		**std.**		**p-value ks-test**
		empirical	**VISSIM**	**empirical**	**VISSIM**	**empirical**	**VISSIM**	**VISSIM**
TTC	off-ramp Delft	796	2865	11.37	8.92	10.03	8.11	0
	on-ramp Delft	336	1294	10.74	7.07	10.66	7.47	0
	weaving Klaverpolder-south	675	2877	11.64	6.71	11.18	8.58	0
	weaving Ridderkerk-south	894	3173	10.73	8.79	9.74	8.08	0
PET	off-ramp Delft	958	3413	0.74	0.8	0.61	0.59	0
	on-ramp Delft	437	1452	1.22	0.74	1.22	0.59	0
	weaving Klaverpolder-south	953	3740	1.23	1.41	1.29	2.77	0
	weaving Ridderkerk-south	1037	3625	0.74	0.78	0.55	0.62	0

Table 6.6. Descriptive statistics of TTC and PET distributions.

site	**maxTTC = 5 s, maxPET = 1 s**			**maxTTC = 2.5 s, maxPET = 2.5 s**			**maxTTC = 1.5 s, maxPET = 5 s**		
	emp.	**VISSIM**	**diff.**	**emp.**	**VISSIM**	**diff.**	**emp.**	**VISSIM**	**diff.**
off-ramp Delft	251	762	67%	937	3,351	72%	956	3,405	72%
on-ramp Delft	285	945	70%	1,022	3,552	71%	1,036	3,620	71%
weaving Klaverpolder-south	350	441	21%	1,357	1,834	26%	1,420	1,866	24%
weaving Ridderkerk-south	323	1,340	76%	1,201	4,335	72%	1,277	4,400	71%

Table 6.7. Number of traffic conflicts.

6.5. Discussion

In this study we determined whether a (calibrated) microscopic simulation software package (VISSIM) is able to reproduce the traffic safety implications of manoeuvres that are performed by drivers near motorway ramps and weaving segments. The results of this study give two perspectives to this matter.

The first perspective involves the collective of all manoeuvres performed by all vehicles. The results show that the simulated distribution of traffic over the different motorway lanes, the distribution of speeds at the different lanes, the headway distribution over the different lanes and the total number of lane changes differ from the empirical data. However, driving behaviour on lane 1 is considerably more accurate than on lane 2 and 3. The smaller mean headway and the lower mean speed on lane 2 and lane 3 indicate that slower vehicles in VISSIM hinder faster vehicles to drive at their desired speed. This is a problem when studying traffic safety, since the difference in speed is a major factor (Aarts and Van Schagen 2006). Furthermore, the overestimates the number of lane changes indicates that vehicles are eager to change lanes to the faster lane when a slower vehicle is driving in front. These differences are probably caused by how VISSIM deals with 'right side rule' and will decrease when slower vehicles move towards the slower lane sooner and are more hesitative to change to faster lane. VISSIM is therefore stated to be unsuitable for assessing the implications for traffic safety that is related to lane change locations and distribution of traffic over different motorway lanes.

The second perspective involves the close interaction of different vehicles during the lane change procedure.

The calibration procedure improved the gap acceptance and car following behaviour on lane 1 (the right most lane) considerably. Since turbulence around ramps is mainly caused by vehicles that enter or exit the motorway, the most relevant lane changes will occur from or to lane 1. Also the calculated SSM from the empirical data and VISSIM correspond reasonably well. The distributions have comparable shapes, but differ statistically significant. These results are to be expected, since TTC and PET for lane changes are closely related to gap acceptance, and most lane changes are performed to or from lane 1. VISSIM is therefore stated to be suitable for assessing the traffic safety implications of vehicle interactions during lane changes.

The results also emphasize that using microscopic simulation model to evaluate safety without proper model calibration should be avoided. VISSIM was calibrated for the on-ramp and off-ramp. For the weaving segment the model parameters were derived from the calibrated on-ramp and off-ramp. The results show considerable improved results for the on-ramp and off-ramp, compared to the weaving segment. The weaving segment results would probably be better when they were also calibrated individually. This suggests that accurate results for a specific situation can only be acquired when good quality empirical data is available, which contradicts the main benefit of this approach: no need for empirical data.

The use of empirical data should be dealt with carefully. The empirical data that was used for this study contains measurement errors; for example: the longitudinal position of the vehicles. A slight deviation for within each 10th of a second will result in unrealistically high acceleration/deceleration values. The data was smoothed (Toledo, Koutsopoulos, and Ahmed 2007) to reduce these high values, but after the data was smoothed the values remain high. A higher level of smoothing could improve the match between the observed and simulated conflicts, since abrupt movements would be removed from the empirical data. Extra smoothing however, might result in over smoothing and underestimate the applied acceleration/deceleration values.

6.6. Conclusions and recommendations

In this study a calibrated VISSIM model was used to analyse whether simulated traffic conflict in weaving segments are comparable in number and severity to traffic conflicts as identified during field measurements. In previous studies, the lack of high quality empirical data was reported to be a major limitation regarding the calibration of the microscopic simulation software (Wang et al. 2014; Young et al. 2014).

This study used empirical trajectory data that was collected at an on-ramps, an off-ramps and 2 weaving segments on motorways in The Netherlands to perform a thorough calibration of VISSIM's driving behaviour parameters. The calibrated VISSIM model was used to quantify the difference between simulated and empirical driving behavioural aspects.

The main findings of this study are:

- the simulated accepted gap distributions are reasonably accurate; for lane changes towards the right at the off-ramp the difference between the simulated and the empirical gap acceptance distribution was not statistically significant;
- the difference between simulated and empirical headway distributions decreased considerably after calibration; at the on-ramp the difference between the simulated and the empirical headway distributions is not statistically significant for lane 1 and 2;
- the simulated headway distribution on lane 3 deviates considerably from the empirical data, even after calibration;
- the simulated speed distribution on lane 1, 2 and 3 deviate considerably from the empirical data, even after calibration. The difference is greatest for lane 3; the utter left lane;
- the number of traffic conflicts is overestimated by VISSIM, due to an overestimation of lane changes;
- the distribution of derived TTC and PET values, from simulated data and empirical data, show comparable shapes but the difference between the distributions is statistically significant.

The findings show that VISSIM overestimates the number of traffic conflicts, regardless the threshold values that are used to identify a traffic conflict. This overestimation is mainly explained by differences in location and intensity of lane changes, changes in headway distribution and changes in speed as simulated by VISSIM, compared to the empirical data. Simulated vehicles in VISSIM tend to change lanes towards the faster lane, where they hinder faster vehicles to drive at their desired speed. This results in an overestimation of the number of lane changes, an unrealistically high amount of traffic on the fast lane (left lane) and a lower mean speed on the left lane. Therefore it is recommended to focus future research on modelling driver's short term lane selection strategies and path planning.

The findings also show that the severity of conflicts (as measured by the distributions of TTC and PET) is simulated reasonably accurate by VISSIM. Gap acceptance and car following during lane changes from and to lane 1 (most right lane), are simulated reasonably well by VISSIM. Also the distributions of TTC and PET during identified conflicts have comparable shapes. Therefore it is stated that VISSIM holds the potential to be used for traffic safety evaluation.

The main contribution of this study is the use of a large amount of high quality empirical trajectory data, for calibration and analysis. In the analysis however, the use of empirical trajectory data has also shown that the unavoidable measurement errors in the data (especially data noise in x-values), can have a major impact in the calculation of SSM. The data was smoothed, but the right level of smoothing is difficult to determine and we now face a dilemma between under and over smoothing. Therefore , it is recommended to aim future research on the available smoothing techniques for empirical trajectory data and their impact on derived SSM.

7. Conclusions, recommendations and discussion

On-ramps, off-ramps and weaving segments are parts of the motorway that suffer high levels of turbulence. These locations more often function as bottlenecks and show higher crash rates, compared to road segments with low turbulence. The primary goal of this thesis is to gain empirical knowledge about the characteristics of turbulence and how this is affected by the road design (weaving segment length) and the amount of traffic.

Currently, no explicit definition of turbulence is available in literature and motorway design guidelines. In this thesis, therefore, an explicit definition for turbulence is introduced: "*individual changes in speed, headways, and lanes (i.e. lane-changes) in a certain road segment, regardless of the cause of change*".

Turbulence is expected to be present in the traffic stream at any given time and therefore also an additional definition is introduced: the level of turbulence, which is defined as "*the frequency and intensity of individual changes in speed, headways and lane-changes in a certain road segment, over a certain period of time*".

The level of turbulence is expected to increase at some distance upstream of a motorway ramp and is expected to decrease at some distance downstream of a motorway ramp. These distances are used in motorway design guidelines to determine the distance for ramp spacing and the length of weaving segments. These guidelines are important tools for road designers, influence decision making in road design to a large extent, and can eventually have an enormous influence on the physical layout of a road. However, in different countries different approaches are used in guidelines for dealing with turbulence (AASHTO 2011; RAA 2008; HCM 2010; Rijkswaterstaat 2017; DMRB 1994), and to the best of our knowledge there is only one example available in literature, that describes the start and end of a raised level of turbulence (Kondyli and Elefteriadou 2012). Furthermore, the guidelines do not indicate the implications of deviating from the guidelines in terms of traffic operations and traffic safety.

Therefore, there are two major problems for applying current motorway design guidelines with respect to turbulence:

- a solid theoretical and empirical underpinning regarding the required length for a raised level of turbulence is lacking;
- a thorough understanding of (quantitative) implications in terms of impacts on traffic operations and traffic safety, when deviating from the design guidelines, is missing.

To gain the desired empirical knowledge on the characteristics of turbulence, a unique set of trajectory data was collected (Van Beinum 2018). This dataset contains precise vehicle location information (*x,y,time*) of each individual vehicle at fourteen different locations in The Netherlands: three on-ramps, three off-ramps and eight weaving sections. The size, quality and characteristics of this data set are unprecedented. A thorough analysis of the data was performed and gave new, unique, insights in the empirical characteristics of turbulence in weaving segments and the vicinity of ramps.

Currently, several methodologies to assess the impact of turbulence on traffic operations and traffic safety exist, such as: the use of microscopic simulation programs, surrogate safety measures, crash prediction models and driver simulators. The literature review study pointed out that each one of these methods has their own strengths and weaknesses. Considering these strengths and weaknesses, combining microscopic simulation software with surrogate safety measure methodologies was expected to be the most promising way forward. To determine the predictive validity of this method the following studies were performed:

- based on a set of criteria for simulating turbulence, two simulation models were selected: a commonly used commercial microscopic simulation software package (VISSIM) and a recently developed (research) simulation model (MOTUS);
- the selected models were calibrated based on the empirical trajectory data;
- the simulation output (microscopic driving behaviour) of the calibrated models was compared to the empirical data;
- the simulation output (the number and severity of traffic conflicts) of the model that is most often used in traffic safety research (VISSIM) was compared to the empirical data.

This chapter describes the main findings and conclusions of the performed studies within this thesis (section 7.1). Recommendations that followed from the performed studies are described in section 7.2. This chapter concludes with a discussion section where the scientific results of this thesis are related to practical application within the road design process (section 7.3).

7.1. Main findings and conclusions

In this section, the main findings of this thesis are described:

- the characteristics of turbulence around on-ramps and off-ramps (section 7.1.1);
- the characteristics of turbulence in weaving segments (section 7.1.2);
- the performance of available microscopic simulation software packages, in terms of simulating the key elements of driving behaviour around motorway ramps and weaving segments (section 7.1.4);
- the performance of available microscopic simulation software packages to quantify the level of safety of motorway traffic around ramps, in terms of the number and severity of traffic conflicts (section 7.1.4).

7.1.1. Characteristics of turbulence around ramps

The empirical trajectory data that was collected at the on-ramps and the off-ramps was analysed. Different manoeuvres were identified that are performed by drivers that either enter or exit the motorway, and by drivers that anticipate on or cooperate with entering or exiting vehicles. The characteristics of these manoeuvres were analysed in order to gain knowledge on the characteristics of turbulence.

Findings

The most relevant measure to indicate turbulence was found to be the intensity and location of lane-changes. Changes in speed and headway were found to be limited. The results show an increase in the number of lane-changes around motorway ramps, compared to further upstream or downstream of a ramp. Most lane-changes were found to be located within close proximity of a ramp gore: a substantial amount of all lane-changes takes place at the acceleration lane (33-55%) and the deceleration lane (47-61%).

Only a limited amount of lane-changes are performed further downstream or upstream of a ramp:

- for on-ramps it was found that:
    - 4-9% of all lane-changes involved motorway drivers that anticipated on entering traffic, by changing lanes towards the inside of the motorway, at about 25-100 m upstream of the on-ramp, in order to avoid or give room to entering vehicles;
    - drivers performed additional lane-changes towards the inside of the motorway (secondary merge) and towards the outside of the motorway (keeping right) until approximately 475-575 m downstream of the on-ramp;
- for off-ramps it was found that:
    - at the earliest start of the measured area (600, 750 and 500 m upstream of the off-ramp), most exiting drivers (96, 86 and 91%) were already driving on the outside lane;
    - drivers started to pre-allocate upstream of the off-ramp in three different stages:
      1) at more than 750 m upstream of the ramp;
      2) at approximately 600 m upstream of the ramp, where an exit sign is located;
      3) at approximately 200-400 m upstream of the ramp;
    - downstream of the off-ramp the number of lane-changes was limited and mostly involved lane-changes towards the most right lane (keeping right rule). These lane-changes were performed until approximately 200-375 m downstream of the off-ramp gore.

Conclusions

These results indicate that most lane-changes are located in direct proximity of a ramp, near the acceleration/deceleration lane. The number of lane-changes further upstream and further downstream is much less than at the acceleration/deceleration lane. The distance over which the level of turbulence increases further upstream and further downstream of a ramp, is different for on-ramps and off-ramps. At on-ramps an increased level of turbulence is mainly present downstream of the on-ramp, and at off-ramps an increased level of turbulence is mainly present upstream of the off-ramp.

7.1.2. Characteristics of turbulence in weaving segments

The empirical trajectory data that was collected at the weaving segments was analysed similar to the method as described in section 7.1.1.

Findings

For weaving segments, it was shown that most of both the entering and exiting drivers desired to change lanes directly downstream of the first gore. By far most lane-changes (low traffic flow: 73-95%, high traffic flow: 74-85%) occurred in the first quarter of the weaving segment, leaving the remaining three quarters mostly unutilized. The length of a weaving segment was shown to have a small influence on the location where drivers change lanes, for both short (500 m) and long (1,100 m) weaving segments mainly the first quarter was utilized. Furthermore, the length of a weaving segment (500-1,100 m) and the amount of traffic (F/C-ratio between 0.35 and 0.78) were not shown to have a significant impact on gap acceptance (i.e. accepted gap distribution) in free-flow conditions.

Conclusions

The findings suggests that driving behaviour in weaving segments is rather constant and is not strongly influenced by the weaving segment's length. This differs from the concept that is currently used in motorway design guidelines, such as (HCM 2010; Rijkswaterstaat 2017), which states that a weaving segment should have a maximum length, at which the weaving turbulence no longer has an impact on the traffic operations within the segment, or alternatively, on the capacity of the weaving segment. When traffic flow and the amount of weaving traffic increases, a longer weaving segment is desired. In current motorway design guidelines (Rijkswaterstaat 2017), the length of a weaving segment can become as long as 1,300 m.

7.1.3. Microscopic simulation of turbulence

Based on a multi-criteria analysis two simulation software packages (VISSIM and MOTUS) were selected and calibrated using the empirical trajectory data. The characteristics of the simulated driving behaviour were compared to the characteristics that were derived from the empirical data.

Findings

The simulated driving behaviour was found to be unrealistic for the two most important elements of turbulence: the intensity and the location of lane-changes. In this section, the following findings are described in more detail:

- route choice related lane-changes (i.e. mandatory lane-changes);
- lane-changes that are not related to route choice (i.e. discretionary lane-changes).

Location of route choice related lane-changes

The simulated mandatory lane-changes were found to be accurate in number. The location of the simulated lane-change were found to be too deterministic compared to the empirical data. This mainly concerns two situations:

- pre-allocation of vehicles that desire to exit the motorway;
- vehicles that just have merged and desire to make additional lane-changes towards a faster lane on the motorway (i.e. secondary merges).

In simulation, only a limited spread was found in the location where vehicles pre-allocate. This differs from reality, where pre-allocation was found to be performed in different stages, as described in section 7.1.1.

In simulation, the lane-change locations for secondary merges are located more downstream compared to the empirical data. In reality about one-third of the drivers that merge into the motorway almost immediately make a secondary lane-change towards the inside of the motorway. In the Netherlands, the inside lane on the motorway generally has the highest mean speed of all the lanes and the lowest occupation rate. Drivers with a relatively high desired speed, prefer to drive on this outside lane. The empirical data shows that some of these drivers desire to reach this lane at the earliest opportunity.

Locations of discretionary lane-changes

As described in the introduction of this chapter, turbulence is expected to be always present in traffic. This turbulence is created by discretionary lane-changes that are performed to:

- improve driving conditions, for example in order to overtake slow driving vehicles in front, or to move to a lane with a lower density;
- follow the keeping right rule, that obliges drivers to change lanes to the outside of the motorway when there is a suitable opportunity to do so (i.e. keeping right).

The results of this thesis show that, of the two simulation software packages that were examined, also after calibration, the first simulation software package (VISSIM) produced an overestimation of the number of discretionary lane-changes, while the second simulation software package (MOTUS) underestimated the number of discretionary lane changes.

Conclusions

Based on these findings, both VISSIM and MOTUS currently seem unsuitable for assessing the implications on traffic operations for specific motorway designs that deviate from the motorway design guidelines.

The currently available microscopic simulation models need to reproduce rather complex driver decision processes, such as lane selection and path planning. The way driver behaviour is modelled is, for good reasons, often quite simplistic, and is mostly built upon a few basic assumptions and mechanisms. These simple mechanisms result in lane-change locations which are less spread out, as compared to the empirical data.

7.1.4. Microscopic simulation of traffic conflicts

One on-ramp, one off-ramp and two weaving segments were modelled in the calibrated microscopic simulation software package VISSIM. From the simulation output, traffic conflicts were identified using a traffic conflict technique, based on Time-To-Collision (TTC) and Post-Encroachment Time (PET). The traffic conditions in the simulation were comparable to the conditions that were measured in the field, and can be considered as high traffic flow and free-flow conditions.

Findings

The performance of the evaluated microscopic simulation model (VISSIM) can be addressed from the following two perspectives.

The first perspective involves the collective of all manoeuvres, performed by all vehicles. The results show that the simulated distribution of traffic over the different motorway lanes, the distribution of speeds and headways in the different lanes and the total number of lane-changes, differ from the empirical data. These deviations result in an overestimation of the number of traffic conflicts. This perspective has already been presented in section 7.1.3, and will therefore not be further addressed in this section.

The second perspective involves the close interaction of different vehicles during the lane-change procedure, mainly represented by gap acceptance, TTC and PET. The results show that the simulated vehicle interactions in

VISSIM are reasonably comparable to the interactions as measured in the field, in terms of gap acceptance, TTC and PET.

Conclusions

These findings show that the severity of traffic conflicts, as simulated by VISSIM, are reasonably accurate. The severity of traffic conflicts (as measured by TTC and PET) is the result of a combination of the size of an accepted gap and the speed difference between the lane-changing vehicle and its leaders and followers. These aspects of driving behaviour follow directly form the car following model and the lane-change model that are integrated in VISSIM. The findings show that these models are able to simulate vehicle interactions on a microscopic level reasonably well.

From a traffic safety perspective, lane-changes with small accepted gaps and high speed differences between the vehicles involved, are considered to give the highest risk of a collision. These conditions are mainly present at the acceleration/deceleration lane, where only a limited number of opportunities are available to change lanes, and where the level of turbulence is at its highest. Further upstream or downstream, drivers have more time to select suitable gaps. Here the risk of a collision will be lower. Therefore it is stated that VISSIM holds the potential to be used for traffic safety evaluation at on-ramps, off-ramps and weaving segments.

7.2. Recommendations

The results of this thesis have given new insights on the characteristics of turbulence and on the methods that are currently used to design safe roads with a sufficient level of service. Based on the findings of this thesis, recommendations are given for:

- motorway design guidelines;
- microscopic simulation of driving behaviour;
- traffic conflict techniques and microsimulation.

7.2.1. Motorway design guidelines

Ramp influence areas in perspective to the motorway design guidelines

Motorway design guidelines prescribe a ramp influence area upstream and downstream of a ramp (AASHTO 2001; HCM 2010), a set of turbulence distances for different types of ramps (Rijkswaterstaat 2017), or fixed distances for ramp spacing, related to the type of motorway or the legal speed limit (RAA 2008; DMRB 1994).

The results of this thesis show that the size of the ramp influence area is different for on-ramps and off-ramps. At on-ramps, the influence area is mainly located downstream of the ramp, and at off-ramps the influence area is mainly located upstream of the ramp. This is in contradiction with current USA and UK guidelines and is in line with current Dutch design guidelines.
The results of this thesis are compared to different international ramp spacing guidelines in table 2.1, with an example of where an on-ramp is followed by an off-ramp. This example shows that, if no overlap in turbulence is desired, only the German guidelines provide sufficient length. When applying all other guidelines, a certain level of overlap between ramp influence areas will occur. Further research is recommended on the impact of overlapping ramp influence areas on traffic operations and traffic safety. Furthermore it is recommended to reconsider the guidelines regarding ramp influence areas and turbulence distances, and to base these guidelines on the empirical findings.

Country	**Distance**	**Design criteria**
This study	975 m	on-ramp: 575 m + off-ramp: 400 m
The Netherlands (Rijkswaterstaat 2007)	750 m	design speed
Germany (RAA 2008)	1100 m*	minimum value for isolated intersection planning
USA (AASHTO 2001)	600 m**	road category: freeway
	480 m***	road category: freeway
UK (DMRB 1994) , Vol.6, Sec. 2, Cpt 4.7	450 m****	3.75V, where V = design speed = 120 km/h

Table 7.1. Distance between on-ramp and off-ramp prescribed in different road design guidelines.
* 250 m acceleration lane + 600 m between acceleration and deceleration lane + 250 m deceleration lane; ** system to service interchange (weaving); *** service to service interchange (weaving); **** may be increased to the minimum requirements for effective signing and motorway signalling.

Weaving segment length

Most of both entering and exiting drivers desire to change lanes in the first part of the weaving segment. The distances that are prescribed in the design guidelines, to offer drivers space to make lane-changes, are hardly used by these drivers. Therefore, providing long weaving segments lengths seems not to be useful. Further research is recommended to set suitable lower bounds for weaving segment lengths for motorways with two or three continuous motorway lanes.

7.2.2. Microscopic simulation of driving behaviour

In the past decades much effort has been put in developing mathematical models that describe microscopic driver behaviour, such as car following behaviour, lane-change behaviour and gap acceptance. Different approaches were proposed by different researchers and some of these approaches were implemented in microscopic simulation software packages, such as VISSIM, AIMSUN, PARAMICS and others. Also, much effort is put in developing the user interface to make these software packages more user friendly. This makes these software packages an attractive tool to use for making and evaluating motorway designs. However, these models are mostly developed to correctly reproduce macroscopic quantities of traffic, such as speed distributions, headway distributions and traffic densities. This makes these models primarily suitable for assessing motorway capacity and not directly to describe microscopic driver behaviour, such as driver behaviour during manoeuvres as measured in this thesis: merging, diverging, anticipation, cooperation, pre-allocation, relaxation and keeping-right.

The currently available microscopic simulation models and software packages can be improved, in terms of driving behaviour around ramps. The following recommendations for further research to improve driving behavioural models are given:

- categorize driving behaviour, not only by longitudinal and lateral behaviour, but categorize them by type of manoeuvre and model the behaviour during these manoeuvres accordingly. The most prominent manoeuvres to improve are: pre-allocation, secondary merges and keeping right;
- different drivers are expected to have different strategies when entering or exiting a motorway at ramps and at weaving segments. Additional research is recommended to identify these strategies;
- the number of discretionary lane-changes, as reproduced by microscopic simulation models, is not accurate. Additional research is recommended on discretionary lane-change incentives, the desire to change lanes, and the factors that influence lane-change decisions, for discretionary lane-changes.

7.2.3. Traffic conflict techniques and microsimulation

In the recent years microscopic traffic simulation software is commonly used to assess the impact of a road design variants on capacity and traffic safety. Despite a long history of developing driving behaviour models, the use of microscopic simulation software for traffic safety assessment has been subject of debate. To determine to what extent the simulated traffic conflicts are realistic in number and severity, simulated traffic conflicts were compared to traffic conflict as measured in the empirical trajectory data. In the analysis it was shown that the unavoidable measurement errors in the empirical trajectory data (especially data noise in x-values), can have a major impact on the severity of traffic conflicts (as measured by TTC and PET). It is recommended to carry out further research on several available smoothing techniques for empirical trajectory data and their impact on the severity of traffic conflicts.

7.3. Discussion

In this section the scientific results of this thesis are related to practical application within the road design process. The following topics are addressed:

- motorway design guidelines;
- simulation of driving behaviour around ramps;
- a design tool to quantify motorway safety and capacity.

7.3.1. Motorway design guidelines

The increased level of turbulence that is caused by entering and exiting traffic was found to be mainly located in the direct vicinity of a ramp; at the acceleration and deceleration lane. Further upstream and downstream of a ramp only a limited increase in the level of turbulence was measured. Based on the measured increase in the level of turbulence, ramp influence areas were defined. When the length of these influence areas are compared to those that are prescribed in the motorway design guidelines, it was shown that only the German guidelines provide sufficient length. When applying all other guidelines, a certain level of overlap between ramp influence areas will occur. The question is, however, whether a certain level of overlap is problematic, in terms of traffic operations and traffic safety. Since the level of turbulence is much higher at the acceleration and deceleration lane, compared to further upstream and downstream, the most eminent implications for traffic safety and capacity are expected here. Therefore, a certain level of overlap of ramp influence areas further upstream and downstream is not expected to be determinant for the level of traffic safety and capacity of a ramp.

Guidelines for ramp spacing

A different approach to include turbulence in road design guidelines for ramp spacing is proposed. Since most turbulence is measured in direct proximity of the ramp, and turbulence upstream of off-ramps is expected to be correlated with signposting, turbulence does not seem to be the main determinant for ramp spacing. Drivers are hypothesised to plan their path over the different motorway lanes. As a consequence, the available length for planning that path is far more important than the available length for performing the actual manoeuvre. Motorway design guidelines should therefore focus more on the desired lengths to inform drivers on, or psychologically prepare drivers for, upcoming route decision points (e.g. by placing sign posts or by in-car route navigation systems), rather than on turbulence.

Guidelines for weaving segment length

A different approach for guidelines for the determination of the weaving segment length is proposed. Since most of the lane-changes, that are performed by entering and exiting vehicles, occur in the first few hundred meters downstream of the first gore, driving behaviour at weaving segments seems to be comparable to behaviour at on-ramps and off-ramps. In this perspective it can be stated that informing drivers at a sufficient distance upstream of the upcoming route decision point, is more relevant than providing a large weaving segment length. Weaving segment length should therefore be determined based on the required length for signposting, rather than on turbulence. Both entering and exiting drivers desire to change lanes in the first part of the weaving segment. This results in a local high level of turbulence, which can have a negative effect on traffic safety and capacity. It is to be preferred that the lane-change locations of entering and exiting traffic are separated; for example by letting the exiting vehicles change lanes in the first part of the weaving segment and the entering vehicles in the second part of the weaving segment (or vice versa). There are three ways to change this: 1) to enforce the desired lane-change location by altering the design of the road, for example by adding specific road markings, 2) by informing drivers about the preferred lane-change location, for example by road signs or in-car advisory systems, and 3) by changing driver behaviour of the total driver population, for example by means of an informational campaign.

7.3.2. Simulation of driving behaviour around ramps

Location of mandatory lane-changes

The results of this thesis suggest that different drivers hold different strategies to enter and exit the motorway.

Some of the entering drivers, that merge into the motorway, make an additional lane-change towards the inside of the motorway almost immediately after they have merged into the outside lane. Others stay in the outside lane. Simulations show a more step-wise process, where a vehicle first merges onto the motorway and then starts to consider an additional lane-change, when it's desired speed cannot be reached due to a slow driving leader. In this way simulated lane-changes for secondary merges are located further downstream than in reality.

Some of the exiting drivers prefer to pre-allocate long in advance, while others prefer to make a last-moment lane-change. In current simulation models the location where vehicles pre-allocate has less variance.

These different strategies for different drivers are only programmed in microscopic simulation models to a limited extent, for example by implementing an "aggressiveness" factor that increases maximum acceleration and deceleration rates and decreases critical gap values. The current mechanisms in driver behaviour models seem to be unfit to simulate pre-allocation realistically. Implementing a path planning algorithm, that considers different drivers' strategies is needed to simulate driver behaviour downstream of on-ramps and upstream of off-ramps realistically.

Location of discretionary lane-changes

There are two types of discretionary lane-changes:

- change lanes towards the inside of the motorway;
- change lanes towards the outside of the motorway.

Discretionary lane-changes towards the inside of the motorway

In most lane-change models, discretionary lane-changes are triggered by an incentive, or desire, to change lanes. For example: in most car following models a driver overtakes its leader, when it cannot drive at a desired speed. In microscopic simulation software packages, the balance between staying in the current lane or changing lanes seems to be crucial. But this was proven to be difficult to calibrate. The results suggest that the process of lane selection and the decision to change lanes is more complex than is modelled in the simulation models. The difference in speed distributions on the different motorway lanes might suggest that drivers in reality are more hesitative to change lanes. In reality drivers might (temporarily) accept to drive slower when their desired speed is not met, or have a desired speed which is not a fixed number, but has a range between certain boundaries.

Discretionary lane-changes towards the outside of the motorway
Most lane-change models have only one mechanism for drivers to change lanes to the slower lane on the right: a lane-change is performed when there is no slow driving vehicle in front on the target lane and there is a large enough gap on the target lane. In reality the incentive to change lanes to the outside of the motorway can also be influenced by other additional factors, such as: to make way for a faster vehicle that is approaching from behind, or to postpone a lane-change when there is a larger, more convenient, gap further downstream. Additional factors like these can affect the lane-change location.

7.3.3. A design tool to quantify traffic safety and capacity

As already described in sections 7.1.3 and 7.1.4, the currently availably microscopic simulation software packages are yet unable to reproduce the location and intensity of lane-changes accurately, which are the key elements in driving behaviour with respect to turbulence. This is a problem when different designs are evaluated and compared in terms of turbulence. For standard elements of a road design, such as a basic weaving segment, a standard on-ramp or a standard off-ramp, this problem is expected to be limited, since a lot of research and experience is available for these situations. For unconventional, or ‘fit for purpose’, designs this problem is expected to be more eminent. It is recommended not to use microscopic simulation software to quantify traffic safety of complex, unconventional designs.

References

Aarts, E., and J. Korst. (1988). "*Simulated annealing and boltzmann machines*." John Wiley and Sons Inc., New York.

Aarts, L., and I. Van Schagen. (2006). "*Driving speed and the risk of road crashes: A review.*" In: Accident Analysis & Prevention, vol. 38, nr. 2, p. 215-224.

AASHTO. (2001). "*A policy on geometric design of highways and streets*." American Association of State Highway and Transportation Officials.

AASHTO. (2011). "*A policy on geometric design of highways and streets*." American Association of State Highway and Transportation Officials.

Abdel-Aty, and Pande. (2005). "*Identifying crash propensity using specific traffic speed conditions.*" In: Journal of Safety Research, vol. 36, p. 12.

Abdel-Aty, M., A. Pande, L. Y. Hsia, and F. Abdalla. (2005). "*The potential for real-time traffic crash prediction.*" In: ITE Journal, vol. 2005-12, p. 69-75.

Abdel-Aty, M., N. Uddin, and A. Pande. (2005). "*Split models for predicting multivehicle crashes during high-speed and low-speed operating conditions on freeways.*" In: Transportation Research Record: Journal of the Transportation Research Board, vol. 1908, nr. 1, p. 51-58.

Abdel-Aty, M., N. Uddin, A. Pande, F. M. Abdalla, and L. Hsia. (2004). "*Predicting freeway crashes from loop detector data by matched case-control logistic regression.*" In: Transportation Research Record: Journal of the Transportation Research Board, vol. 1897, nr. 1, p. 88-95.

Abdel-Aty, M. A., and R. Pemmanaboina. (2006). "*Calibrating a real-time traffic crash-prediction model using archived weather and ITS traffic data.*" In: Intelligent Transportation Systems, IEEE Transactions on, vol. 7, nr. 2, p. 167-174.

Ahmed, K., M. Ben-Akiva, H. Koutsopoulos, and R. Mishalani. (1996). "*Models of freeway lane changing and gap acceptance behavior.*" In: Transportation and traffic theory, vol. 13, p. 501-515.

Ahmed, K. I. (1999). "*Modeling drivers' acceleration and lane changing behavior*." Doctoral thesis, Massachusetts Institute of Technology.

Ahn, S., J. Laval, and M. Cassidy. (2010). "*Effects of merging and diverging on freeway traffic oscillations: theory and observation.*" In: Transportation Research Record: Journal of the Transportation Research Board, nr. 2188, p. 1-8.

Amin, M., and J. Banks. (2005). "*Variation in freeway lane use patterns with volume, time of day, and location.*" In: Transportation Research Record: Journal of the Transportation Research Board, nr. 1934, p. 132-139.

Anastasopoulos, P. C., A. P. Tarko, and F. L. Mannering. (2008). "*Tobit analysis of vehicle accident rates on interstate highways.*" In: Accident Analysis & Prevention, vol. 40, nr. 2, p. 768-775.

Antin, J. F. (2011). "*Design of the in-vehicle driving behavior and crash risk study: in support of the SHRP 2 naturalistic driving study*." Transportation Research Board, Washington, DC.

Archer, J. (2005). "*Indicators for traffic safety assessment and prediction and their application in micro-simulation modelling: A study of urban and suburban intersections*." Doctoral Thesis, Royal Institute of Technology.

Astarita, V., G. Guido, A. Vitale, and V. Giofré. (2012). "*A new microsimulation model for the evaluation of traffic safety performances.*" In: European Transport, vol. 2012, nr. 51, p. 1-16.

Banks, J., and M. Amin. (2003). "*Test of behavioral theory of multilane traffic flow: Queue and queue discharge flows.*" In: Transportation Research Record: Journal of the Transportation Research Board, nr. 1852, p. 159-166.

Banks, J. H., M. R. Amin, M. Cassidy, and K. Chung. (2003). "*Validation of Daganzo's behavioral theory of multi-lane traffic flow: final report*." California PATH.

Barceló, J., and J. Casas. (2005). "*Dynamic network simulation with AIMSUN*." Springer, p. 57-98.

Barceló, J., E. Codina, J. Casas, J. L. Ferrer, and D. García. (2004). "*Microscopic traffic simulation: A tool for the design, analysis and evaluation of intelligent transport systems.*" In: Journal of Intelligent and Robotic Systems, vol. 41, nr. 2, p. 173-203. doi: 10.1007/s10846-005-3808-2.

Bared, J. G., P. K. Edara, and T. Kim. (2006). "*Safety impact of interchange spacing on urban freeways*." Paper presented at the Compendium of Papers DVD, Annual Meeting of the Transportation Research Board, Washington, DC.

Bevrani, K., and E. Chung. (2012). "*An examination of the microscopic simulation models to identify traffic safety indicators.*" In: International Journal of Intelligent Transportation Systems Research, vol. 10, nr. 2, p. 66-81.

Bin, M., N. Uno, and Y. Iida. (2003). "*A study of lane-changing behavior model at weaving section considering conflicts.*" In: Journal of the Eastern Asia Society for Transportation Studies, vol. 5, p. 2039-2052.

Blanco, M., R. J. Hanowski, R. L. Olson, J. F. Morgan, S. A. Soccolich, S.-C. Wu, and F. Guo. (2011). "*The impact of driving, non-driving work, and rest breaks on driving performance in commercial motor vehicle operations*." Virginia Tech Transportation Institute.

Bonneson, J., and J. Ivan. (2013). "*Theory, explanation, and prediction in road safety: promising directions.*" In: Transportation Research E-Circular, nr. E-C179.

Brackstone, M., B. Sultan, and M. McDonald. (2002). "*Motorway driver behaviour: studies on car following.*" In: Transportation Research Part F: Traffic Psychology and Behaviour, vol. 5, nr. 1, p. 31-46.

Calvi, A., and M. R. De Blasiis. (2011). "*Driver behavior on acceleration lanes.*" In: Transportation Research Record: Journal of the Transportation Research Board, vol. 2248, nr. 1, p. 96-103.

Carter, M., H. Rakha, and M. V. Aerde. (1999). "*Variability of traffic-flow measures across freeway lanes.*" In: Canadian Journal of Civil Engineering, vol. 26, nr. 3, p. 270-281.

Cassidy, M. J., S. B. Anani, and J. M. Haigwood. (2002). "*Study of freeway traffic near an off-ramp.*" In: Transportation Research Part A: Policy and Practice, vol. 36, nr. 6, p. 563-572.

Cassidy, M. J., and J. Rudjanakanoknad. (2005). "*Increasing the capacity of an isolated merge by metering its on-ramp.*" In: Transportation Research Part B: Methodological, vol. 39, nr. 10, p. 896-913. doi: https://doi.org/10.1016/j.trb.2004.12.001.

Chen, D., and S. Ahn. (2018). "*Capacity-drop at extended bottlenecks: Merge, diverge, and weave.*" In: Transportation Research Part B: Methodological, vol. 108, p. 1-20. doi: https://doi.org/10.1016/j.trb.2017.12.006.

Chih-Sheng, C., and A. P. Nichols. (2015). "*Deriving a surrogate safety measure for freeway incidents based on predicted end-of-queue properties.*" In: Intelligent Transport Systems, IET, vol. 9, nr. 1, p. 22-29. doi: 10.1049/iet-its.2013.0199.

Choi, S., and C. Oh. (2016). "*Proactive strategy for variable speed limit operations on freeways under foggy weather conditions.*" In: Transportation Research Record: Journal of the Transportation Research Board, vol. 2551, p. 29-36. doi: 10.3141/2551-04.

Chong, L., M. M. Abbas, A. Medina Flintsch, and B. Higgs. (2013). "*A rule-based neural network approach to model driver naturalistic behavior in traffic.*" In: Transportation Research Part C: Emerging Technologies, vol. 32, p. 207-223. doi: http://dx.doi.org/10.1016/j.trc.2012.09.011.

Choudhury, C., V. Ramanujam, and M. Ben-Akiva. (2009). "*Modeling acceleration decisions for freeway merges.*" In: Transportation Research Record: Journal of the Transportation Research Board, vol. 2124, p. 45-57. doi: 10.3141/2124-05.

Choudhury, C. F. (2007). "*Modeling driving decisions with latent plans*." Doctoral Thesis, Massachusetts Institute of Technology.

Chung, K., J. Rudjanakanoknad, and M. J. Cassidy. (2007). "*Relation between traffic density and capacity drop at three freeway bottlenecks.*" In: Transportation Research Part B: Methodological, vol. 41, nr. 1, p. 82-95.

Coifman, B., and S. Kim. (2011). "*Extended bottlenecks, the fundamental relationship, and capacity drop on freeways.*" In: Transportation Research Part A: Policy and Practice, vol. 45, nr. 9, p. 980-991. doi: http://dx.doi.org/10.1016/j.tra.2011.04.003.

Coifman, B., S. Krishnamurthy, and X. Wang. (2005). "*Lane-change maneuvers consuming freeway capacity*." Springer, p. 3-14.

CROW. (2009). "*Utvraag herziening Nieuwe Ontwerprichtlijn Autosnelwegen (NOA).*"

Daamen, W., M. Loot, and S. P. Hoogendoorn. (2010). "*Empirical analysis of merging behavior at freeway on-ramp.*" In: Transportation Research Record: Journal of the Transportation Research Board, vol. 2188, nr. 1, p. 108-118.

Daganzo, C. F. (2002a). "*A behavioral theory of multi-lane traffic flow. Part I: Long homogeneous freeway sections.*" In: Transportation Research Part B: Methodological, vol. 36, nr. 2, p. 131-158. doi: http://dx.doi.org/10.1016/S0191-2615(00)00042-4.

Daganzo, C. F. (2002b). "*A behavioral theory of multi-lane traffic flow. Part II: Merges and the onset of congestion.*" In: Transportation Research Part B: Methodological, vol. 36, nr. 2, p. 159-169. doi: http://dx.doi.org/10.1016/S0191-2615(00)00043-6.

Davis, G. A., and T. Swenson. (2006). *"Collective responsibility for freeway rear-ending accidents?: An application of probabilistic causal models."* In: Accident Analysis & Prevention, vol. 38, nr. 4, p. 728-736.

De Ceunynck, T. (2017). "*Defining and applying surrogate safety measures and behavioural indicators through site-based observations*." Doctoral Thesis, Hasselt University and Lund University.

De Waard, D., C. Dijksterhuis, and K. A. Brookhuis. (2009). "*Merging into heavy motorway traffic by young and elderly drivers.*" In: Accident Analysis & Prevention, vol. 41, nr. 3, p. 588-597.

Dijker, T., and P. Knoppers. (2004). "*Fosim 5.0 user manual.*" In: Technical specification report, Delft University of Technology, Transport and Planning Department, Netherlands, ISSN, nr. 0920-0592.

Dijkstra, A. (2011). "*En route to safer roads: how road structure and road classification can affect road safety*." Doctoral Thesis, University of Twente.

Dijkstra, A., P. Marchesini, F. Bijleveld, V. Kars, H. Drolenga, and H. Van Maarseveen. (2010). "*Do calculated conflicts in microsimulation model predict number of crashes?*" In: Transportation Research Record: Journal of the Transportation Research Board, vol. 2147, p. 105-112. doi: 10.3141/2147-13.

DMRB. (1994). "*Design Manual for Roads and Bridges, Volume 6, Section 2, Part 4 'The design of major interchanges'.*" The Highways Agency, Transport Scotland, Transport Wales, The Department for Regional Development.

Duncan, G. (2000). *"Paramics technical report: car-following, lane-changing and junction modelling."* In: Tech. rep., Quadstone, Ltd., Edinburgh, Scotland.

Duret, A., S. Ahn, and C. Buisson. (2011). "*Passing rates to measure relaxation and impact of lane-changing in congestion.*" In: Computer-Aided Civil and Infrastructure Engineering, vol. 26, nr. 4, p. 285-297. doi: 10.1111/j.1467-8667.2010.00675.x.

El-Basha, R., Y. Hassan, and T. Sayed. (2007). "*Modeling freeway diverging behavior on deceleration lanes.*" In: Transportation Research Record: Journal of the Transportation Research Board, vol. 2012, p. 30-37. doi: 10.3141/2012-04.

Fan, R., H. Yu, P. Liu, and W. Wang. (2013). "*Using VISSIM simulation model and Surrogate Safety Assessment Model for estimating field measured traffic conflicts at freeway merge areas.*" In: IET Intelligent Transport Systems, vol. 7, nr. 1, p. 68-77. doi: 10.1049/iet-its.2011.0232.

Farah, H., S. Bekhor, and A. Polus. (2009). "*Risk evaluation by modeling of passing behavior on two-lane rural highways.*" In: Accident Analysis & Prevention, vol. 41, nr. 4, p. 887-894.

Fellendorf, M., and P. Vortisch. (2010). "*Microscopic traffic flow simulator VISSIM.*" Springer, New York, NY, p. 63-93.

Fitzpatrick, K., R. Porter, G. Pesti, C.-L. Chu, E. Park, and T. Le. (2011). "*Guidelines for spacing between freeway ramps.*" In: Transportation Research Record: Journal of the Transportation Research Board, nr. 2262, p. 3-12.

Fritzsche, H.-T. (1994). "*Amodel for traffic simulation.*" In: Traffic Engineering and Control, vol. 35, p. 317-321.

Garber, N. J., and A. A. Ehrhart. (2000). "*Effect of speed, flow, and geometric characteristics on crash frequency for two-lane highways.*" In: Transportation Research Record: Journal of the Transportation Research Board, vol. 1717, nr. 1, p. 76-83.

Garber, N. J., and M. Fontaine. (1999). "*Final report-guidelines for preliminary selection of the optimum interchange type for a specific location.*" In: Virginia Transportation Research Council.

Gazis, D. C., R. Herman, and R. W. Rothery. (1961). "*Nonlinear follow-the-leader models of traffic flow.*" In: Operations Research, vol. 9, nr. 4, p. 545-567.

Gazis, D. C., R. Herman, and R. W. Rothery. (1963). "*Analytical methods in transportation: Mathematical car-following theory of traffic flow.*" In: Journal of Engineering Mechanics, vol. 89, nr. EM6.

Gettman, D., and L. Head. (2003). "*Surrogate safety measures from traffic simulation models.*" In: Transportation Research Record: Journal of the Transportation Research Board, vol. 1840, nr. 1, p. 104-115.

Gettman, D., L. Pu, T. Sayed, and S. G. Shelby. (2008). "*Surrogate safety assessment model and validation*." Siemens Energy & Automation.

Gipps, P. G. (1981). "*A behavioural car-following model for computer simulation.*" In: Transportation Research Part B: Methodological, vol. 15, nr. 2, p. 105-111. doi: http://dx.doi.org/10.1016/0191-2615(81)90037-0.

Gipps, P. G. (1986). "*A model for the structure of lane-changing decisions.*" In: Transportation Research Part B: Methodological, vol. 20, nr. 5, p. 403-414.

Goh, K., G. Currie, M. Sarvi, and D. Logan. (2013). "*Exploring bus lane safety impacts using traffic microsimulation*." Paper presented at the Australasian Transport Research Forum (ATRF), 36th, 2013, Brisbane, Queensland, Australia.

Golob, T. F., W. W. Recker, and V. M. Alvarez. (2004). "*Freeway safety as a function of traffic flow.*" In: Accident Analysis & Prevention, vol. 36, nr. 6, p. 933-946.

Guido, G., F. Saccomanno, A. Vitale, V. Astarita, and D. Festa. (2010). "*Comparing safety performance measures obtained from video capture data.*" In: Journal of transportation engineering, vol. 137, nr. 7, p. 481-491.

Guo, Y. Q. (2012). "*The relationship between freeway safety and geometric design elements.*" In: Advanced Materials Research, vol. 424, p. 215-219.

Habtemichael, F., and L. De Picado Santos. (2013). "*Safety and operational benefits of variable speed limits under different traffic conditions and driver compliance levels.*" In: Transportation Research Record: Journal of the Transportation Research Board, vol. 2386, p. 7-15. doi: 10.3141/2386-02.

Habtemichael, F. G., and L. de Picado Santos. (2014). "*Crash risk evaluation of aggressive driving on motorways: Microscopic traffic simulation approach.*" In: Transportation Research Part F: Traffic Psychology and Behaviour, vol. 23, p. 101-112. doi: https://doi.org/10.1016/j.trf.2013.12.022.

Halati, A., H. Lieu, and S. Walker. (1997). "*CORSIM-corridor traffic simulation model.*" Paper presented at the Traffic congestion and traffic safety in the 21st century: Challenges, innovations, and opportunities.

Hamdar, S. H., H. S. Mahmassani, and M. Treiber. (2015). "*From behavioral psychology to acceleration modeling: Calibration, validation, and exploration of drivers' cognitive and safety parameters in a risk-taking environment.*" In: Transportation Research Part B: Methodological, vol. 78, p. 32-53. doi: http://dx.doi.org/10.1016/j.trb.2015.03.011.

Hayward, J. C. (1972). "*Near miss determination through use of a scale of danger.*" In: Highway Research Record, nr. 384, p. 24-34.

HCM. (2000). "*Highway Capacity Manual.*" Transportation Research Board.

HCM. (2010). "*Highway Capacity Manual.*" Transportation Research Board.

Hidas, P. (2005). "*Modelling vehicle interactions in microscopic simulation of merging and weaving.*" In: Transportation Research Part C: Emerging Technologies, vol. 13, nr. 1, p. 37-62.

Hill, C., L. Elefteriadou, and A. Kondyli. (2015). "*Exploratory analysis of lane changing on freeways based on driver behavior.*" In: Journal of transportation engineering, vol. 141, nr. 4. doi: doi:10.1061/(ASCE)TE.1943-5436.0000758.

Hogema, J., and W. Janssen. (1996). "*Effects of intelligent cruise control on driving behaviour: a simulator study.*" TNO.

Holm, P., D. Tomich, J. Sloboden, and C. Lowrance. (2007). "*Traffic analysis toolbox volume iv: guidelines for applying corsim microsimulation modeling software.*" ITT Industries.

Hoogendoorn, S., R. G. Hoogendoorn, and W. Daamen. (2011). "*Wiedemann Revisited.*" In: Transportation Research Record: Journal of the Transportation Research Board, vol. 2260, nr. 1, p. 152-162.

Hoogendoorn, S. P., and P. H. Bovy. (2001). "*State-of-the-art of vehicular traffic flow modelling.*" In: Proceedings of the Institution of Mechanical Engineers, Part I: Journal of Systems and Control Engineering, vol. 215, nr. 4, p. 283-303.

Hoogendoorn, S. P., H. Van Zuylen, M. Schreuder, B. Gorte, and G. Vosselman. (2003). "*Traffic data collection from aerial imagery.*" Paper presented at the CTS2003, 10th IFAC symposium on control in transportation systems.

Hovenga, M. (2014). "*Measuring turbulence distance of acceleration lanes.*" MSc Thesis, Delft University of Technology.

HSM. (2010). "*Highway Safety Manual.*" American Association of state highway and Transportation Officials (AASHTO).

Hydén, C. (1987). "*The development of a method for traffic safety evaluation: The Swedish Traffic Conflicts Technique.*" In: Bulletin Lund Institute of Technology, Department, nr. 70.

Kesting, A., and M. Treiber. (2008). "*Calibrating car-following models by using trajectory data: Methodological study.*" In: Transportation Research Record: Journal of the Transportation Research Board, vol. 2088, nr. 1, p. 148-156.

Kesting, A., M. Treiber, and D. Helbing. (2007). "*General lane-changing model MOBIL for car-following models.*" In: Transportation Research Record: Journal of the Transportation Research Board, vol. 1999, nr. 1, p. 86-94.

Khorashadi, A. (1998). "*Effect of ramp type and geometry on accidents.*" California Department of Transportation.

Kim, S., and B. Coifman. (2013). "*Driver relaxation impacts on bottleneck activation, capacity, and the fundamental relationship.*" In: Transportation Research Part C: Emerging Technologies, vol. 36, p. 564-580. doi: https://doi.org/10.1016/j.trc.2013.06.016.

Kita, H. (1999). "*A merging–giveway interaction model of cars in a merging section: a game theoretic analysis.*" In: Transportation Research Part A: Policy and Practice, vol. 33, nr. 3, p. 305-312.

Knoop, V., M. Keyvan-Ekbatani, M. De Baat, H. Taale, and S. Hoogendoorn. (2017). "*Strategy-based driving behaviour on freeways: findings of test-drive and on-line survey study.*" Delft University of Technology.

Knoop, V. L., A. Duret, C. Buisson, and B. Van Arem. (2010). "*Lane distribution of traffic near merging zones influence of variable speed limits.*" Paper presented at the 13th International IEEE Conference on Intelligent Transportation Systems, Madeira Island, Portugal.

Kondyli, A., and L. Elefteriadou. (2009). "*Driver behavior at freeway-ramp merging areas.*" In: Transportation Research Record: Journal of the Transportation Research Board, vol. 2124, nr. 1, p. 157-166.

Kondyli, A., and L. Elefteriadou. (2011). "*Modeling driver behavior at freeway-ramp merges.*" In: Transportation Research Record: Journal of the Transportation Research Board, vol. 2249, nr. 1, p. 29-37.

Kondyli, A., and L. Elefteriadou. (2012). "*Driver behavior at freeway-ramp merging areas based on instrumented vehicle observations.*" In: Transportation Letters, vol. 4, nr. 3, p. 129-142.

Koutsopoulos, H. N., and H. Farah. (2012). "*Latent class model for car following behavior.*" In: Transportation research part B: methodological, vol. 46, nr. 5, p. 563-578.

Kraay, J., and A. Van der Horst. (1985). "*The trautenfels study: a diagnosis of road safety using the dutch conflict observation technique doctor.*" Institute for Road Safety Research SWOV.

Kusuma, A., R. Liu, C. Choudhury, and F. Montgomery. (2015). "*Lane-changing characteristics at weaving section.*" Paper presented at the Transportation Research Board 94th Annual Meeting.

Laureshyn, A., Å. Svensson, and C. Hydén. (2010). "*Evaluation of traffic safety, based on micro-level behavioural data: Theoretical framework and first implementation.*" In: Accident Analysis & Prevention, vol. 42, nr. 6, p. 1637-1646.

Laval, J. A. (2011). "*Hysteresis in traffic flow revisited: An improved measurement method.*" In: Transportation Research Part B: Methodological, vol. 45, nr. 2, p. 385-391. doi: http://dx.doi.org/10.1016/j.trb.2010.07.006.

Laval, J. A., and C. F. Daganzo. (2006). "*Lane-changing in traffic streams.*" In: Transportation Research Part B: Methodological, vol. 40, nr. 3, p. 251-264.

Laval, J. A., and L. Leclercq. (2008). "*Microscopic modeling of the relaxation phenomenon using a macroscopic lane-changing model.*" In: Transportation Research Part B: Methodological, vol. 42, nr. 6, p. 511-522.

Laval, J. A., and L. Leclercq. (2010). "*A mechanism to describe the formation and propagation of stop-and-go waves in congested freeway traffic.*" In: Philosophical Transactions of the Royal Society of London A: Mathematical, Physical and Engineering Sciences, vol. 368, nr. 1928, p. 4519-4541.

Leclercq, L., V. L. Knoop, F. Marczak, and S. P. Hoogendoorn. (2016). "*Capacity drops at merges: New analytical investigations.*" In: Transportation Research Part C: Emerging Technologies, vol. 62, p. 171-181. doi: https://doi.org/10.1016/j.trc.2015.06.025.

Lee, C., and M. Abdel-Aty. (2008). "*Two-level nested logit model to identify traffic flow parameters affecting crash occurrence on freeway ramps.*" In: Transportation Research Record: Journal of the Transportation Research Board, vol. 2083, p. 145-152. doi: doi:10.3141/2083-17.

Lee, C., and M. Abdel-Aty. (2009). "*Analysis of crashes on freeway ramps by location of crash and presence of advisory speed signs.*" In: Journal of Transportation Safety & Security, vol. 1, nr. 2, p. 121-134.

Lee, C., B. Hellinga, and F. Saccomanno. (2003a). "*Proactive freeway crash prevention using real-time traffic control.*" In: Canadian Journal of Civil Engineering, vol. 30, nr. 6, p. 1034-1041.

Lee, C., B. Hellinga, and F. Saccomanno. (2003b). "*Real-time crash prediction model for the application to crash prevention in freeway traffic.*" In: Transportation Research Board, vol. 82, p. 21.

Lee, C., B. Hellinga, and F. Saccomanno. (2004). "*assessing safety benefits of variable speed limits.*" In: Transportation Research Record: Journal of the Transportation Research Board, vol. 1897, p. 183-190. doi: 10.3141/1897-24.

Lee, C., F. F. Saccomanno, and B. Hellinga. (2002). "*Analysis of crash precursors on instrumented freeways.*" In: Transportation Research Record: Journal of the Transportation Research Board, vol. 1784, p. 1-8. doi: 10.3141/1784-01.

Li, S., Q. Xiang, Y. Ma, X. Gu, and H. Li. (2016). "*Crash risk prediction modeling based on the traffic conflict technique and a microscopic simulation for freeway interchange merging areas.*" In: International Journal of Environmental Research and Public Health, vol. 13, nr. 11, p. 1157.

Li, Z., S. Ahn, K. Chung, D. R. Ragland, W. Wang, and J. W. Yu. (2014). "*Surrogate safety measure for evaluating rear-end collision risk related to kinematic waves near freeway recurrent bottlenecks.*" In: Accident Analysis & Prevention, vol. 64, p. 10.

Lord, D., and F. Mannering. (2010). "*The statistical analysis of crash-frequency data: a review and assessment of methodological alternatives.*" In: Transportation Research Part A: Policy and Practice, vol. 44, nr. 5, p. 291-305.

Louah, G., D. Daucher, P. Conde-Céspedes, F. Bosc, and J.-P. Lhuillier. (2011). "*Traffic operations at an entrance ramp of a suburban freeway first results.*" In: Procedia-Social and Behavioral Sciences, vol. 16, p. 162-171.

Lownes, N., and R. Machemehl. (2006). "*Sensitivity of simulated capacity to modification of VISSIM driver behavior parameters.*" In: Transportation Research Record: Journal of the Transportation Research Board, vol. 1988, p. 102-110. doi: 10.3141/1988-15.

Lunenfeld, H. (1993). "*Human factors associated with interchange design features.*" In: Transportation Research Record, vol. 1385, p. 84-89.

Mahmud, S. M. S., L. Ferreira, M. S. Hoque, and A. Tavassoli. (2017). "*Application of proximal surrogate indicators for safety evaluation: A review of recent developments and research needs.*" In: IATSS Research, vol. 41, nr. 4, p. 153-163.
doi: https://doi.org/10.1016/j.iatssr.2017.02.001.

Marczak, F., and C. Buisson. (2014). "*Analytical derivation of capacity at diverging junctions.*" In: Transportation Research Record: Journal of the Transportation Research Board, vol. 2422, p. 88-95. doi: 10.3141/2422-10.

Marczak, F., and C. Buisson. (2015). "*A macroscopic model for freeway weaving sections.*" In: Computer-Aided Civil and Infrastructure Engineering, vol. 30, nr. 6, p. 464-477.

Marczak, F., W. Daamen, and C. Buisson. (2013). "*Key variables of merging behaviour: empirical comparison between two sites and assessment of gap acceptance theory.*" In: Procedia-Social and Behavioral Sciences, vol. 80, p. 678-697.

Marczak, F., W. Daamen, and C. Buisson. (2014). "*Empirical analysis of lane changing behavior at a freeway weaving section*." Paper presented at the Transportation Research Board 93rd Annual Meeting.

Martínez, M. P., A. Garcia, and A. T. Moreno. (2011). "*Traffic microsimulation study to evaluate freeway exit ramps capacity.*" In: Procedia - Social and Behavioral Sciences, vol. 16, nr. 0, p. 139-150. doi: http://dx.doi.org/10.1016/j.sbspro.2011.04.437.

Mathew, T. V., and P. Radhakrishnan. (2010). "*Calibration of microsimulation models for nonlane-based heterogeneous traffic at signalized intersections.*" In: Journal of Urban Planning and Development, vol. 136, nr. 1, p. 59-66. doi: doi:10.1061/(ASCE)0733-9488(2010)136:1(59).

McDonald, M., J. Wu, and M. Brackstone. (1997). "*Development of a fuzzy logic based microscopic motorway simulation model.*" In: Proceedings of Intelligent Transportation Systems Council, Institute of Electrical and Electronics Engineers.

McKay, M. D., R. J. Beckman, and W. J. Conover. (1979). "*Comparison of three methods for selecting values of input variables in the analysis of output from a computer code.*" In: Technometrics, vol. 21, nr. 2, p. 239-245. doi: 10.1080/00401706.1979.10489755.

Michaels, R. (1963). "*Perceptual factors in car following*." Paper presented at the Proceedings of the 2nd International Symposium on the Theory of Road Traffic Flow, London, England.

Minderhoud, M. M. (1999). "*Supported driving: impacts on motorway traffic flow*." Doctoral Thesis, Delft University of Technology.

Minderhoud, M. M., and P. H. Bovy. (2001). "*Extended time-to-collision measures for road traffic safety assessment.*" In: Accident Analysis & Prevention, vol. 33, nr. 1, p. 89-97.

MIT. (2018). "*MITSIMlab web page*." Accessed Jan. 16, 2018. https://its.mit.edu/software/mitsimlab.

MOTUS. (2018). "*MOTUS*." Accessed Jan. 24, 2018. http://homepage.tudelft.nl/05a3n/.

Muñoz, J. C., and C. F. Daganzo. (2002). "*The bottleneck mechanism of a freeway diverge.*" In: Transportation Research Part A: Policy and Practice, vol. 36, nr. 6, p. 483-505. doi: http://dx.doi.org/10.1016/S0965-8564(01)00017-9.

NCHRP. (2012). "*Design guidance for freeway mainline ramp terminals*." Transportation Research Board, Washington, DC.

NDS. "*NDS website*." Accessed 12-10-2015. http://www.trb.org/StrategicHighwayResearchProgram2SHRP2/Blank2.aspx.

NDW. "*NDW website*." Accessed 21-12-2015. http://ndw.dysi.nl/.

Nezamuddin, N., N. Jiang, J. Ma, T. Zhang, and S. T. Waller. (2011). "*Active traffic management strategies: Implications for freeway operations and traffic safety*." Paper presented at the 90th annual meeting of the Transportation Research Board.

Ngoduy, D. (2008). "*Operational effects of acceleration lane on main traffic flow at discontinuities.*" In: Transportmetrica, vol. 4, nr. 3, p. 195-207. doi: 10.1080/18128600808685687.

NGSIM. "*NGSIM website*." Accessed 22-06-2015. http://ngsim-community.org/.

Oh, C., and T. Kim. (2010). "*Estimation of rear-end crash potential using vehicle trajectory data.*" In: Accident Analysis & Prevention, vol. 42, nr. 6, p. 1888-1893.

Olson, R. L., R. J. Hanowski, J. S. Hickman, and J. L. Bocanegra. (2009). "*Driver distraction in commercial vehicle operations*." Virginia Tech Transportation Institute.

Pan, T. L., W. H. K. Lam, A. Sumalee, and R. X. Zhong. (2016). "*Modeling the impacts of mandatory and discretionary lane-changing maneuvers.*" In: Transportation Research Part C: Emerging Technologies, vol. 68, p. 403-424. doi: https://doi.org/10.1016/j.trc.2016.05.002.

Park, B., and H. Qi. (2005). "*Development and evaluation of a procedure for the calibration of simulation models.*" In: Transportation Research Record: Journal of the Transportation Research Board, vol. 1934, p. 208-217. doi: 10.3141/1934-22.

Park, H., C. Oh, J. Moon, and S. Kim. (2018). "*Development of a lane change risk index using vehicle trajectory data.*" In: Accident Analysis & Prevention, vol. 110, p. 1-8. doi: https://doi.org/10.1016/j.aap.2017.10.015.

Piao, J., and M. McDonald. (2008). "*Safety impacts of variable speed limits-a simulation study*." Paper presented at the 11th International IEEE Conference on Intelligent Transportation Systems.

Pilko, P., J. Bared, P. Edara, and T. Kim. (2007). "*Safety assessment of interchange spacing on urban freeways.*" In: Tech Brief.

PTV. (2017). "*PTV VISSIM 10 user manual*." PTV, Karlsruhe Germany.

Punzo, V., M. Montanino, and B. Ciuffo. (2015). "*Do we really need to calibrate all the parameters? Variance-based sensitivity analysis to simplify microscopic traffic flow models.*" In: IEEE Transactions on Intelligent Transportation Systems, vol. 16, nr. 1, p. 184-193. doi: 10.1109/TITS.2014.2331453.

RAA. (2008). "*Richtlinie für die anlage von autobahnen*." Forschungsgesellschaft für strassen- and Verkehrswesen (FGSV).

Rahman, M., M. Chowdhury, Y. Xie, and Y. He. (2013). "*Review of microscopic lane-changing models and future research opportunities.*" In: IEEE Transactions on Intelligent Transportation Systems, vol. 14, nr. 4, p. 1942-1956.

Reason, J., E. Hollnagel, and J. Paries. (2006). "*Revisiting the Swiss cheese model of accidents*." European Organisation for the Safety of Air Navigation.

Rijkswaterstaat. (1975). "*Richtlijnen voor het Ontwerpen van Autosnelwegen.*"

Rijkswaterstaat. (1992). "*Richtlijnen voor het Ontwerpen van Autosnelwegen.*"

Rijkswaterstaat. (2004). "*Ondernemingsplan 2004-2008.*"

Rijkswaterstaat. (2007). "*Nieuwe Ontwerprichtlijn Autosnelwegen.*"

Rijkswaterstaat. (2017). "*Richtlijn Ontwerp Autosnelwegen 2017.*"

Roshandel, S., Z. Zheng, and S. Washington. (2015). "*Impact of real-time traffic characteristics on freeway crash occurrence: Systematic review and meta-analysis.*" In: Accident Analysis & Prevention, vol. 79, p. 198-211. doi: http://dx.doi.org/10.1016/j.aap.2015.03.013.

RVV. (1990). "*Reglement verkeersregels en verkeerstekens*." The Netherlands.

Saleem, T., B. Persaud, A. Shalaby, and A. Ariza. (2014). "*Can microsimulation be used to estimate intersection safety?*" In: Transportation Research Record: Journal of the Transportation Research Board, vol. 2432, p. 142-148. doi: 10.3141/2432-17.

Schakel, W., B. van Arem, H. van Lint, and G. Tamminga. (2013). "*A modular approach for exchangeable driving task models in a microscopic simulation framework*." Paper presented at the 16th International IEEE Conference on Intelligent Transportation Systems.

Schakel, W. J. (2015). "*Development, simulation and evaluation of In-car advice on headway, speed and lane*." Doctoral Thesis, Delft University of Technology.

Schakel, W. J., V. L. Knoop, and B. van Arem. (2012). "*Integrated lane change model with relaxation and synchronization.*" In: Transportation Research Record: Journal of the Transportation Research Board, vol. 2316, nr. 1, p. 47-57.

Shahdah, U., F. Saccomanno, and B. Persaud. (2014). "*Integrated traffic conflict model for estimating crash modification factors.*" In: Accident Analysis & Prevention, vol. 71, p. 228-235. doi: https://doi.org/10.1016/j.aap.2014.05.019.

Sharma, S., and I. Chatterjee. (2007). "*Performance evaluation of the diverging diamond interchange in comparison with the conventional diamond interchange*." Paper presented at the Transportation Scholars Conference, Iowa State University, Ames.

Shi, Q., and M. Abdel-Aty. (2015). "*Big Data applications in real-time traffic operation and safety monitoring and improvement on urban expressways.*" In: Transportation Research Part C: Emerging Technologies, vol. 58, Part B, p. 380-394. doi: http://dx.doi.org/10.1016/j.trc.2015.02.022.

Smith, S. A. (1985). "*Freeway data collection for studying vehicle interactions -appendices H and I.*" US Department of Transportation, Federal Highway Administration, Washington, DC.

Sparmann, U. (1979). "*The importance of lane-changing on motorways.*" In: Traffic engineering & control, vol. 20, nr. 6.

Sultan, B., M. Brackstone, B. Waterson, and E. Boer. (2002). "*Modeling the dynamic cut-in situation.*" In: Transportation Research Record: Journal of the Transportation Research Board, nr. 1803, p. 45-51.

Sun, D., and L. Elefteriadou. (2010). "*Research and implementation of lane-changing model based on driver behavior.*" In: Transportation Research Record: Journal of the Transportation Research Board, vol. 2161, p. 1-10. doi: 10.3141/2161-01.

Sun, D. J., and A. Kondyli. (2010). "*Modeling vehicle interactions during lane-changing behavior on arterial streets.*" In: Computer-Aided Civil and Infrastructure Engineering, vol. 25, nr. 8, p. 557-571.

Svensson, Å. (1998). "*A method for analysing the traffic process in a safety perspective*." Doctoral Thesis, Lund University.

Tang, T.-Q., H.-J. Huang, S. C. Wong, Z.-Y. Gao, and Y. Zhang. (2009). "*A new macro model for traffic flow on a highway with ramps and numerical tests.*" In: Communications in Theoretical Physics, vol. 51, nr. 1, p. 71-78.

Tang, T.-Q., H.-J. Huang, G. Xu, and Y. Zhang. (2008). "*Wave properties of a traffic flow model on highway with ramps.*" In: EPL (Europhysics Letters), vol. 84, nr. 1, p. 14006.

Tarko, A., G. Davis, N. Saunier, T. Sayed, and S. Washington. (2009). "*Surrogate measures of safety.*" In: White paper, ANB20 (3) Subcommittee on Surrogate Measures of Safety.

Tarko, A. P. (2012). "*Use of crash surrogates and exceedance statistics to estimate road safety.*" In: Accident Analysis & Prevention, vol. 45, p. 230-240.

Toledo, T. (2003). "*Integrated driving behavior modeling*." Doctoral Thesis, Massachusetts Institute of Technology.

Toledo, T., C. F. Choudhury, and M. E. Ben-Akiva. (2005). "*Lane-changing model with explicit target lane choice.*" In: Transportation Research Record: Journal of the Transportation Research Board, vol. 1934, nr. 1, p. 157-165.

Toledo, T., H. N. Koutsopoulos, and K. I. Ahmed. (2007). "*Estimation of vehicle trajectories with locally weighted regression.*" In: Transportation Research Record: Journal of the Transportation Research Board, vol. 1999, nr. 1, p. 161-169.

Toledo, T., H. N. Koutsopoulos, and M. Ben-Akiva. (2007). "*Integrated driving behavior modeling.*" In: Transportation Research Part C: Emerging Technologies, vol. 15, nr. 2, p. 96-112.

Toledo, T., H. N. Koutsopoulos, and M. Ben-Akiva. (2009). "*Estimation of an integrated driving behavior model.*" In: Transportation Research Part C: Emerging Technologies, vol. 17, nr. 4, p. 365-380.

Treiber, M., A. Hennecke, and D. Helbing. (2000). "*Congested traffic states in empirical observations and microscopic simulations.*" In: Physical Review E, vol. 62, nr. 2, p. 1805.

Uittenbogerd, P., and A. Van Beinum. (2010). "*Wittevlekkenlijst ROA2010.*" Witteveen+Bos.

Uno, N., Y. Iida, S. Itsubo, and S. Yasuhara. (2002). "*A microscopic analysis of traffic conflict caused by lane-changing vehicle at weaving section.*" Paper presented at the 13th Mini-Euro Conference" Handling Uncertainty in Transportation Analysis of Traffic and Transportation Systems.

Van Beinum, A. (2018). "*Empirical trajectory data.*" Delft University of Technology. doi: https://doi.org/10.4121/uuid:6be1aefa-0803-4ce2-91b2-caaa7982abcd.

Van Beinum, A., H. Farah, F. Wegman, and S. Hoogendoorn. (2016). "*Critical assessment of methodologies for operations and safety evaluations of freeway turbulence.*" In: Transportation Research Record: Journal of the Transportation Research Board, vol. 2556, p. 39-48. doi: 10.3141/2556-05.

Van Beinum, A., H. Farah, F. Wegman, and S. Hoogendoorn. (2018). "*Driving behaviour at motorway ramps and weaving segments based on empirical trajectory data.*" In: Transportation Research Part C: Emerging Technologies, vol. 92, p. 426-441. doi: https://doi.org/10.1016/j.trc.2018.05.018.

Van Beinum, A., M. Hovenga, V. Knoop, H. Farah, F. Wegman, and S. Hoogendoorn. (2017). "*Macroscopic traffic flow changes around ramps.*" In: Transportmetrica A: Transport Science, p. 1-32. doi: 10.1080/23249935.2017.1415997.

Van Lint, H., W. Schakel, G. Tamminga, P. Knoppers, and A. Verbraeck. (2016). "*Getting the human factor into traffic flow models.*" In: Transportation Research Record: Journal of the Transportation Research Board, vol. 2561, p. 25-33. doi: 10.3141/2561-04.

Van Winsum, W., and A. Heino. (1996). "*Choice of time-headway in car-following and the role of time-to-collision information in braking.*" In: Ergonomics, vol. 39, nr. 4, p. 579-592.

Voorrips, R. (2013). "*Freeway work zone driving behaviour - the influence of work zone configurations.*" MSc Thesis, TUDelft.

Wan, X., P. J. Jin, and B. Ran. (2014). "*Modeling vehicle interactions during freeway ramp merging in congested weaving section.*" Paper presented at the Transportation Research Board 93rd Annual Meeting.

Wang, X., M. Hadiuzzaman, T. Z. Qiu, and X. Yan. (2014). "*Sensitivity analysis of freeway capacity at a complex weaving segment.*" Changsha, China.

Wegman, F. (2010). "*De prijs van water bij de wijn [The price of making a compromise] - Inaugural lecture.*" Delft University of Technology.

Wegman, F., L. Aarts, and C. Bax. (2008). "*Advancing sustainable safety: National road safety outlook for The Netherlands for 2005–2020.*" In: Safety Science, vol. 46, nr. 2, p. 323-343. doi: http://dx.doi.org/10.1016/j.ssci.2007.06.013.

Wiedemann, R. (1974). "*Simulation des Straßenverkehrsflusses.*" Doctoral Thesis, Univ., Inst. für Verkehrswesen.

Wiedemann, R. (1991). "*Modelling of RTI-elements on multi-lane roads.*" In: Advanced telematics in road transport., vol. II.

Willmann, G. (1978). "*Zustandsformen des Verkehrsablaufs auf Autobahnen.*" In: Schriftenr Inst Verkehrswes Univ Karlsruhe, nr. 19.

Wu, J., M. Brackstone, and M. McDonald. (2003). "*The validation of a microscopic simulation model: A methodological case study.*" In: Transportation Research Part C: Emerging Technologies, vol. 11, nr. 6, p. 463-479. doi: 10.1016/j.trc.2003.05.001.

Xin, W., J. Hourdos, P. Michalopoulos, and G. Davis. (2008). "*The less-than-perfect driver: a model of collision-inclusive car-following behavior.*" In: Transportation Research Record: Journal of the Transportation Research Board, vol. 2088, nr. 1, p. 126-137.

Xu, C., P. Liu, W. Wang, and Z. Li. (2012). "*Evaluation of the impacts of traffic states on crash risks on freeways.*" In: Accident Analysis & Prevention, vol. 47, p. 162-171.

Yang, Q. I., and H. N. Koutsopoulos. (1996). "*A microscopic traffic simulator for evaluation of dynamic traffic management systems.*" In: Transportation Research Part C: Emerging Technologies, vol. 4, nr. 3, p. 113-129.
doi: http://dx.doi.org/10.1016/S0968-090X(96)00006-X.

Yao, R., Q. Xiang, X. Gu, Y. Guo, and T. Zhang. (2017). "*Safety assessment of auxiliary lanes in freeway interchange weaving areas based on traffic conflict technique.*" In: MATEC Web Conf., vol. 124, p. 04005.

Young, W., A. Sobhani, M. G. Lenné, and M. Sarvi. (2014). "*Simulation of safety: A review of the state of the art in road safety simulation modelling.*" In: Accident Analysis & Prevention, vol. 66, p. 89-103.

Zhang, L., S. Cai, Y. Zhang, and M. Zhang. (2010). "*Comparison of lane changing algorithms between NGSIM and CORSIM.*" Paper presented at the 71st Vehicular Technology Conference, 16-19 May 2010.

Zheng, L., K. Ismail, and X. Meng. (2014a). "*Freeway safety estimation using extreme value theory approaches: A comparative study.*" In: Accident Analysis & Prevention, vol. 62, p. 32-41.

Zheng, L., K. Ismail, and X. Meng. (2014b). "*Traffic conflict techniques for road safety analysis: open questions and some insights.*" In: Canadian Journal of Civil Engineering, vol. 41, nr. 7, p. 633-641. doi: 10.1139/cjce-2013-0558.

Zheng, Z. (2014). "*Recent developments and research needs in modeling lane changing.*" In: Transportation Research Part B: Methodological, vol. 60, p. 16-32.
doi: http://dx.doi.org/10.1016/j.trb.2013.11.009.

Zheng, Z., S. Ahn, D. Chen, and J. Laval. (2011a). "*Applications of wavelet transform for analysis of freeway traffic: Bottlenecks, transient traffic, and traffic oscillations.*" In: Transportation Research Part B: Methodological, vol. 45, nr. 2, p. 372-384.
doi: http://dx.doi.org/10.1016/j.trb.2010.08.002.

Zheng, Z., S. Ahn, D. Chen, and J. Laval. (2011b). "*Freeway traffic oscillations: Microscopic analysis of formations and propagations using Wavelet Transform.*" In: Transportation Research Part B: Methodological, vol. 45, nr. 9, p. 1378-1388.
doi: http://dx.doi.org/10.1016/j.trb.2011.05.012.

Zheng, Z., S. Ahn, D. Chen, and J. Laval. (2013). "*The effects of lane-changing on the immediate follower: Anticipation, relaxation, and change in driver characteristics.*" In: Transportation Research Part C: Emerging Technologies, vol. 26, p. 367-379.
doi: https://doi.org/10.1016/j.trc.2012.10.007.

Summary

In the vicinity of motorway ramps, multiple manoeuvres are performed by drivers that are entering or exiting the motorway, and by drivers that anticipate on, or cooperate with, the other entering and exiting vehicles. These manoeuvres involve lane-changes, changes in speed, and changes in headways. This results in changes in lane flow distribution, greater speed variability and changes in headway distribution on the different lanes, with presumably a greater share of small gaps on the outside lane. In literature and motorway design guidelines, this phenomenon is referred to as turbulence. Currently, an explicit definition for turbulence is unavailable. In this thesis, therefore, an explicit definition for turbulence is introduced: "*individual changes in speed, headways, and lanes (i.e. lane-changes) in a certain road segment, regardless of the cause of change*". Turbulence is expected to be present in the traffic stream at any given time, and therefore a second definition is introduced: the level of turbulence, which is defined as: "*the frequency and intensity of individual changes in speed, headways and lane-changes in a certain road segment, over a certain period of time*".

A raised level of turbulence is expected around motorway ramps, and is expected to have a negative impact on traffic operations and traffic safety. In free flow conditions, the level of turbulence is expected to increase a few hundred meters upstream of a ramp, and expected to dissolve a few hundred meters downstream of the ramp. According to current motorway design guidelines, turbulence has to be taken into account for the length of weaving segments and the distance between succeeding ramps (i.e. ramp spacing).

In different countries, different approaches for dealing with turbulence are used in motorway design guidelines (AASHTO 2011; RAA 2008; HCM 2010; Rijkswaterstaat 2017; DMRB 1994). To the best of our knowledge, there is only one example available in literature, that describes the start and the end of a raised level of turbulence (Kondyli and Elefteriadou 2012). Furthermore, the current guidelines do not indicate the implications on traffic operations and traffic safety when deviating from the guidelines.

Therefore, there currently are two major problems when applying current motorway design guidelines with respect to turbulence:

- a solid theoretical and empirical underpinning regarding the required length for a raised level of turbulence is lacking;
- a thorough understanding of (quantitative) implications in terms of the impacts on traffic operations and traffic safety, when deviating from the motorway design guidelines, is missing.

The first and primary goal of this thesis is to gain empirical knowledge about the characteristics of turbulence. From a motorway design perspective, knowledge is desired especially of the distance from a discontinuity, where turbulence starts and dissolves, and knowledge of the manner in which driving behaviour near ramps and weaving segments is affected by the road design and the amount of traffic. The secondary goal of this thesis is to provide a tool to assess the level of turbulence, resulting from a specific motorway design, and its impact on traffic operations and traffic safety.

In this thesis it was found that the most relevant measure to indicate turbulence is the intensity and location of lane-changes. Changes in speed and headways were found to be limited. Most lane-changes were found to be located within a close proximity of the ramp gore. Only a limited amount of lane-changes were performed further upstream or downstream of a ramp. For on-ramps it was found that 4-9% of all lane-changes involved motorway drivers that anticipated on entering traffic, by changing lanes towards the inside of the motorway, at about 25-100 m upstream of the on-ramp, in order to avoid or to give room to entering vehicles. Drivers performed additional lane-changes towards the inside of the motorway (secondary merge) and towards the outside of the motorway (keeping right) until approximately 475-575 m downstream of the on-ramp. For off-ramps it was found that most exiting drivers (86%) were already driving on the outside lane at the earliest start of the measured area (750 m upstream of the off-ramp). Drivers started to pre-allocate upstream of the off-ramp in three different stages: 1) at more than 750 m upstream of the ramp, 2) at approximately 600 m upstream of the ramp, where an exit sign is located, and 3) at approximately 200-400 m upstream of the ramp. Downstream of the off-ramp the number of lane-changes was limited and involved mostly lane-changes towards the most right lane (keeping right rule). These lane-changes were performed until approximately 200-375 m downstream of the off-ramp gore. For weaving segments it was shown that most of the entering and exiting vehicles desired to change lanes directly downstream of the first gore. By far most lane-changes (low traffic flow: 73-95%, high traffic flow: 74-85%) occurred in the first quarter of the weaving segment, leaving the remaining three quarters mostly unutilized. The length of a weaving segment was shown to have a limited influence on the lane-change location.

In this thesis different methodologies were considered to quantify the implications of turbulence on traffic operations and traffic safety, such as the use of microscopic simulation software packages, surrogate safety measures, crash prediction models and driver simulators. Traditionally, the safety of a road is assessed by studying crash statistics. However, crash statistics are only available for existing roads and existing situations, and crash data is not always sufficient due to low quality (i.e. underreporting) and small sample sizes. These limitations make crash statistics unsuitable for assessing traffic safety implications of different motorway designs. An alternative method, in which microscopic simulation software is combined with surrogate safety measure methodologies, was expected to be the most promising way forward. To this end, several microscopic simulation software packages were evaluated. The two packages with the highest potential to simulate driving behaviour around ramps (VISSIM and MOTUS) were calibrated. The simulation output was compared to empirical trajectory data (collected from video recordings, which were taken from a camera mounted on a helicopter). It was found that both VISSIM and MOTUS failed to accurately simulate the turbulence related driving behaviour. Especially the most relevant aspects of turbulence (the location and intensity of lane-changes) are not simulated realistically. VISSIM overestimates the number of lane-changes and MOTUS underestimates the number of lane-changes. Also, the locations where lane-changes take place are not simulated accurately. The results regarding gap acceptance and headway distribution show a reasonable similarity between simulated and empirical data. However, this similarity was only found to be statistically significant for a limited number of cases.

To quantify the implications of turbulence on traffic safety, the most commonly used microscopic simulation software package (VISSIM) was evaluated, in terms of its capability to reproduce the number and the severity of traffic conflicts realistically. It was found that VISSIM overestimates the number of traffic conflicts. This overestimation can mainly be explained by the overestimation of the number of lane-changes by VISSIM. It was also found that the severity of conflicts (as measured by the distributions of Time To Collision (TTC) and Post Encroachment Time (PET)) is simulated reasonably accurate by VISSIM. Gap acceptance and car following during lane-changes from and to the most right lane, are simulated reasonably well by VISSIM. Also the distributions of TTC and PET have comparable shapes. Therefore it is stated that simulation software packages hold the potential to be used for traffic safety evaluation, but are yet unable to reproduce the location and intensity of lane-changes accurately. The location and intensity of lane-changes however, are the key elements in driving behaviour with respect to turbulence. This is a problem when different design variants are evaluated and compared with respect to turbulence. For standard elements of a road design, such as a basic weaving segment, a standard on-ramp or a standard off-ramp, this problem is expected to be limited, since a lot of research and experience on these situations is available. For unconventional, or 'fit for purpose', designs this problem is expected to be more eminent. It is recommended not to use microscopic simulation software to quantify traffic safety of complex, unconventional designs.

The desired distance for ramp spacing and the length of weaving segments as described in motorway design guidelines are based on specific ramp influence areas and turbulence distances. In this thesis however, a different approach is proposed. Since most turbulence is measured in direct proximity of the ramp, and turbulence is expected to be correlated with signposting, turbulence does not seem to be the determining factor for ramp spacing. Drivers seem to plan their path over the different motorway lanes. The available length for planning that path seems to be far more important than the available length for performing the actual manoeuvre. It is therefore recommended that motorway design guidelines focus more on the desired lengths to inform drivers on, or to psychologically prepare drivers for, upcoming route decision points (e.g. by placing route signs), rather than focusing on turbulence.

Samenvatting

In de directe omgeving van toe- en afritten van autosnelwegen worden verschillende manoeuvres uitgevoerd door automobilisten die de autosnelweg op willen rijden of willen verlaten. Maar ook door automobilisten die anticiperen op, of ruimte bieden aan, de in- en uitvoegende voertuigen. Deze manoeuvres omvatten rijstrookwisselingen, snelheidsaanpassingen en veranderingen in de afstand tot de voorligger. Dit resulteert in wijzigingen in de verdeling van het verkeer over de verschillende rijstroken, verschillen in snelheid en verschillen in de volgtijdverdeling op de verschillende rijstroken, met waarschijnlijk een groter aandeel grote hiaten op de linker rijstrook.

In de literatuur en in de ontwerprichtlijnen wordt dit fenomeen aangeduid met turbulentie. Turbulentie is op dit moment echter nog niet expliciet gedefinieerd. Daarom is in deze dissertatie een expliciete definitie voor turbulentie gedefinieerd: "*individuele veranderingen in snelheid, volgtijden en rijstroken (rijstrookwisselingen) binnen een specifiek wegsegment, onafhankelijk van de oorzaak van de veranderingen*". Verwacht wordt dat turbulentie altijd aanwezig is in de verkeersstroom en niet alleen bij toe- en afritten. Daarom is ook een tweede definitie geïntroduceerd: de mate van turbulentie. Deze is gedefinieerd als: "*de frequentie en intensiteit van individuele veranderingen in snelheid, volgtijden en rijstrookwisselingen binnen een specifiek wegsegment, binnen een specifiek tijdsinterval*".

Rond in- en uitvoegstroken wordt een verhoogde mate van turbulentie verwacht. Deze verhoogde turbulente heeft een negatieve invloed op de verkeersveiligheid en de doorstroming. In verkeerssituaties met vrije doorstroming (geen filevorming) wordt verwacht dat de mate van turbulentie een paar honderd meter stroomopwaarts van de toe- of afrit begint toe te nemen en dat deze een paar honderd meter stroomafwaarts van de toe- of afrit weer is afgenomen.

Volgens de huidige ontwerprichtlijnen voor autosnelwegen moet er, onder andere, bij het vaststellen van de onderlinge afstand tussen toe- en afritten, en bij het vaststellen weefvaklengtes, rekening worden gehouden met turbulentie.
In verschillende landen worden verschillende benaderingen voor het omgaan met turbulentie beschreven in ontwerprichtlijnen (AASHTO 2011; RAA 2008; HCM 2010; Rijkswaterstaat 2017; DMRB 1994). Voor zover

bekend is er slechts één literatuurbron beschikbaar, die beschrijft waar een verhoogde mate van turbulentie bij toe- of afritten begint en eindigt: Kondyli and Elefteriadou (2012). Daarnaast geven de huidige richtlijnen geen inzicht in de gevolgen voor doorstroming en verkeersveiligheid, wanneer er wordt afgeweken van de richtlijn. Op basis van deze constateringen worden er op hoofdlijnen twee problemen gezien bij het toepassen van de huidige richtlijn met betrekking tot turbulentie:

- Een solide theoretische en empirische onderbouwing van de benodigde lengte in het wegontwerp voor een verhoogde mate van turbulentie ontbreekt.
- Een goede doorgronding van de (kwalitatieve) gevolgen voor doorstroming en verkeersveiligheid, wanneer wordt afgeweken van de richtlijn voor turbulentielengtes, ontbreekt.

Het eerste en belangrijkste doel van deze dissertatie is het verkrijgen van empirische kennis over de karakteristieken van turbulentie. Vanuit het oogpunt van wegontwerp is het gewenst om kennis te verkrijgen van de afstand, ten opzichte van de discontinuïteit, waarbinnen sprake is van een verhoogde mate van turbulentie en van de manier waarop het rijgedrag bij invoegstroken, uitvoegstroken en in weefvakken wordt beïnvloed door het wegontwerp en de verkeersintensiteit.

Het secundaire doel van deze dissertatie is het verkrijgen van een tool voor het beschouwen van de mate van turbulentie, dat het gevolg is van een bepaald wegontwerp, en de invloed daarvan op doorstroming en verkeersveiligheid.

In deze dissertatie is aangetoond dat de hoeveelheid rijstrookwisselingen en de locatie van rijstrookwisselingen het meest relevant zijn voor de mate van turbulentie. De gemeten veranderingen in snelheid en volgtijden blijken gering te zijn.

Het grootste aantal waargenomen rijstrookwisselingen bevindt zich in de directe omgeving van het puntstuk van de toe- of afrit. Slecht een klein aandeel van de rijstrookwisselingen werd verder stroomop- of stroomafwaarts waargenomen. Bij toeritten is gebleken dat 4-9% van alle rijstrookwisselingen werd uitgevoerd door bestuurders op de hoofdrijbaan die anticiperen op een invoegend voertuig, door naar links van rijstrook te wisselen om het invoegend voertuig ruimte te geven om in te voegen. Deze rijstrookwisselingen vonden circa 25-100 m stroomopwaarts van het puntstuk plaats. Een aantal invoegende bestuurders voerden aanvullende rijstrookwisselingen naar links uit (secundaire invoegingen) richting de linker rijstrook van de

hoofdrijbaan en een aantal bestuurders op de hoofdrijbaan voerden rijstrookwisselingen naar rechts uit (in verband met niet onnodig links rijden). Deze rijstrookwisselingen vonden plaats tot circa 475-575 m stroomafwaarts van het puntstuk.
Voor afritten is waargenomen dat de meeste uitvoegende bestuurders (86%) al buiten de grenzen van de meting (circa 750 m stroomopwaarts van het puntstuk) de op de rechter rijstrook reden. Uitvoegende bestuurders voeren hun voorsorterende rijstrookwisselingen uit in drie onderscheidende locaties: 1) op meer dan 750 m stroomopwaarts van de afrit, 2) op ongeveer 600 m stroomopwaarts van de afrit (waar de voorwegwijzer van de afrit staat), en 3) op ongeveer 200-400 m stroomopwaarts van de afrit. Stroomafwaarts van de afrit is het aantal waargenomen rijstrookwisselingen beperkt. Deze rijstrookwisselingen waren hoofdzakelijk rijstrookwisselingen naar rechts en zijn waarschijnlijk uitgevoerd in het kader van niet onnodig links rijden. Deze rijstrookwisselingen vonden plaats tot circa 200-375 m stroomafwaarts van het puntstuk. Bij de weefvakken is waargenomen dat de meeste invoegende en uitvoegende voertuigen direct na het eerste puntstuk wensen in of uit te voegen. De meeste rijstrookwisselingen (73-75% bij een lage verkeersintensiteit en 74-85% bij een hoge verkeersintensiteit) vonden plaats in het eerste kwart van het weefvak, waarbij de overige drie kwart nauwelijks benut werd. De lengte van het weefvak bleek slechts een minimale invloed te hebben op de rijstrookwissellocatie.

In deze dissertatie zijn verschillende methodes beschouwd die kunnen worden gebruikt om de gevolgen van turbulentie op doorstroming en verkeersveiligheid te kwantificeren. Enkele voorbeelden zijn: het gebruik van microscopische simulatiemodellen, surrogate safety measures, crash prediction models en rijsimulatoren. De veiligheid van een weg wordt traditioneel beschouwd door het analyseren van verkeersongevallen-registraties. Deze gegevens zijn echter alleen beschikbaar voor bestaande wegen en bestaande situaties. Het gebruik van alleen ongevallenregistraties is daarnaast niet altijd voldoende, vanwege slechte kwaliteit van de data (niet alle ongevallen worden geregistreerd) en een beperkte steekproef-grootte. Hierdoor is het gebruik van ongevallenregistraties ongeschikt om de invloed van het wegontwerp op de verkeersveiligheid in te schatten. Een methode waarbij microscopische verkeerssimulatiesoftware wordt gecombineerd met surrogate safety measures methodieken, wordt gezien als de potentieel meest geschikte alternatieve methode. In dit kader zijn verschillende microscopische simulatiesoftwarepakketten geëvalueerd. Twee van deze pakketten (VISSIM en MOTUS) zijn gekalibreerd. De simulatieresultaten van deze gekalibreerde modellen, zijn vergeleken met empirische trajectoriedata. Deze data zijn gegenereerd van video-opnames die zijn opgenomen door middel van een camera onder een helikopter. Uit de vergelijking is gebleken dat zowel VISSIM als MOTUS het werkelijke rijgedrag niet accuraat kunnen simuleren. Vooral het meest relevante aspect van turbulentie (de hoeveelheid en de locatie van rijstrookwisselingen) werd niet realistisch gesimuleerd. VISSIM simuleert meer rijstrookwisselingen dan waargenomen en MOTUS simuleert minder rijstrookwisselingen dan waargenomen. Ook de locaties waar de rijstrookwisselingen plaatsvinden komen niet overeen met de werkelijkheid. Verder is gebleken dat de gesimuleerde hiaatacceptatie en volgtijdverdelingen wel redelijk overeen komen met de empirische data. Deze overeenkomsten bleken echter alleen voor een beperkt aantal gevallen statistisch significant.

Voor het microscopische simulatiesoftwarepakket dat in de literatuur het meest wordt gebruikt voor verkeersveiligheidsonderzoeken (VISSIM), is onderzocht in hoeverre het gesimuleerde aantal verkeersconflicten en de zwaarte daarvan realistisch zijn. Hieruit is gebleken dat VISSIM het aantal conflicten overschat. Deze overschatting kan worden verklaard door de overschatting in VISSIM van het aantal rijstrookwisselingen. Daarnaast is gebleken dat de zwaarte van de conflicten (gemeten als de verdelingen van de Time To Collision (TTC) en de Post Encroachment Time (PET)) redelijk realistisch worden gesimuleerd in VISSIM. Vooral hiaatacceptatie en voertuig-volggedrag tijdens rijstrookwisselingen van en naar de meest rechter rijstrook worden redelijk nauwkeurig gesimuleerd in VISSIM. Ook de verdelingen van TTC en PET hebben vergelijkbare vormen. Op basis van deze constateringen wordt gesteld dat simulatiesoftwarepakketten de potentie hebben om gebruikt te worden voor het evalueren van verkeersveiligheid, maar dat deze vooralsnog niet in staat zijn om het aantal rijstrookwisselingen en de locatie daarvan realistisch te simuleren. Het aantal rijstrookwisselingen en de locatie daarvan zijn echter het belangrijkste aspect van turbulentie. Dit is een probleem wanneer verschillende ontwerpvarianten worden vergeleken en beoordeeld op het gebied van turbulentie. Voor standaard elementen in het wegontwerp, zoals een continu stuk weg, een standaard toerit of een standaard afrit, wordt verwacht dat dit probleem minimaal is, omdat voor dergelijke situaties veel onderzoek en ervaring beschikbaar is. Voor onconventionele of 'maatwerk'-oplossingen, wordt verwacht dat dit probleem relevant is. Daarom wordt aanbevolen om microscopische verkeerssimulatie-software niet te gebruiken om de verkeersveiligheid van onconventionele ontwerpen te kwantificeren.

De gewenste afstand tussen toe- en afritten en de lengte van weefvakken, zoals beschreven in de ontwerprichtlijnen voor autosnelwegen, zijn gebaseerd op turbulentielengtes. In deze dissertatie wordt echter een andere benadering voorgesteld. Om dat de verhoogde mate van turbulentie zich hoofdzakelijk concentreert in de directe omgeving van de in- of uitvoegstrook, en omdat turbulentie waarschijnlijk correleert met de bewegwijzering, lijkt turbulentie niet de maatgevende factor voor de spreiding van discontinuïteiten. Bestuurders lijken hun pad over de verschillende rijstroken naar de afrit te plannen. De benodigde lengte om dit pad te plannen lijkt veel belangrijker dan de benodigde lengte om een rijstrookwissel uit te voeren. Daarom wordt aanbevolen om de focus in ontwerprichtlijnen te leggen op de benodigde lengte die nodig is om bestuurders te informeren over, of psychologisch voor te bereiden op, aanstaande routekeuzemomenten (bijvoorbeeld door bewegwijzering), in plaats van op turbulentie.

Curriculum Vitae

Aries van Beinum was born in on the 28th of May 1980 in Heemstede, The Netherlands. In 2000 he finished the Dutch secondary vocational education *Grond-Weg en Waterbouwkunde* at Nova College in Santpoort-Noord. In 2003 he finished the Dutch Bachelor of Built Environment programme *Civiele techniek* at Hoogeschool In-Holland in Haarlem. In the same year he started the MSc programme *Civil Engineering* at the faculty of Civil Engineering and Geosciences of Delft University of Technology, choosing the *Transport & Planning* track. As part of an internship at Witteveen+Bos in The Hague, he wrote his Master thesis on the performance of Turbo Roundabouts in the Netherlands. He received his Master's degree in 2007.

Aries started his professional career in 2007 at Witteveen+Bos. From 2007 until 2009 he was outsourced as a researcher to Delft University of Technology, for two days a week, to continue his research on the capacity of Turbo Roundabouts and to upgrade the road design course.
During his professional career at Witteveen+Bos, Aries worked on several major motorway design projects in The Netherlands. During these projects, he gained experience in motorway design practice. From 2009 he worked as an author within the Rijkswaterstaat project to revise the Dutch motorway design guidelines. During this project he gained experience on the theoretical aspect regarding motorway design.

During his career at Witteveen+Bos, Aries worked as a part time PhD researcher (two days a week) at the Transport & Planning department of Delft University of Technology from 2014 until 2018. As of 2018 he continues working full time at Witteveen+Bos as manager of the business line Traffic and Roads.

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