Simulated traffic safety in tunnels

A comparison study of traffic safety in simulated road tunnels and simulated regular road stretches

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SIMULATED TRAFFIC SAFETY IN TUNNELS

A comparison study of traffic safety in simulated road tunnels and simulated regular road stretches

By

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PREFACE

This report is the final report of my study Civil Engineering and Management at the University of Twente in Enschede. I am happy to present you this report after 5 months working on this research. With this report, an end has come to six years of studying and student life in Enschede.

This research is carried out at Witteveen + Bos in Deventer. I would like to thank Witteveen + Bos for the opportunity to do my thesis over there. I also really want to thank all colleagues at Witteveen + Bos for their help, input and for the 'gezelligheid' during my thesis. Due to the corona virus, I started working on my thesis from my student room. Sometimes, it was hard to stay motivated while sitting completely in my own bubble, but the daily video calls strengthened the motivation to work on my thesis every day. Luckily, when I was halfway of my thesis, I could visit the office once a week and see my colleagues and supervisor in real life. This was a nice outing every week and helped me to get more familiar with the company.

There are some people that I want to thank specifically. First, I want to thank the direct colleagues of the Traffic and Roads groups in Deventer and Heerenveen. Special thanks go to my daily supervisor Dedjer. He helped me during the whole process, gave useful feedback, but was also a sympathetic ear if something was not going well. Especially the feedback on the writing and the structure of my thesis was very useful. Besides Dedjer, I want to thank Aries van Beinum, Jan-Auwke Verspuij and Jeroen Hoogvliet for helping me with the content of my thesis. Your help and input were very useful, especially at the beginning of my research. I also want to thank Julian Bodar for providing me with the alignments of the used tunnels.

From the University of Twente, I want to thank Kostas for having a critical view on my draft versions and for the supervision during my thesis. I also want to thank Eric van Berkum for helping me with the proposal for this research and for all other projects and courses he guided me in. I learned a lot from working together with him during my study.

Finally, I would like to thank my family, friends and fellow students for my great student life and the support during my thesis. Special thanks go to Anouk, also for reading my thesis and check for mistakes and inconsistencies. Other special thanks go to my room mates of the Pimpelpatio. During the intelligent lockdown they tried to keep the atmosphere in the house great. Furthermore, I want to thank my former fellow board-members for the 'burger-rondjes' during the breaks. And last, but not least, I want to thank my parents for their support during my whole study.

Ramon Oppers
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ABSTRACT

More and more tunnels are constructed in the Dutch highway network. Most of these tunnels are the 'new generation' landtunnels, mainly constructed for the mitigation of externalities of highways, such as noise, barrier function and air pollution. While safety is an important aspect when constructing new roads, construction of more tunnels comes with the question if the new designed tunnels are safe. Often, tunnel safety research is about operational safety, such as fire safety, escape routes and emergency exits. However, traffic safety is an important aspect because tunnels can be considered as a special object in the road, with specific effects on driver behaviour.

Traditionally, safety assessment is based on accident data of a comparable road lay-out. However, tunnels are always tailor-made products, so this is not possible for most tunnels. Rijkswaterstaat has developed alternative methods that assess safety in a qualitative way, performed by qualified auditors. However, a quantitative approach to assess traffic safety in tunnels does not exist. This creates research gap in knowledge that can be filled with new insights.

Changed behaviour in and around tunnels can cause conflicts between vehicles or even accidents. There are several aspects of tunnels that affect traffic safety. For this research, the suitable and quantifiable aspects that are used, are lane width, slopes, intensity and tunnel length.

Already since the eighties of last century, research has been done on the assessment of traffic safety in a quantitative way. Researches showed that micro-simulation software can be used to assess traffic safety by using so called 'surrogate safety measures' (SSM). This approach is based on 'near misses' or 'conflicts'. With qualitative measures, such as speed, direction, acceleration, deceleration, it is possible to calculate the number of conflicts, type of conflict and severity of conflict between vehicles. Other researchers discovered a relation between these conflicts and the number of accidents in real life. So, SSM is a way to assess traffic safety in a quantitative way.

In this research, the safety impact of tunnels on traffic is determined with micro-simulation. Four Dutch highway tunnels are selected as case study. For these tunnels, the quantitative safety assessment, by using SSM, is performed and compared to a normal road stretch with similar properties. The goal of this assessment and comparison is to identify if the effects of tunnels on traffic safety can be quantified with the use of micro-simulation software and SSM and what those effects are.

The research resulted in four main observations. The first observation is that the **number of conflicts per vehicle increases if the intensity increases**, what is expected based on the literature. This is the case for normal road stretches as well as for tunnels. The second observation is that, based on the simulated roads, **tunnel length has no remarkable result on the number of conflicts**.

The third and fourth main observation are related to the simulated tunnel aspects. The slopes of the tunnel are recreated in Vissim using reduced speed areas. **Slopes in tunnels result in a displacement of conflicts**, compared to a normal road stretch. On the uphill slope, more conflicts occur, but just after the slope, less conflicts occur (after the exit of the tunnel). There is no increase in the total number of conflicts. The fourth observation is about the smaller object distance in tunnels. This is simulated by narrowing the lane width. **The effect of narrower lanes is an overall increase of conflicts** which are located on the location of the narrow lane.

Concluding, the assessment of traffic safety in tunnels with the use of micro-simulation is possible. The safety assessment produces explainable results. However, more research is necessary and more empirical data is required to optimise the safety assessment tool and include more detailed effects of tunnels on safety. Hence, in the end, an assessment tool that assess safety will create more insight in traffic safety issues in tunnels and provides a quantitative method that can be standardized.

SAMENVATTING

Er worden steeds meer tunnels gebouwd in het Nederlandse Rijkswegennet. De meeste nieuwe tunnels zijn de zogenaamde 'nieuwe generatie landtunnels', die gebouwd worden om de negatieve effecten van een autosnelweg door dichtbevolkte gebieden te mitigeren. Voorbeelden van deze negatieve effecten zijn geluidsoverlast, luchtvervuiling en de vorming van fysieke blokkades. Bij de bouw van nieuwe tunnels, is veiligheid een belangrijk aspect. Vaak wordt bij tunnelveiligheid uitgegaan van zaken zoals brandveiligheid, vluchtroutes en nooduitgangen. Echter is de verkeersveiligheid van tunnels ook een belangrijk issue, omdat een tunnel gezien kan worden als een bijzondere discontinuïteit in het wegbeeld. Deze discontinuïteit heeft specifieke effecten op het rijgedrag van bestuurders en kan leiden tot meer conflicten tussen voertuigen en in het ergste geval zelfs tot ongelukken.

Traditioneel is veiligheidsanalyse gebaseerd op het verzamelen en analyseren van ongevallendata op vergelijkbare wegvakken. Echter, tunnels zijn nagenoeg altijd unieke ontwerpen, dus het gebruik van deze methode is geen goede optie. Rijkswaterstaat heeft in de loop der jaren alternatieve methodes bedacht die de (verkeers)veiligheid van tunnels kwalitatief beoordelen met behulp van gekwalificeerde auditors. Een kwantitatieve methode om de verkeersveiligheid in tunnels te bepalen bestaat nog niet. Dit creëert een interessant gat in de bestaande kennis en kan gevuld worden met nieuwe inzichten.

Er zijn diverse aspecten van tunnels die effect hebben op de verkeersveiligheid. Voor dit onderzoek bleken rijstrookbreedte/objectafstand, hellingen, intensiteiten en de lengte van tunnels bruikbaar en kwantificeerbaar.

Al sinds de jaren '80 van de vorige eeuw wordt er onderzoek gedaan naar een kwantitatieve beoordeling van verkeersveiligheid. Onderzoekers toonden aan dat micro-simulaties in combinatie met zogenaamde 'Surrogate Safety Measures' (SSM) een goede manier zijn om dit te doen. Deze methode is gebaseerd op 'bijna-ongevallen' of 'conflicten'. Met kwalitatieve meetwaarden, zoals snelheid, richting, acceleratie en deceleratie is het mogelijk om het aantal conflicten tussen voertuigen, het type conflict en de ernst van een conflict te bepalen. Andere onderzoekers toonden aan dat deze conflicten een directe relatie hebben met daadwerkelijke ongevallen, wat SSM een goede manier maakt om verkeersveiligheid te kwantificeren.

In dit onderzoek worden de impact van tunnels op verkeersveiligheid bepaald met behulp van microsimulatie. Vier Nederlandse snelwegtunnels zijn gebruikt als casestudy. Voor deze tunnels is een kwantitatieve verkeersveiligheidsanalyse met behulp van SSM uitgevoerd. De resultaten van de tunnel zijn vergeleken met de verkeersveiligheidsanalyse van een vergelijkbare normale weg. Het doel van deze analyse en vergelijking is te onderzoeken of de effecten van tunnels op verkeersveiligheid te kwantificeren zijn met behulp van micro-simulatie en SSM en wat deze effecten daadwerkelijk zijn.

Uit het onderzoek komen vier opvallende zaken naar boven. De eerste observatie is dat **het aantal conflicten per voertuig stijgt als de intensiteit op een weg hoger is**. Dit correspondeert met de verwachtingen uit de literatuur. Dit effect geldt zowel voor de tunnels als voor de normale wegvakken. De tweede observatie is dat **de lengte van de tunnel geen verklaarbare effecten geeft op het aantal conflicten**. De derde en vierde observatie zijn gerelateerd aan de gesimuleerde aspecten van de tunnels. De hellingen in tunnels worden in Vissim gerepresenteerd door de zogenaamde 'reduced speed areas'. **Het effect van hellingen in tunnels is een verplaatsing van de conflicten** ten opzichte van de normale weg. Op de opgaande hellingen vinden meer conflicten plaats, maar net na een opgaande helling vinden minder conflicten plaats. In beide gevallen vinden evenveel conflicten plaats, alleen op een andere locatie. De laatste observatie gaat over kleinere objectafstanden in tunnels. Dit is gesimuleerd doormiddel van het versmallen van rijstroken. **Het effect van smallere rijstroken, is dat er meer conflicten plaatsvinden** op de locaties waar de rijstrook smaller is.

Concluderend is het mogelijk om de verkeersveiligheid in tunnels te bepalen aan de hand van micro-simulatie. De verkeersveiligheidsanalyse resulteert in verklaarbare uitkomsten. Desalniettemin is meer onderzoek nodig op basis van empirische trajectoriën. Uiteindelijk kan een verkeersveiligheidbeoordelingstool meer inzicht creëren in de verkeersveiligheidsrisico's in tunnels en kan het dienen als gestandaardiseerde kwantitatieve beoordelingsmethode.

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LIST OF ABBREVIATIONS

Abbreviation	Meaning	Remark / Reference	English
AHN	Actueel Hoogtebestand Nederland	(AHN, 2020)	Up-to-date Height Model of the Netherlands
BL	Beneluxtunnel		
CIA	Capaciteitswaarden Infrastructuur Autosnelwegen	(Heikoop, 2015)	‘Highway capacity manual’
COM	Component Object Model		
CPI	Crash Potential Index		
DRAC	Deceleration Rate to Avoid the Crash		
DTB	Digitaal Topografisch Bestand	(Rijkswaterstaat, 2020)	Digital Topographical File
EU	European Union		
FHWA	Federal Highway Association		
GDP	Gross domestic product		
GUI	Graphical User Interface		
I/C ratio	Intensity / Capacity ratio		
INWEVA	Inschatting Wegvak intensiteiten	(Rijkswaterstaat, 2020)	Estimation of road section intensities
KNMI	Koninklijk Nederlands Meteorologisch Instituut		Royal Dutch Weather Institute
KPI	Key Performance Indicator		
KWA	Koning Willem-Alexandertunnel		
LR	Leidscherijntunnel		
MADR	Maximum Available Deceleration Rate of a car		
NDW	Nationale Databank Wegverkeersgegevens	(NDW, 2020)	National Database of Road traffic data
PET	Post encroachment time		
RMSE	Root mean square error		
RSA(s)	Reduced Speed Area(s)	Input for Vissim	
RQ	Research Question		
RWS	Rijkswaterstaat		
SSAM	Surrogate Safety Assessment Model	(FHWA, 2007)	
SSM	Surrogate safety measures		
SWOV	Stichting Wetenschappelijk Onderzoek Verkeersveiligheid		Foundation Scientific Research Traffic safety
TTC	Time to collision		
Veh/h	Vehicles per hour		
VOA	Verkeersongevallenanalyse		Traffic accident analysis
VVA	Verkeersveiligheidaudit		Traffic safety audit
VVE	Verkeersveiligheids-effectbeoordeling		Traffic safety effect assessment
WK	Wijkertunnel		
ZOAB	Zeer Open Asfalt Beton		Very porous asphalt concrete

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INTRODUCTION

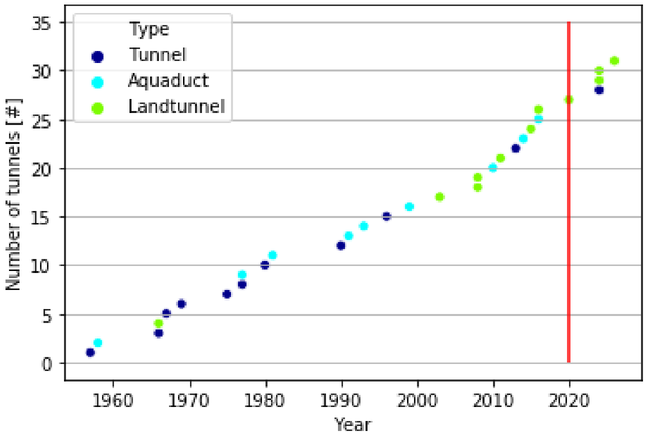
In 2019, the road section of 1 km with the most accidents in the Netherlands was the entrance of the Coentunnel at the ring road A10 of Amsterdam. 63 reported accidents took place in this road section according to the Stichting Incident Management Nederland. (Stichting Incident Management Nederland, 2020) The question rises what the cause for all these accidents is. Just in front of the Coentunnel, there is a complicated junction with lots of convergences and divergences that might cause these accidents. However, the old (1966 (Rijkswaterstaat, 2020)) and narrow tunnel with steep slopes, might also be the cause of these accidents.

Another remarkable development is the growing number of tunnels constructed in the Netherlands the last decade and the planned tunnels for the coming years. This is illustrated in Figure 1.1. An important reason for this growth, is the relatively new concept of the so called 'landtunnel', which is a tunnel with limited or no slope through populated urban areas. The amount of road traffic is growing already for years and the expectation is that this will not change in the nearby future (Francke, 2018)[1]. A big part of the Dutch highway system is located near or in cities and cause a lot of pollution (noise, nitrogen, CO2, particular matter). A second effect is the physical and social barrier of a highway that might create inequity (Boon, Van Wee, & Geurs, 2003; Rijkswaterstaat, 2020). To mitigate these negative effects, a landtunnel can be a solution. Therefore, it is expected that the number of tunnels in the Netherlands will increase the coming decades.

Obviously, accidents are in no aspect good for society. But, to put the (social) costs of traffic accidents in more context, it is good to know that all traffic accidents costs more than 1500€ per year per person with a driver's license or 2% of the Dutch GDP, and still growing every year (SWOV, 2020; CBS, 2019).

The growing number of tunnels in the Dutch highway network and the increasing social costs for traffic accidents makes research on traffic safety in tunnels an interesting and social relevant research topic. In the next section, first some background information is given. Furthermore, a research gap is identified and based on this gap, the goal of this research and the research questions to accomplish this goal are formulated.

Figure 1.1 Number of tunnels in the Dutch highway network with the year of opening and the tunnel type (Rijkswaterstaat, 2020)



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[1] The effects of the Covid-19 pandemic are not included in this research, while the pandemic was still ongoing while writing this research and the effects are unknown

1.1 Background

In this section, first a short history of tunnels in the Netherlands is described. Afterwards, an introduction on traffic safety and accidents in tunnels is given. The last part describes shortly the history of traffic safety assessment.

History of tunnels in the Netherlands

In a relatively flat country as the Netherlands, tunnels are not needed to pass difficult mountainous areas. However, since the sixties of last century, tunnels in roads appeared in the Netherlands. The first need for tunnels was to cross important waterways. The old movable bridges caused a lot of delay for road traffic as well for shipping. In 1957, the first tunnel in the Dutch highway network was opened: The Velsertunnel beneath the Noordzeekanaal (Rijkswaterstaat, 2020). A dozen of tunnels followed and in 1991, the minister decided to organise an expert mission to Japan to gain knowledge about drilled tunnels (in Dutch: Boortunnels) in soft soil undergrounds. This led to a new impulse for tunnel construction in the Netherlands (van Beek, Ceton-O'Prinsen, & Tan, 2003). Around 15 tunnels were present in the Dutch highway system in the year 2000, and all of them, except for the Schipholtunnel were under waterways. However, the growing economy and demand for more asphalt in combination with more attention for environmental issues, initiated a new era in tunnel construction. The multi-functional landtunnel was introduced in the Netherlands (van der Hoeven, 2010). The first two multi-functional landtunnels were opened in 2008 in Roermond and many tunnels followed in the next decade. As can be seen in Figure 1.1, most of the tunnels constructed since 2000 are landtunnels, and most of the planned tunnels will be landtunnels. Landtunnels that will open in the next years are the Gaasperdammertunnel (A9), Hollandtunnel (A24) and the Lansingerlandtunnel (A13/A16) (Rijkswaterstaat, 2020).

Traffic safety & accidents in tunnels

Due to several disasters at the end of the last century, like the fires in the Tauern tunnel (1999, Austria) and the Mont Blanc tunnel (1999, France) tunnel safety became a real issue in the European Union (EU). Therefore, the EU created the new European Tunnel Law due to these disasters. This law provides a design guideline that should be applied to every tunnel on the Trans-European road network.

Also, lots of scientific research is performed about accidents in tunnels. A Norwegian research (2000) showed that the number of accidents in tunnels is not higher than on a normal road section, however the severity of accidents in tunnels is higher. However, just outside tunnels (near the entrance and exit of tunnels), the accident rate is relatively high (Amundsen & Ranes). In China, another study (2009), partly based on the Norwegian experience is performed. Also, the conclusion is that the severity of accidents in tunnels is higher compared to a normal highway section and the entrance zone is the location with most accidents. Another remarkable conclusion is that most accidents are not particular for a tunnel but are due to 'normal' failures such as speeding and not maintaining enough distance (Ma, Shao, & Zhang). A study in Singapore (2013) confirms the observation that the entrance zone is the location with the highest accident rate. This is supported by the fact that in this location, remarkably more 'multi vehicle accidents' took place, while the 'single vehicle accident' rate is rather stable over the tunnel length (Yeung & Wong, 2013). Also studies in Italy (2012), Switzerland (2007) and Austria (2004) draw the same conclusions (Caliendo & De Guglielmo, 2012; Nussbaumer, 2007; Allenbach, Cavegn, Hubacher, Siegrist, & Cavegn, 2004). In Greece, they also see these findings, however, they performed a survey (2017) under road users and concluded that the human factor is of important influence on the severity of accidents in tunnels (Kirytopoulos, Kazaras, Papapavlou, Ntzeremes, & Tatsiopoulos, 2017).

The Dutch traffic safety organisation SWOV performed a study about tunnel safety in the Netherlands in 2008. This was before the opening of the 'new generation multi-functional landtunnels' as presented in the previous section. However, the study did not give a clear view about the number of accidents in tunnels compared to normal highway stretches. Nevertheless, also in the Netherlands, the severity of accidents is higher in tunnels compared to normal roads (SWOV, 2011). There is also a lot of scientific research performed on the safety of tunnels, however almost all focussed on the mitigation of unexpected events. Examples of research topics are evacuation, fire safety and human behaviour in case of an accident. Nevertheless, recent in-depth research about traffic safety in Dutch tunnels is lacking in the scientific debate.

Estimation of traffic safety

The classical approach to estimate traffic safety, is to derive the safety from accident data. This approach has several difficulties, but the most important difficulty is that road accidents occur rarely, and the reporting is inaccurate. This results in a lack of useable data. Also, a safety assessment for planned unique road configurations is impossible. To overcome these disadvantages, two solution directions are developed over time: safety assessment by qualified auditors and the use of traffic simulation.

One approach is a qualitative safety assessment, performed by qualified auditors. Examples are the VOA, VVE and VVA analyses of Rijkswaterstaat (Rijkswaterstaat, 2020). Another approach is a quantitative approach based on trajectories of vehicles. In this research field, several approaches are developed over the years. The first technique was already proposed by Perkins and Harris in 1967 (Hauer, 1982; Young, Sobhani, Lenné, & Sarvi, 2014). This technique consists of an estimation of the safety based on 'near misses' or 'conflicts' between cars. The advantage of using near misses or conflicts is that they occur more frequent and therefore short periods of observations are necessary (Pirdavani, Brijs, Bellemans, & Wets, 2010).

In the last decades, traffic simulation has become a more powerful and more applied tool to gain information about the traffic system in various subjects. Young et al. created an extensive overview of traffic safety simulation models (Young, Sobhani, Lenné, & Sarvi, 2014). The quantitative approach based on 'near misses' or 'conflicts' has as great advantage that it can use the output of traffic simulations to create insight in the traffic safety. The practical implementation of this 'conflict approach' is embedded in the Surrogate Safety Measures (SSM) approach. These measures consist out of several mathematical formulas that can quantify the number and the severity of those conflicts. In 2.3, this topic is more elaborated on.

1.2 Research gap

The background information stated developments that make this research of relevance. These developments can be summarised by the following three aspects. First, there is a trend of constructing more tunnels in the Netherlands in the last years, and while a tunnel is almost never a 'one size fits all' construction, every structure needs a tailored safety assessment. Another observed development is the increasing number of accidents in and around road tunnels. Finally, computers and computer simulations are becoming more relevant in academic research to automate of simplify aspects of engineering. All these developments make it that a quantitative tool, that assesses the traffic safety in tunnels will support designers and engineers.

Identifying many literature sources, there is a lot of research done about traffic safety in road tunnels. These researches consist out of driving simulator studies, calibration studies and studies about accidents in tunnels. Also, the effects of several aspects in tunnels that affect the traffic safety are researched inexhaustibly.
On the other hand, there has been a lot of research, already since the eighties, on the assessment of traffic safety using SSM. In the last two decades, this field of research focuses more and more on the safety assessment using micro-simulation software. However, there are no examples found in the literature where the traffic safety of tunnels is assessed using micro-simulation software. This type of research is lacking and therefore an interesting field of research.

1.3 Research questions & Goal

To gain more insight in the described research gap, the following research goal is formulated. This research goal is twofold.

Research goal

The first goal of this research is to investigate if it is possible to assess traffic safety in tunnels with micro-simulation software. The second goal is to determine what aspects of tunnels have which effect on traffic safety and how these effect can be quantified with micro-simulation software.

To be able to achieve the goals and fill the identified research gap, the following main question is answered in this research.

Main research question
What is the safety impact of a tunnel on traffic?

To answer this main research question, a comparison between simulated normal road stretches and simulated tunnels is made. To design a suitable micro-simulation model for this comparison, four sub questions are defined. After every sub question, a short clarification is given.

1 WHAT ASPECTS ARE SUITABLE AND QUANTIFIABLE FOR TRAFFIC SAFETY ASSESSMENT IN TUNNELS?

The aspects that affect traffic safety in tunnels are determined by literature research and based on that research the suitable and quantifiable traffic safety aspects are determined.

2 HOW TO IMPLEMENT THE TUNNEL CHARACTERISTICS IN VISSIM?

To answer this sub question, three aspects are important. The first aspect that is described are the behavioural aspects of the drivers in the simulation, based on literature. The second aspect concerns the road characteristics that are not part of the tunnel. The third and last aspect are the effects of the tunnel on the driving behaviour.

3 HOW TO CALIBRATE THE VISSIM MODEL ON LOOP DETECTOR DATA?

To answer this question, three steps are taken. First, the selection procedure of the calibration data is described. This holds the selection and the preparation of the data. Second, key performance indicators (KPI) are identified so a calibration is possible. Lastly, a calibration method is selected based on the available data and the key performance indicators.

4 WHAT IS THE TRAFFIC SAFETY IN A SIMULATED TUNNEL, COMPARED TO A SIMULATED REGULAR ROAD STRETCH?

To answer this question, a comparison is made between simulated normal road stretches and tunnel road stretches. This is done using SSM. In total, 4 different tunnels are compared to a similar normal road stretch.

1.4 Scope

The scope of this research is limited in two ways: spatially and content wise.

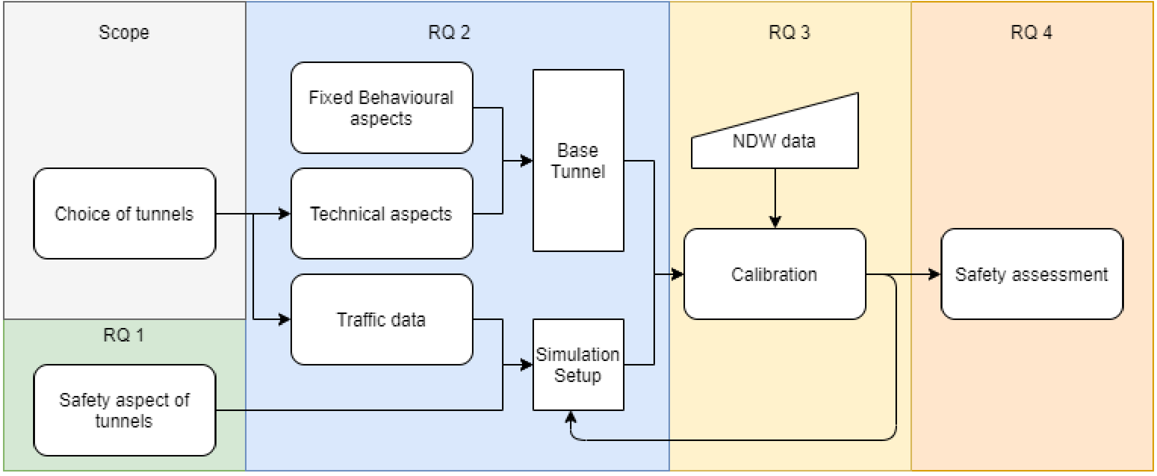
Spatial limitation
This research focusses on highway tunnels in the Netherlands. The reason for the limitation to one country is that general road lay-out aspects are the same for all tunnels. Another reason for this choice, is the lack of research in the Netherlands, while the research topic is relevant. This research can add knowledge to the scientific gap and be a starting point for further research. Furthermore, this research is not meant to compare the behaviour of drivers for different countries. This does not hold that useful information from other countries is worthless. The choice for highway tunnels of Rijkswaterstaat has multiple reasons. First, these tunnels deal with high intensities, are vital to the Dutch road network and relatively many data is available. Second, some of the tunnels are part of the Trans-European road network and must comply to European standards. Third, these tunnels are all multi-lane, unidirectional tunnels which simplifies the research, as will be described in 2.1. An overview of the existing tunnels in the Netherlands is given in Appendix J.

Content limitation
Concerning the content this research is limited to traffic safety issues. This holds that for safety of tunnels, the accessibility for emergency vehicles, ventilation, etc. are not included. The focus is on the traffic dynamics and the aspects of tunnels that affect those traffic dynamics. The safety aspects used in this research are described in 2.1.

1.5 Research design

In Figure 1.2 an overview of the research design is shown. In this research, a model is designed that simulates traffic in tunnels and afterwards, the model output is used for a safety assessment. The outcomes for different tunnels are compared with normal simulated road stretches and with each other to determine the effects on safety of certain tunnel aspects. First, the tunnel choice and the safety aspects of the tunnels are determined. With this info, the input parameters for the model can be determined. Then the calibration process takes place and if this is finished, the assessment of the safety is performed.

Figure 1.2 Short overview of aspects of this research in relation to each other



1.6 Report outline

This report consists out of 8 chapters. In chapter 2, the relevant literature is described. Afterwards, the used methodology is described in chapter 3. Chapter 4 provided the assessment framework and chapter 5 gives more in-depth information about the simulation settings. The results are presented in chapter 6 and discussed in chapter 7. The used methodology and corresponding assumptions and limitations are also discussed in chapter 7. Chapter 8 provides the conclusion of this research.

2

LITERATURE

Traffic safety in tunnels and the use of micro-simulation software to assess traffic safety are both researched inexhaustible. Lots of scientific and grey literature is available in this field of research. In this chapter, the relevant literature is described.

From the research question, **"What are the safety impacts of a tunnel on traffic?",** three issues are of interest in the view of a literature study. In order to assess traffic safety, it is important to identify which road aspects have effect on traffic safety in tunnels. The second issue is how to implement these aspects into a simulation. The final question is how to quantify the safety based on the outcomes of simulations.

In this chapter, first the traffic safety aspects are discussed, afterwards the scientific side of implementing these aspects into a simulation are discussed and the last section describes the assessment of safety based on simulation output. All sections consist out of a describing part ("What say others about this subject?") and an interpretation part ("What can be used in this research?").

2.1 Traffic safety in tunnels

Before describing the traffic safety aspects in a tunnel, it is important to describe what a tunnel exactly is. Multiple definitions of a tunnel can be found in the literature. As definition of a tunnel, Rijkswaterstaat describes it as: "A tunnel is an artificial created (under)passing or roof with the purpose to make transport between two points possible"[1] (Rijkswaterstaat, 2020). However, in the Netherlands, there are also a lot of aqueducts that satisfy to this definition. In that view, Van Beek et al. distinguishes between aqueducts and tunnels based on their length. If the underpass is below a waterway and has a length ≤ 80 meter, it is called an aqueduct. If the length is > 80 meter, it is called a tunnel (van Beek, Ceton-O'Prinsen, & Tan, 2003). Furthermore, legally, a tunnel has another definition. According to the Dutch tunnel law an underpass is only subject to the Dutch tunnel law if the longest enclosed space is > 250 meter (National Government, 2006). In this research, only tunnels with a length > 250 meter are used.

Tunnels have several aspects that are different from normal open road stretches. Examples are the tunnel walls near the road and, obviously, the roof. The relevant aspects that affect traffic safety in tunnels are derived from the found literature, but the base are guidelines from Rijkswaterstaat (Rijkswaterstaat, 2020; Rijkswaterstaat GPO m.m.v. Witteveen + Bos, 2017). In this paragraph, the most important aspects are described, with the corresponding effects as stated in the literature. For every aspect, a short conclusion and the relevance for this research is described. In the literature, there are contradictions, which will be discussed as well. An overview of the aspects is given in Table 2.1. For all aspects, the choice for taking an aspect into account in this research is clarified. This is also included in the table.

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[1] Original Dutch text: "Een tunnel is een kunstmatig aangelegde (onder)doorgang of overkapping die als doel heeft transport tussen 2 punten mogelijk te maken."

Table 2.1 Overview of traffic safety aspects in tunnels and the use in this research

Safety Aspect	Effect	Reason	Consistent?	Part of this research?
Intensity	Higher intensity, more accidents	More interaction between vehicles	✗	✓
	Lower intensity, more accidents	Less attention		
Uni- and bidirectional	Bidirectional tunnels cause more accidents	More interaction between vehicles	✓	✗
Length	Short tunnels have more accidents	Most accidents occur in the first part of the tunnel	✗	✗
	Longer tunnels have more accidents	Decreasing attention in longer tunnels		
Lighting	Bad lighting decreases speed	Drivers cannot look into the tunnel	✗	✗
Colour of the walls	Light-coloured walls increase attention	People are less distracted by light-coloured walls	✓	✗
Lane width	Smaller lanes lead to more accidents	More interaction between vehicles	✓	✓
Object distance	Small distance force drivers to change lateral position	People are afraid of running into the wall	✓	✓
Slopes	More speed difference between vehicles	Several reasons	✓	✓

Intensity

The first aspect that can have influence on the traffic safety of tunnels is the traffic intensity. Several researches are performed, but the results are contradicting. On one hand, Amundsen and Ranes did a research in Norway and concluded that the amount of crashes is higher for roads with a lower average intensity. However, they also mentioned that this might be caused by the lower safety standards applied for such tunnels (Amundsen & Ranes, 2000). On the other hand, Nussbaumer claims the opposite, while there is more vehicle interaction when the intensity is higher (Nussbaumer, 2007). These findings are also found by Allenbach et al. (Allenbach, Cavegn, Hubacher, Siegrist, & Cavegn, 2004).

Although there is no consistent conclusion from the literature, the hypothesis for the Dutch highway tunnels is that an increasing intensity, increases the chance on an accident. This hypothesis is based on the findings of Nussbaumer, who mentioned the increased vehicle interaction as main reason for conflicts. While the Dutch highway tunnels face high intensities and high I/C-ratios (especially compared to tunnels in the Norwegian countryside), this effect is more likely to happen than less attention due to an empty road.

Unidirectional and bi-directional tunnels

In the same research from Nussbaumer, the difference in safety of unidirectional and bi-directional tunnels is determined. In bi-directional tunnels occur more crashes compared to unidirectional tunnels (Nussbaumer, 2007).

However, in the Dutch highway system, all tunnels are unidirectional so the effect of more accidents in bi-directional tunnels will not take place. This aspect will therefore not be a part of this research.

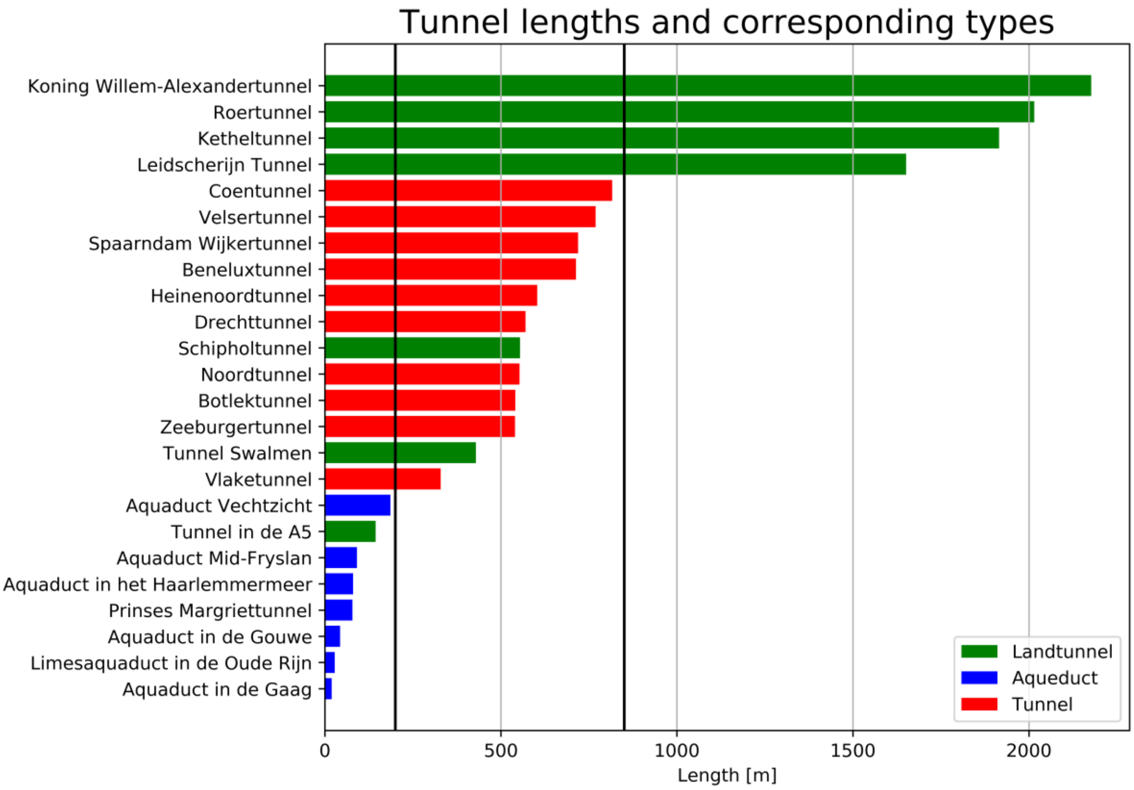
Tunnel length

Another issue that may have influence on the safety, is tunnel length. In 1997, Martens and Kaptein stated that long tunnels should be avoided, because the effect on safety is not objectively studied (Martens & Kaptein, 1997). However, Amundsen and Ranes concluded that most accidents in tunnels occur in the first section of the tunnel. This has also as result that in a longer tunnel, relatively less accidents occur (Amundsen & Ranes, 2000). Allenbach et al. support these findings (Allenbach, Cavegn, Hubacher, Siegrist, & Cavegn, 2004). However, there are researches that state that in longer (>> 2 km) tunnels, more accidents occur, because the lowered concentration of drivers, as described by Bassan (Bassan, 2016). Nevertheless, Bassan concludes with a graph, derived from another research from Amundsen et al. that states that the number of accidents decreases in a longer tunnel (Amundsen, 2009).

Extreme long tunnels, like tunnels in Norway or the Alps are not present in the Netherlands. In the Dutch situation, tunnels can be roughly divided into 3 different length classes. There are exceptions but in general this classification holds. See Figure 2.1 for an overview of all tunnels in the Dutch highway system.

- Aqueducts / short underpasses	(< 200 m)
- Tunnels under waterways	(200 - 850 m)
- Landtunnels	(800 - 2600 m)

Figure 2.1 Tunnel lengths and corresponding tunnel types (Rijkswaterstaat, 2020)



While long tunnels (>> 2 km) are not present in the Netherlands, the hypothesis is that most of the accidents take place in the first part of the tunnel. This is the location where several circumstances are changing instantaneously. These circumstances are described in the following sections.

Lighting

A cause for the higher chance of accidents in the first part of the tunnel, is the lighting in tunnels. Carmody described in the nineties that drivers slow down at the entrance of a tunnel. This is due to lighting conditions, as well to the narrower space (Carmody, 1997). Drivers need a short period of time to adapt their eyes to different light conditions is also stated by Bassan (Bassan, 2016).

This effect is important in the safety assessment of the tunnel. However, the quantification of the effect is quite hard and not described by the literature. Furthermore, it is hard, to implement lighting in micro-simulation software. Therefore, lighting as specific aspect is not used in this research. However, the effect on the speed will be considered via other aspects (slopes & lane width).

Colour of the wall

In addition, Kircher and Ahlstrom state the importance of the colour of the walls. These must be light-coloured (Kircher & Ahlstrom, 2012). However, there are also contradicting studies. Allenbach et al. state that light density is not of significant influence on traffic safety (Allenbach, Cavegn, Hubacher, Siegrist, & Cavegn, 2004).

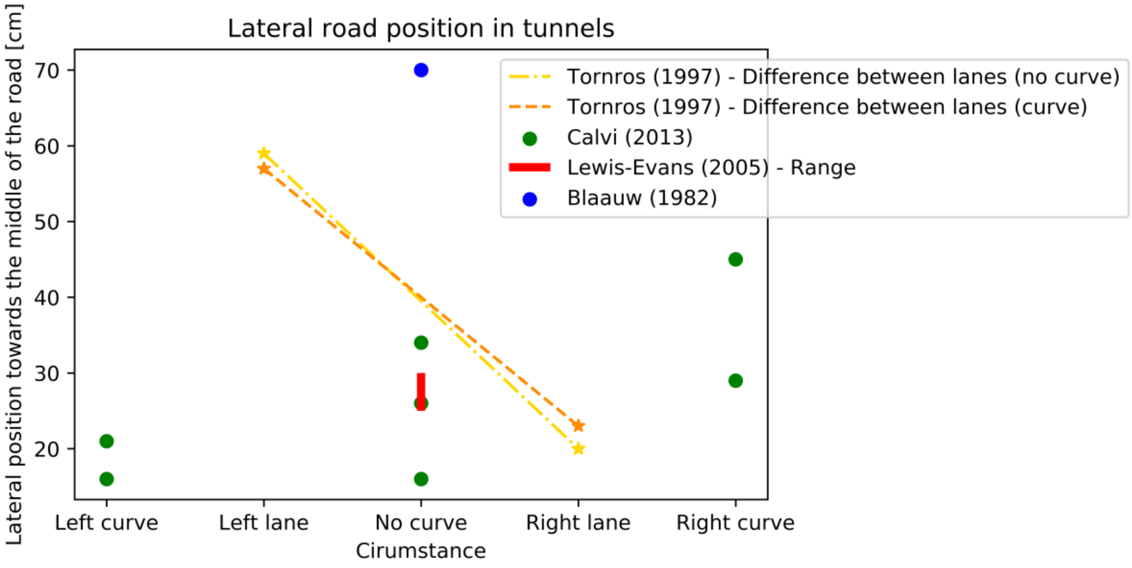
For the colour of the wall, basically the same holds as for the lighting. The quantification is hard and the effect will be dealt with in other effects. Therefore, this aspect will not be part of this research.

Lane width & Object distance

The lane width, but even more the distance to objects near the road, such as walls, are of great importance on the behaviour of drivers. The Capaciteitswaarden Infrastructuur Autosnelwegen (CIA) states that the absence of an emergency lane solely does not lead to capacity decrease (Heikoop, 2015). However, in a tunnel, the absence of an emergency lane often comes together with a decreased object distance. Blaauw and van der Horst did a comparison research between two tunnels in the Netherlands, one with emergency lane and one without. The conclusion was that without an emergency lane, drivers drive more to the centre of the road (Blaauw & van der Horst, 1982). The research from Blaauw and van der Horst also showed that if no emergency lane is present in the tunnel, the average speed before entering the tunnel is lower. Törnros showed that drivers take more distance towards the wall if the wall is on their left side. That research showed also the effect of curves on this effect (Törnros, 1998). Also, Martens and Kaptein state that fear of the tunnel wall causes lateral displacements (Martens & Kaptein, 1997). Calvi et al. did a simulator study in 2012 that showed the same results (Calvi, Blasiis, & Guattari, 2012). As already said by Törnros, also the Federal Highway Association in the United States (FHWA) states that narrow roads with small object distances leads to speed reductions. In their (archived) document, several speed decreases for different road widths are stated (FHWA, sd).

It is clear that the lane width and reduced object distance in tunnels are of influence on the lateral road position of cars and on the speed (as mentioned by Blaauw and van der Horst). However, the literature does not give a clear quantification of this effect. The effects identified by the literature are visualised in Figure 2.2. Nevertheless, this aspect is quantifiable and implementable in the micro-simulation software, so this will be part of this research. Furthermore, driving more towards the middle of the roads affects the traffic safety in the tunnel, so it is an important aspect and will therefore be taken into account.

Figure 2.2 Visualisation of effects of the decreased road width in tunnels identified in literature.



Slopes

The last aspect that has important influence on the driving behaviour in tunnels are (steep) slopes. Especially tunnels beneath (important) waterways face significant differences in height on a relatively small distance. The effect of slopes on traffic is described by several researchers. Lan et al. did research with a cellular automation approach and found that if the uphill slope is >3%, the effects are noticeable (Lan, et al., 2011). Van den Bos described several results of slopes on the Dutch Highway system and described how he implemented this in a model (van den Bos, 2002). The effect of speed differences leads to a non-homogeneous (or at least less homogeneous) traffic situation and that leads to less safety (Martens & Kaptein, 1997). Laureshyn et al. state that the speed difference might be more important on collision impact than the actual speed (Laureshyn, Svensson, & Hydén, 2010).

For the estimation of the speed drop of trucks, Rijkswaterstaat developed a tool, called SimVra+. SimVra+ is a software program developed by Rijkswaterstaat in 1998 (Bouwdienst Rijkswaterstaat, 1999). The simulation program can calculate the speed profile of trucks on (steep) uphill slopes. It is specially designed for tunnels and bridges on the Dutch road network. The program needs three inputs: the vertical alignment, a representative vehicle and some general circumstances.

While slopes cause a lot of effect on the speed of vehicles in tunnels, this aspect will be taken into account and actually be one of the main aspects.

2.2 Micro-simulation

As stated in the introduction, the goal of this research is to identify how micro-simulation software can be used to identify or compare traffic safety. In this section, literature about a calibration process of micro-simulation software, in this case Vissim, is described.

Calibration of Vissim

Several researchers did already calibration studies for Vissim on the Dutch highway system. Calibration is important because this improves the representation of the reality.

The researchers used empirical trajectory data to calibrate several parts of the Dutch highway system in Vissim. A few examples are described by Bosdikou, Oud and Rossen (Bosdikou, 2017; Oud, 2016; Rossen, 2018). Bosdikou stated in her conclusion that SSM derived from a calibrated Vissim model holds the potential (under certain conditions) to be used for traffic safety evaluation. This is also researched extensively by van Beinum in his PhD research (van Beinum, 2018). The following information is gained from this research, unless stated differently.

Basically, the effect of a tunnel on the traffic flow is increased turbulence. As van Beinum state in his PhD research,"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 of lane change locations, headway distribution (on each lane) and gap acceptance." (p.110) Furthermore he stated that it is important that the traffic is distributed realistically over the lanes, with fast driving vehicles on the left lane and slow driving vehicles on the right lane. A measure for this is the mean headway per lane (what is basically the intensity) and the mean speed and corresponding standard deviation on each lane. The simulation error in VISSIM is calculated for the following aspects (γ):

- Mean speed
- Std. of the speed
- Mean headway
- Mean accepted gap
- Std. of the accepted gap

For the calibration of the model, van Beinum minimized the root-mean-square error (RMSE). The used formula is shown in equation (2.1) .

$$\varepsilon_i = \beta_i \cdot \sum_{n=1}^{N} \sqrt{(\hat{y}_t - y_t)^2} \tag{2.1}$$

Where: β_i is a scaling parameter for different factors
n is the lane number

From the literature, it would be preferable to calibrate the model on the aspects speed, headway (or intensity) and gap acceptance (or lane change location). If these indicators match reality, the safety assessment will also match reality.

2.3 Surrogate safety measures

'Surrogate safety measures' (SSM) is a term the FHWA introduced in 2003 (FHWA). SSM is an alternative for the estimation of safety based on accident data. This is of great use because accident data is often incomplete, inaccurate and unreliable. With the use of SSM, micro-simulation software can be used to estimate the traffic safety.

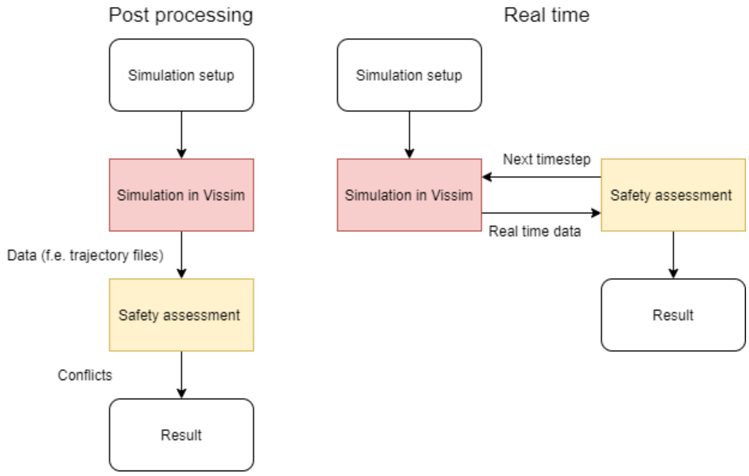
SSM is the general term for alternative measures that can assess traffic safety based on trajectories. There are many surrogate safety measures, amongst others described or put together by the FHWA, (FHWA) Young at al. (Young, Sobhani, Lenné, & Sarvi, 2014), Pirdavani et al. (Pirdavani, Brijs, Bellemans, & Wets, 2010) and Wu et al. (Wu & Jovanis, 2013). Also van Beinum created a clear description in his research (van Beinum, 2018). However, the three measures described below (TTC, PET and DRAC) might be suitable for this research. Those measures are the most occurring and accepted measures and supported by the FHWA.

Real time versus Post processing

Before introducing the SSM, it is important to distinguish between post processor measures and real time measures. Post processor measures can be calculated after an initial simulation. The simulation saves the necessary data (for example trajectories) and afterwards this data can be analysed by a tool or in a self-programmed analysis environment. Real time measures must be calculated during the simulation and requires a direct connection between the simulation software and a programming environment for this calculation. A visualisation is shown in Figure 2.3

Real time simulations might create good insights, however, there are several disadvantages. First, the simulation time is much higher because of the calculation of the SSM every simulation step. Second, the risk on simulation failures will be higher (such as a crash of the simulation software) because of the constant interruption via the programming environment. Due to these practical disadvantages, the use of post processor measures is favourable above real time simulations, if it is possible to derive the wanted results with post processor measures.

Figure 2.3 Visualisation of Post processing and Real time safety assessment



TTC

FHWA studied several measures and concluded that the measure that is proposed primarily is the time to collision (TTC). The TTC is defined by Hayward as: ”the time required for two vehicles to collide if they continue at their present speeds and on the same path” (Hayward, 1972). However, TTC has a disadvantage: it is often calculated in a post processor on the simulation model outputs (Young, Sobhani, Lenné, & Sarvi, 2014). The TTC can be explained as the time it takes for a vehicle to hit another vehicle without deceleration or acceleration of both vehicles.

PET

Another SSM is the post encroachment time (PET). The PET is defined as “the representation of the difference in time between the passage of the ‘offending’ and ‘conflicting’ road users over a common area of potential conflict” (Pirdavani, Brijs, Bellemans, & Wets, 2010).

TTC is only applicable if two vehicles are on ‘crash course’, so basically if they are on the same line. However, a potentially dangerous situation also occurs if vehicles are on a different course and just miss each other. These situations can be quantified by using the PET. Van der Horst defines the PET as the time between the moment that the first road user leaves the path of the second and the moment that the second road user reaches the path of the first (van der Horst, 1990).

Crash Potential Index

A third surrogate safety measure that can be used is the deceleration rate to avoid the crash (DRAC). The DRAC is reflecting the deceleration rate of a car needed to come to a safe standstill without causing a crash. In combination with the maximum available deceleration rate of a car (MADR), the so-called Crash Potential Index (CPI) can be calculated. This measure is described and calibrated by Cunto (Cunto & Saccomanno, 2008; Cunto, 2008). However, this measure requires a real time simulation approach, and has therefore practical disadvantages compared to the TTC and PET. Therefore, this SSM is not used in this research.

SSAM-tool

The FHWA has created a tool, the SSAM tool, that can calculate the TTC and PET after running the simulation in Vissim (a post processing approach). A disadvantage of this is that lots of data need to be transferred between different software programmes. However, it makes the process more stable, more transparent and the SSAM tool is used in several researches already, and therefore scientifically proven. Also, the SSAM tool is very straight forward in use. Another advantage is that the PET is the only SSM that can identify conflicts due to lane changes. So, on highways, it is useful to calculate the PET.

2.4 Recap of important issues

From the literature, important issues for traffic safety are determined. In short, the main aspects that have influence on traffic safety in tunnels, and can be quantified for micro-simulation, are lane width/object distance, intensity, tunnel length and slopes. These findings are the preliminary answers to research question 1: "**What aspects are suitable and quantifiable for traffic safety assessment in tunnels?"**

The calibration of the micro-simulation model can be performed by comparing intensity, speeds and gap acceptance for different (measurement) locations. By calculating the root mean square error (RMSE) different parameter settings can be compared to each other and create insight if the simulations are representing reality.

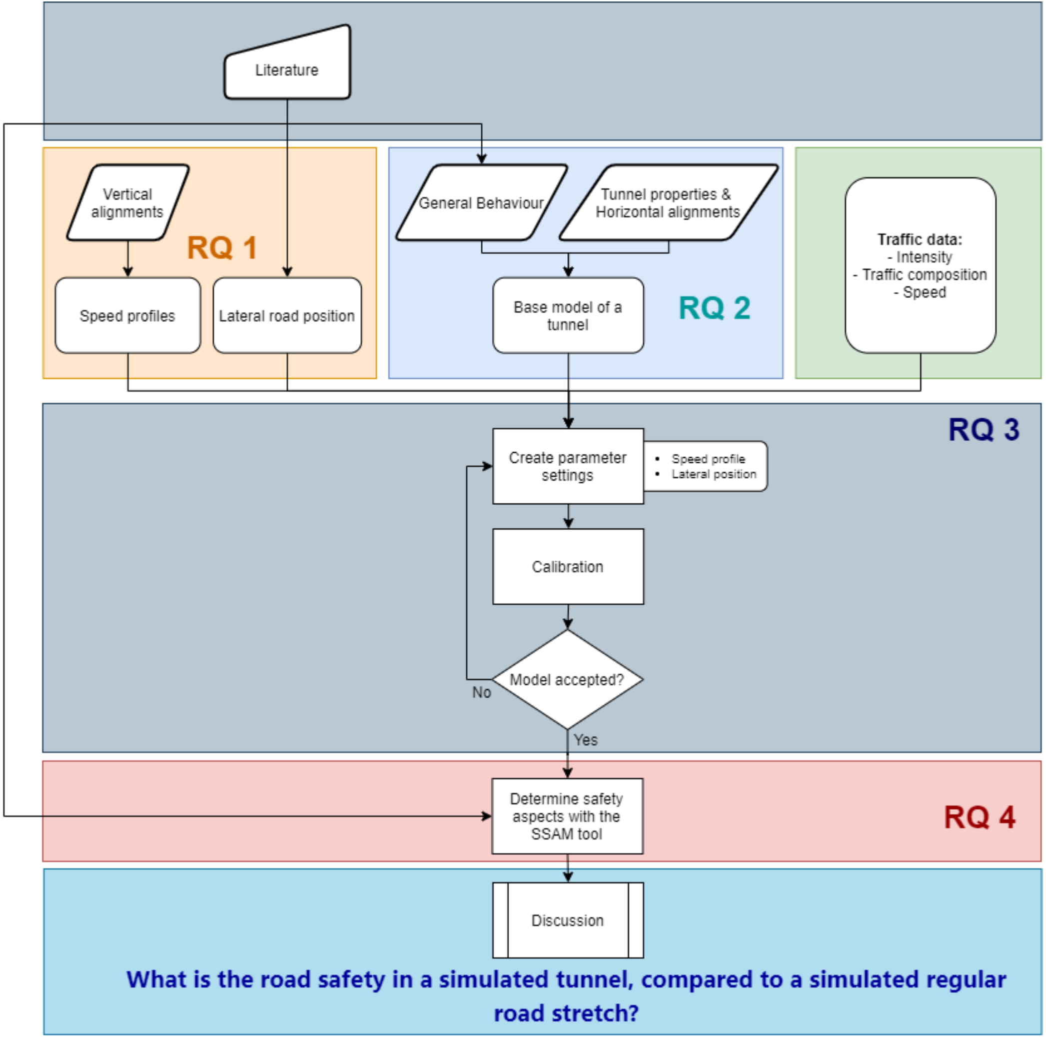
The last important finding from the literature is the procedure to assess safety with the use of micro-simulation software. The most commonly used surrogate safety measures that can be used are TTC and PET. These can easily be calculated with the SSAM tool. This provides also the first step to answer research question 4: **"What is the traffic safety in a simulated tunnel, compared to a simulated regular road stretch?"** while the literature provides methodologies and a tool to assess the traffic safety.

3

METHODOLOGY

This chapter describes the research methodology and consists out of six sections. The complete research methodology is shown in Figure 3.1 and further explained in section 3.1. The numbers in the different boxes correspond with the research questions. Secondly, the fixed model settings for Vissim are described, followed by the variable model settings in paragraph 3.2 and 3.3 **(RQ 1 & RQ 2)**. In paragraph 3.4, the processing of NDW loop detector data is explained. In 3.5, the calibration process of the model is elaborated (**RQ 3)**. In the last section, section 3.6, the calculation of the surrogate safety measures and the use of the SSAM tool is described **(RQ 4)**.

Figure 3.1 Extended overview of the research process



3.1 General methodology

The general methodology of this research is explained in the following seven steps.

1. **Select tunnels based on suitable and quantifiable tunnel aspects**
   Four existing tunnels are chosen by the use of selection criteria. These selection criteria are based on the suitable and quantifiable aspects, derived from the literature (RQ 1). The exact selection procedure is described in Appendix N.

2. **Design model / tool**
   With Python, a tool is designed and build that makes traffic simulations with multiple parameter settings possible. This tool has a two folded function. The first function is to perform calibration with as goal to derive the parameter setting that represents the reality the best. The other function is to derive trajectory data from Vissim that can be used for the safety assessment in the SSAM tool. The user interface of the tool is shown in Appendix P.

3. **Design tunnels**
   The next step is the design of the tunnels in Vissim. The design approach is described in sections 3.2 and 3.3. The tunnel design is connected to the tool, so it is easy to research multiple tunnels and multiple parameter settings.

4. **Simulation of tunnels**
   The chosen tunnels are simulated with different parameter settings. The best parameter set is determined (calibration, see 4.1) and for the best parameter setting, the safety is assessed with SSM (see 4.2).

5. **Simulation of normal road stretches**
   To compare the results of the tunnels, a reference normal road stretch is needed. For a fair comparison, a road stretch with an identical lay-out as the tunnel is used but no tunnel aspects (slope, object distance) are implemented. It is assumed that the normal road stretch without tunnel aspects represents reality with the used behavioural settings. This normal road stretch is simulated and the traffic safety is assessed with the SSAM tool.

6. **Comparison tunnels and normal road stretches**
   To identify the differences in safety between the tunnel and the normal road stretch, quantitative and qualitative comparisons are performed. Insight in the differences is created by making visualisations of the conflict density on the road. The results of this comparison are shown in chapter 6 and discussed in chapter 7.

7. **Comparison between tunnels**
   In order to create more insight in the effect of specific tunnel aspects, also the results of different tunnels, with different tunnel aspects, are compared with each other. This qualitative comparison creates insight in the specific effect of a tunnel aspect. Together with the comparison between a tunnel and a normal road stretch, this provides an answer to the main research question.

3.2 Fixed model settings

Research question 1 & 2

The implementation of the tunnels in Vissim consists out of two different parts. The fixed part, that does not change for a specific tunnel, and the variable part, what can be changed in the settings. In this section, the fixed parameters are explained. First, the 'hardware' is described and afterwards the behavioural parameter setting is explained.

General properties

In Vissim, several properties of the roads must be defined. The first property is the road lay-out. In Vissim, the satellite image is used as background and the road is projected on that background. This assures the correct horizontal alignment.

The second aspect is the maximum speed for all vehicle classes. The maximum speed in Vissim is a distribution where each vehicle draws a desired maximum speed for itself. For example, if the maximum speed is 120 km/h, one vehicle would choose 125 km/h as appropriate, while another vehicle will pick 115 km/h. The maximum speed is set based on the information of Rijkswaterstaat (Rijkswaterstaat, 2020) and a check is done if this corresponds with the time period of the calibration data.

The third aspect are the locations of the loop detectors. With the NDW data (NDW, 2020), these loop detectors are placed into Vissim as Data Collection Points.

Behavioural parameters normal road stretch

While there is a lack of individual car data in tunnels, an assumption made is that the basic driving behaviour in tunnels is the same as on a normal road stretch. As stated in the literature review, some calibration studies for the Dutch highways are performed. The study of Rossen is focused on automated vehicles and therefore not very useful (Rossen, 2018). The study of Oud focusses on the desired headway, the Free Driving Time and the Safety Distance Reduction Factor (Oud, 2016). Bosdikou did an extensive calibration study for Dutch weaving sections and also included a sensitivity analysis to determine the factors that are the most important. While the study of Bosdikou is the only complete calibration study known, those calibrated values are used in this study. (Bosdikou, 2017) All behavioural factors and the final settings are shown in Appendix C.

3.3 Variable model settings

Research question 1 & 2

In the research, two aspects of the traffic behaviour are varying: speed and the lateral road position. For the simulation in Vissim, two aspects are important: relevant and logic input values and correct and useful results. First, the speed input is described and second the lateral road position.

Speed profiles

In Vissim, there is a possibility to create slopes, however, the effect of these slopes on the traffic dynamics is very ambiguous. Therefore, another approach is chosen with the help of SimVra+.

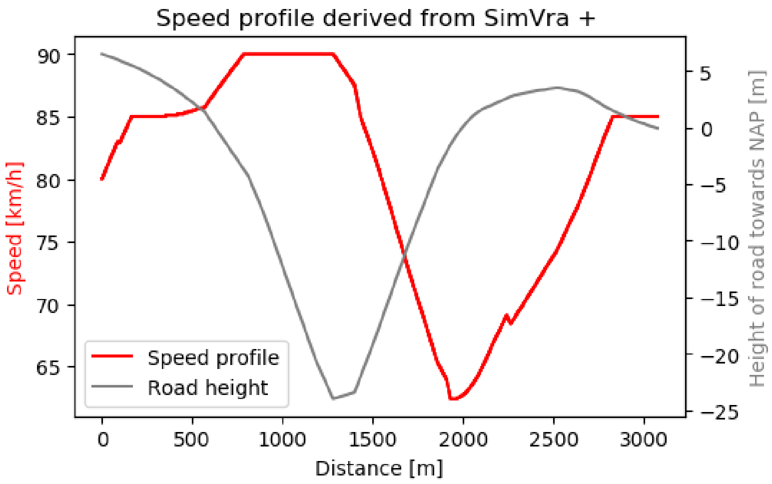
SimVra+

Simvra+ is a software program developed by Rijkswaterstaat that creates speed profiles for freight traffic on slopes (see also 2.1). For the vertical alignment, an ASCII-file can be imported. This file contains x- and z-coordinates of the road. The height profiles are derived from the DTB (Rijkswaterstaat, 2020) and via a Python-script transformed into the correct format. More information about this procedure can be found in Appendix A. Also, the maximum speed and road surface must be chosen. While the maximum speed in SimVra+ is the absolute maximum speed of a vehicle (it will not exceed that limit), that value is set to 90 km/h. The road surface is ZOAB (default value).

The second input requires a representative vehicle. According to expert users of the program, the standard vehicle is used. This is underpinned by the idea that the SimVra+ output is only a guide for the simulations, as described in the next paragraph.

The third input are the circumstances. The starting speed of a truck is set to 85 km/h. While the scope is limited to dry situations in the spring (see 3.4), there is no wet or slippery road surface. The wind force is set to 0 because the wind does not have a lot of influence on the speed profile and the wind is varying and therefore difficult to take into account. Because the SimVra+ output is only a guide, this does not cause problems. In Figure 3.2, an example of the output of SimVra+ is shown.

Figure 3.2 Example of speed profile derived from SimVra+



Implementation in Vissim

While SimVra+ only creates a speed profile for a truck and is only calibrated for uphill slopes, it is not sure if the derived speed profile is the speed profile that applies to the tunnel. Also, no speed profile for cars can be derived from SimVra+. Preferably, one would first check the validity of SimVra+ with the help of loop detector data, but due to the lack of vehicle classification in the available loop detectors, this is not possible. Therefore, several speed profiles are simulated to obtain the most appropriate input value.

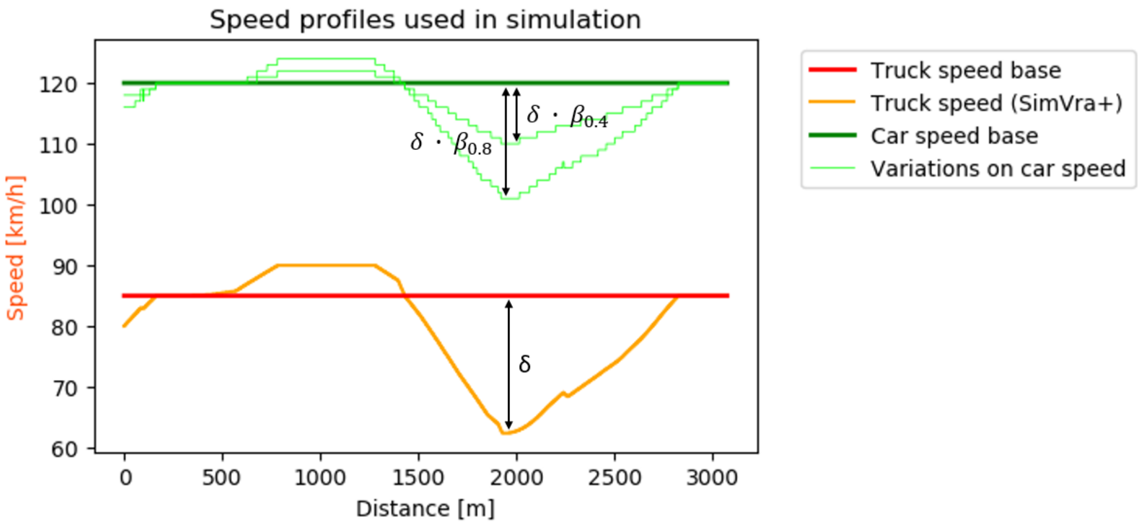
The speed profiles are created in two ways. First, there is a variation on the truck speed profile by just multiplying the derived speed profile with a factor. This is described in equation (3.1).

$$v_{truck,\alpha} = v_{truck_{base}} * \alpha \qquad \forall\, \alpha \in (0.8, 0.85,\ 0.9, 0.95, 1, 1.05, 1.1, 1.15, 1.2) \tag{3.1}$$

The estimation of a car speed profile is a little bit more complex. The idea is that cars follow the same profile as trucks (speeding on downhill slopes, losing speed on uphill slopes) but in a limited amount. The chosen approach is described by equation (3.2) and illustrated in Figure 3.3.

$$v_{car,\beta} = v_{car_{base}} - (v_{truck_{base}} - v_{truck_{SimVra+}}) * \beta \qquad \forall\, \beta \in (0, 0.2, 0.4, 0.6, 0.8, 1) \tag{3.2}$$

Figure 3.3 Illustration of the design of the car speed profiles



For the implementation in Vissim, the speed profiles are divided into sections of 100 meters and rounded to an available speed distribution in Vissim. Then, the speeds are assigned to the reduced speed areas in Vissim. These areas 'tell' the vehicles driving on it what their desired speed is. The vehicle tries to reach this speed, within the limitations of surrounding traffic, maximum acceleration and deceleration.

Lateral road position

Literature

The lateral road position is the other variable of the implementation in Vissim. From several researches (for example Blaauw and Van der Horst (Blaauw & van der Horst, 1982)), it is deduced that vehicles tend to drive more to the centre of the tunnel, if the tunnel wall is close by. However, there is no consensus on the exact effects and it is dependent on the circumstances. From the literature, no exact values can be derived.

Implementation in Vissim

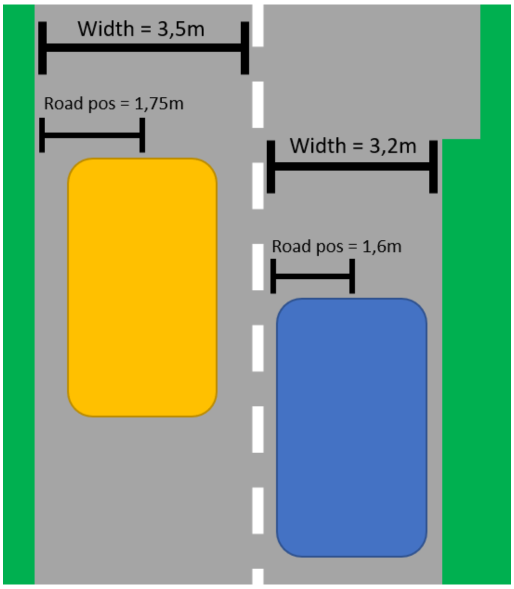
To implement this in Vissim, two different approaches are used, of which one was applicable. However, the non-applicable option is explained first to clarify why the second approach is used. The first option consists of tweaking the actual lateral road position of vehicles in Vissim. The setting for lateral road position can be set to:

- Left side of the lane
- Middle of the lane (default)
- Right side of the lane
- Any

This setting is fixed, so the middle of the lane means the exact middle of the lane for every vehicle. While in real life, this is not the case, a distribution might be more suitable. The 'Any' option unfortunately does not offer a clear distribution, so this option is also not feasible. The analysis of the 'Any' option is shown in Appendix D. However, every vehicle in Vissim has a lateral road position and this position can be read at every time step. To change the lateral road position for a vehicle manually (via a Python script) would be a good solution, however, the COM interface of Vissim does not allow this.

While the pre-defined settings and manually setting the lateral road positions are not applicable, an alternative approach is used. As mentioned, the middle of the lane setting is a fixed value. This property is used to put the cars more to the middle of the road by change the actual road width. So, if the lane width is narrowed with 20 cm, the lateral road position is effectively replaced 10 cm towards the centre of the road. In Figure 3.4 an example is shown.

Figure 3.4 Setting lateral road position in Vissim by changing the physical lane width.



3.4 Processing of (loop detector) data

Research question 3

For the calibration process and input of several scenarios, the NDW loop detector data is used (NDW, 2020). This data is obtained via the data explorer and exporter of the NDW named Dexter. In this section, the use of this data is explained. First, the selection of data is described. Secondly the processing methodology is presented and the last section describes the estimation of traffic composition.

Data selection

The data selection process consists out of two different steps. First, the temporal and spatial selection takes place, and second a quality filter is applied. In the CIA, it is stated that standard capacity values are valid in cases of day-light and dry weather (Heikoop, 2015). To limit the scope, only 'standard' circumstances are taken into account. So, the selection and filter should fulfil these requirements.

The temporal and spatial data selection basically consists out of 3 different aspects: time, aggregation level and location. The Dexter interface allows users to already pre-process the data before exporting it. As stated by the CIA only day-light hours are selected. However, rush hours are of great interest, because of the high intensities. These two aspects result in a time restriction from **07:00:00 till 18:59:59** in the months **April till June**. In this research the data of **2018** is used. Weekends and holidays are not representative for daily traffic and therefore removed from the data.

The aggregation level can also be selected in Dexter and no more manual aggregation is needed. The aggregation period are 5-minute intervals. 5-minute intervals produce quite stable outcomes (compared to 1-minute intervals) but are short enough to limit simulation time. An example is shown in Appendix C.

Selecting the locations for the data has to be performed manually. In Dexter, it is possible to just zoom in on the tunnel and select the correct loop detectors.

The day-light constraint is already taken care of in the temporal selection. For the weather constraint, the data is filtered by the use of hourly KNMI data (KNMI, 2020). For every tunnel, the nearest weather station is selected. In the CIA, dry weather is defined as < 2 mm precipitation per hour. If the precipitation in an hour is ≥ 2 mm, the corresponding datapoints are deleted from the dataset (Heikoop, 2015).

The data quality is already checked and filtered by Dexter. Data errors are filtered automatically and if there is a data error in more than 20% of the data, it is completely ignored.

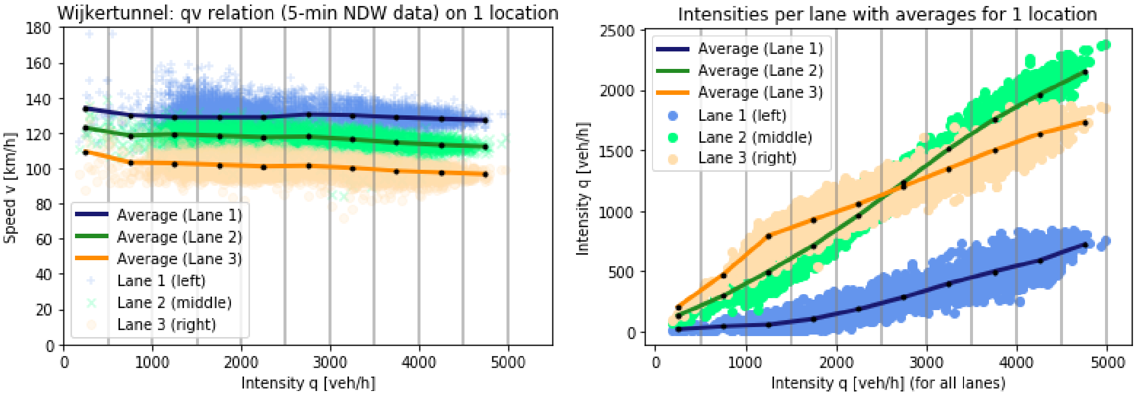
Data preparation

The data of the NDW consists out of two important measurements: speed and intensity. To make it possible to compare simulated values with the measured values, the measurement data needs to be transformed into usable data. This transformation consists out of two steps: filtering congestion and determine average values.

The first step is to filter congested datapoints. This is necessary, because of two reasons. First, it is hard to calibrate the model on congested datapoints while congestion can have several causes with different results in behaviour. Second, driver behaviour is different in congested traffic compared to free-flow traffic so determining conflicts will give different results. So, to limit the scope of this research, only free-flow situations are taken into account. The filtering is done by using an intensity-density plot. In this intensity-density plot, a filter is applied which filters out all datapoints that are in the congested branch of the plot. The result is a dataset with only measurements in free-flow traffic. The exact methodology, including an example, is explained in Appendix G.

With the filtered data, it is possible to determine the average values. This is done for both measurement values: speed and intensity. While the vehicle input in Vissim consists out of a fixed number, the measurement data is aggregated in predefined batch sizes. In the research, these batch sizes are dependent on the input values of Vissim. The average is the mean of all (filtered) measurement points for a lane in a specific batch. In Figure 3.5, an example of these averages (the black dots) is shown, for a batch size of 500 veh/h on a 3 lane road.

Figure 3.5 Average speeds for 3 lanes on 1 location in the Wijkertunnel and the intensities per lane [1]



Traffic composition

For the traffic composition, the traffic is divided into two classes: cars and trucks. This classification is based on the NDW classification. The NDW has three classifications, with 1, 3 and 5 different vehicle classes. In Table 3.1, the classification in 3 vehicle classes is shown. For the translation to 5 vehicle classes, the description of the NDW can be consulted (Unknown, 2013).

Table 3.1 Categories of the NDW and the classification in this research.

Category NDW	Name of category	Vehicle length	Category research
Cat 1	Motor, scooter, car, delivery van	< 5.60m	Car
Cat 2	Rigid truck, rigid bus	>= 5.60m & <= 12.20m	Truck
Cat 3	Articulated truck	> 12.20m	Truck

To keep the research limited, for each tunnel direction only one percentage of freight traffic will be used. This percentage is gained by calculating the percentage of freight traffic for every 5-minute interval of the NDW data used in the research. An example of the Wijkertunnel are shown in Appendix B.

Only a limited number of loop detectors of the NDW distinguish vehicle classes. For some tunnels, determining the exact percentage freight traffic is not possible. In that case, an estimation is made by using loop detectors that are close by. Also, the use of INWEVA data is possible to check if unexpected values are gathered (Rijkswaterstaat, 2020).

3.5 Calibration process

Research question 3

A very straight forward one-factor-at-a-time approach is used to search for the best parameter setting. This is done because the created model is already quite extensive and creating a mathematical minimisation problem would cost a lot of resources. For the calibration of the model, the key performance indicators should be minimised. The specific used key performance indicators are described in chapter 4.1.

---

[1] One would expect more cars on lane 1 on a 3-lane road. However, this is an example from the Wijkertunnel where lane 1 is a crawler lane on the left side of the tunnel that converges after +/- 1 km. Therefor the intensity on lane 1 is quite low and the speed quite high.

3.6 Surrogate Safety Measures

Research question 4

In this section, the use of the SSAM tool is explained.

SSAM tool

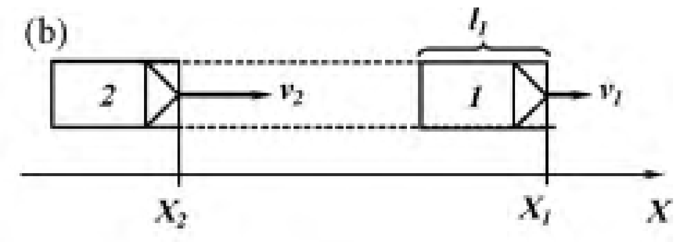
The SSAM tool needs three threshold values. Here those values are briefly explained. For a more technical description of the SSAM tool, see the report of Gettman et al. (Gettman, Pu, Sayed, & Shelby, 2008). The used SSM are extensively described in 2.3.

The first threshold value is the maximum TTC value. This value defines the accepted time where a TTC value is defined as conflict or not. The default value is 1.5s, so if a TTC ≤ 1.5 s, a conflict is identified. According to Gettman et al., a TTC > 1.5 s is not seen as a problem. An important issue is that TTC values of 0 should be filtered out of the conflict data because this value simulates a real crash and that is not realistic, according to Gettman et al. and applied by Bosdikou (Bosdikou, 2017).

In equation (3.3) and Figure 3.6, the TTC is showed in a mathematical formula and a schematic overview. The letters in the equation and the figure correspond with each other. If the TTC value drops below a certain threshold value (in the SSAM tool 1.5 s), this can be seen a potentially dangerous situation, and therefor as a conflict.

$$\mathrm{TTC} = \frac{X_1 - X_2 - l_1}{v_1 - v_2}, \qquad if\ v_2 > v_1 \tag{3.3}$$

Figure 3.6 Schematic figure of the TTC calculation in a straight road example (Laureshyn, Svensson, & Hydén, 2010)

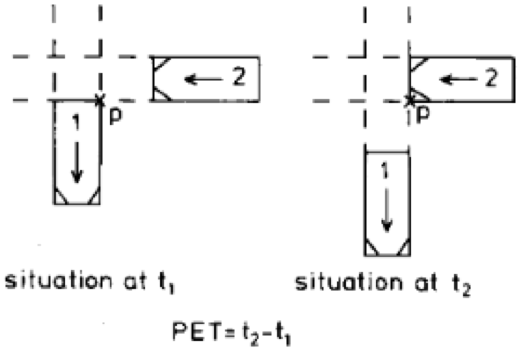


The second threshold value is the maximum PET value. The default value is 5 s. This is not changed because this value is based on scientific research of Gettman et al. The mathematical formula is shown in equation (3.4) (Mullakkal-Babu, Wang, Farah, van Arem, & Happee, 2017) and the PET is schematized in Figure 3.7. Both, the TTC and the PET are included in the SSAM software developed by the FHWA. (FHWA)

$$\mathrm{PET} = \frac{X^e - X_j}{v_j} - \frac{X^e - X_i}{v_i} \tag{3.4}$$

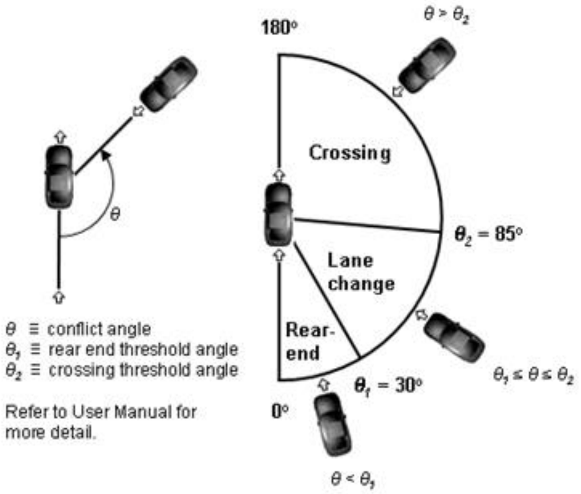
where: *X_j and v_j are the position and velocity of the first vehicle*
X_i and v_i are the position and velocity of the second vehicle
X^e is the longitudinal position of the encroachment line

Figure 3.7 Schematization of PET (van der Horst, 1990)



The third threshold value defines the angles of conflicting vehicles that distinguishes different conflict types. In Figure 3.8 this is visualised. As can be observed, if a conflict angle < 30˚ this is classified as rear-end conflict, if it is >= 30˚ and =< 85˚ it is classified as lane change conflict and if it is > 85˚, this is a crossing conflict. The last one, does not occur in a uni-directional tunnel. The used values are the default values of the SSAM tool.

Figure 3.8 Different conflict classifications based on the defined angles (derived from the SSAM tool)



4

ASSESSMENT FRAMEWORK

The assessment framework describes how the raw results of the simulations are transformed into explainable data. To give senseful meanings to the outcome of the simulations, Key Performance Indicators (KPI's) are described. These KPI's are measures that are derived from the results that describe the results in such a way that a comparison is possible.

In this research, there are two points where a set of KPI's is used. The first point is during the calibration. The KPI is used to compare different parameter settings to each other and determine which parameter setting give results that are closest to reality. The second set of KPI's is defined to assess the safety of the simulated roads. This KPI consists out of the Surrogate Safety Measures. In this chapter, first the calibration KPI is described and afterwards the safety assessment KPI's are described.

4.1 Calibration

The calibration consists out of two parts, the qualitative and quantitative calibration. The qualitative calibration is based on visual inspection of figures. The figures plot the differences in speed and intensity for all locations for different input intensities. With these figures, it is possible to check what the general trends are and if this corresponds with reality.

The second part is the quantitative assessment. The calibration KPI is based on the RMSE. The lower the RMSE, the closer a result is to reality. The RMSE is calculated for all measurement locations for all lanes separately and summed for all input intensities. In equations (4.1) and (4.2) the formulas for the RMSE are given.

$$RMSE_{q,p} = \sum_{i=1}^{I} \sqrt{\frac{\sum_{x=1}^{X} \sum_{l=1}^{L} (q_{Vissim,x,l,i} - q_{NDW,x,l,i})^2}{X * L}} \tag{4.1}$$

where: *x is the location in the set X of all locations*
l is the lane in the set L of all locations
i is the input intensity in veh/h in the set I of all input intensities
q is the average intensity in veh/h over 5 min

$$RMSE_{v,p} = \sum_{i=1}^{I} \sqrt{\frac{\sum_{x=1}^{X} \sum_{l=1}^{L} (v_{Vissim,x,l,i} - v_{NDW,x,l,i})^2}{X * L}} \tag{4.2}$$

where: *x is the location in the set X of all locations*
l is the lane in the set L of all locations
i is the input intensity in veh/h in the set I of all input intensities
v is the average speed in km/h over 5 min

While it is convenient to have one value which is comparable, the KPI value for a parameter setting is defined as the average between the normalised RMSE values for intensity and speeds. So, for parameter setting p, the speed RMSE value is divided by the average of all speed RMSE values. The result is a value that lays around 1. The same is done for the intensity RMSE and the mean of those values is the KPI value. This is mathematical described by equation (4.3).

$$KPI_{cal,p} = 0.5 * \left(\frac{RMSE_{q,p}}{\frac{\sum_{p=1}^{P} RMSE_{q,p}}{P}} + \frac{RMSE_{v,p}}{\frac{\sum_{p=1}^{P} RMSE_{v,p}}{P}}\right) \qquad (4.3)$$

where: *p is a parameter setting out of set P with all parameter settings*

4.2 Surrogate safety measures

The KPI of the surrogate safety measures is also both qualitative as quantitative. The qualitative assessment consists out of figures where the number of conflicts is plotted per location and different input intensities. The plot is normalised by dividing the number of conflicts by the input intensity, so the final figure shows the number of conflicts per vehicle. Also, difference plots between normal road stretches and the corresponding tunnels are created to identify the safety effects of the tunnel aspects.

Besides the qualitative assessment, there is also the quantitative assessment. The quantitative assessment consists out of the comparison of a few KPI's:

- Total number of conflicts
- Percentage of different conflict types.
- Mean TTC for all conflicts
- Mean PET for all conflicts

Total number of conflicts

The first quantitative KPI is the total number of conflicts. While the vehicle input and the road length are the same for as well a tunnel as the normal road sections, this creates insight in the 'total' difference in safety.

Percentage of conflicts per conflict type

While the SSAM tool distinguish in conflict type, based on the angle of impact, these values can be compared. SSAM distinguishes between rear end conflicts, lane changing conflicts and crossing conflicts. However, the latter will not occur in highway tunnels. If there is a significant difference in the conflict types, it is interesting to identify the cause of this difference.

Mean TTC and PET for all conflicts

The mean of the TTC value and of the PET value create insight in the 'severity' of the conflicts. If the values are lower, the conflict is more severe. Therefore, it is interesting to see if the TTC and PET values for the tunnel are different from the straight road section.

5

SIMULATION SETUP

In this chapter, the simulation setup is described. First, the tunnel choice is described. After this tunnel choice, the parameter settings and other simulation issues, like run length, number of simulations and the technical description of the model are described. For a clear way of reporting, this chapter focusses for some aspects only on one tunnel in one direction (Wijkertunnel from South to North). While the methodology for all tunnels is the same, this single tunnel gives a representative example for the other tunnels.

5.1 Tunnel choice

After the application of the choice process, 8 tunnels are accepted and classified, as shown in Table 5.1. The complete selection process is shown in Appendix N.

Table 5.1 Accepted tunnels with classification (in brackets: short notation)

With emergency lane, with slope	**With emergency lane, without slope**
Wijkertunnel (WK)	Leidscherijn Tunnel (LR)
Without emergency lane, with slope	**Without emergency lane, without slope**
Beneluxtunnel (BL) Koning Willem-Alexandertunnel * (KWA) Heinenoordtunnel Botlektunnel Zeeburgertunnel Noordtunnel	-- No Tunnels --

** It appeared to be that the KWA tunnel has a significant slope, what is unexpected because it is a landtunnel and therefore cannot be used for the last classification.*

The above classification makes it possible to compare different aspects of tunnels to each other besides the comparison between a normal road stretch and a tunnel. The proposed comparisons are shown in Table 5.2.

Table 5.2 Proposed comparisons

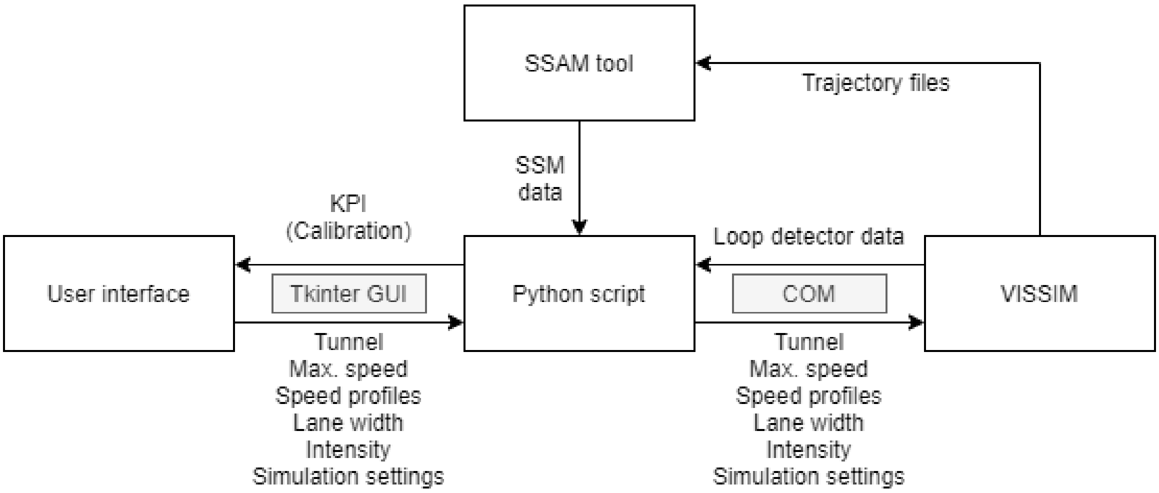
Nr	Tunnel 1	Tunnel 2	Comparison of which effect	Clarification of aspect
1	BL	WK	Emergency lane	No vs. Yes
2	WK	LR	Slope	Yes vs. No (with EL)
3	KWA	LR	Emergency lane	No vs. Yes

5.2 Technical Description Model

The used model consists out of a Python script, with a self-designed user interface, connected with Vissim by COM. While the whole model is extensive, here a general description of the model is presented. The complete model can be derived via the author. Screenshots of the user interface are shown in Appendix P. The model is built around (several) Python scripts. These scripts perform the following steps: (visualised in Figure 5.1)

1 Interpreting the user interface
2 Send interpreted parameters via COM to Vissim
3 Run simulations in Vissim
4 Receive raw loop detector data from Vissim
5 Compare loop detector data from Vissim and NDW (calibration) and return this to the user interface
6 Run multiple runs in Vissim with calibrated values
7 Vissim sends .trj files to SSAM tool
8 Python interpret SSM data and make visualisations

Figure 5.1 Data transportation between several parts of the model



5.3 Experiment settings

In this section, the experiment settings are explained. First, the warm-up length is determined. Second, the chosen method and the number of replications is explained.

Warm-up

In the simulation, it takes some time before a so-called steady state is reached. While this steady state is a realistic condition, the period that it takes before the model reaches it steady state needs to be removed. This can be done in several ways, however, the graphical method is the most straight forward method and gives a good indication, as described by Robinson. (Robinson, 2014) The explanation of this method is shown in Appendix I. For all tunnels, a warm-up time of 600 seconds is sufficient.

Number of runs

For the number of runs, also the graphical method described by Robinson (Robinson, 2014) is used. The principle is the same as for the warm-up method. Perform several runs, plot the moving average and determine when the moving average becomes stable. This method is explained in Appendix J. For all tunnels, 20 batches were sufficient.

For the calibration of the Vissim model, the 20 batches are sufficient, while the intensity as well as the speed are stable after 20 batches. However, the final result that is derived from Vissim, is the input for the SSAM tool. After some trial and error, it became clear that 1 run with of 6000 seconds (corresponds with 20 batches) solely does not cause enough conflicts to create clear results. Therefore, for the SSM assessment, 10 runs of 6000 seconds each are performed.

5.4 Input settings

The input settings consist out of 3 different subgroups. These subgroups are fixed model settings, tunnel dependent settings and variable settings. While Vissim has a tremendous amount of settings, only the ones that are not default, or those who are relevant for this research are described. Non-mentioned settings can be considered as default.

Fixed model settings

The most important fixed parameter settings are the behavioural settings. As derived from the literature, the values of Bosdikou (Bosdikou, 2017) are used as described in Appendix C. Besides those settings, a few changes are made. First, the 'Overtake reduced speed areas' is selected. This makes sure that vehicles do not see reduced speed areas (RSAs) as 'dangerous' place where overtaking is not allowed. The use of RSAs is 'normally' used to create speed drops in for example sharp curves, where overtaking is not desired. However, in this research, the RSAs are meant to model the slopes of the road, where overtaking is not a problem.

The second important setting is the 'Observe adjacent lane(s)'. In this research, it is important that vehicles from different lanes interact with each other. Especially when the lane is narrow due to the tunnel wall, it is expected that drivers might decrease their speed because of the reduced space available. If a truck is driving on the right lane, it can be expected that a car on the left lane suffer some speed drop from this truck. This effect is determined by the minimum lateral distance required between vehicles. In the default settings, cars will not overtake trucks anymore because the required minimum lateral distance is too high. Therefore, this value is decreased. The used values can be seen in Appendix E.

While the Dutch highway system has a 'slow lane rule', where the standard is to drive on the right side of the road, this option is selected as general lane change behaviour.

All those values (behavioural, overtaking RSAs, minimum lateral distance and the slow lane rule) are saved as a new driving behaviour and this driving behaviour is assigned to the road.

Also, an overtake restriction for trucks is implemented in every tunnel, while it is not allowed for trucks to overtake other vehicles.

Tunnel dependent settings

Besides the design aspects of the roads, like horizontal alignment, number of lanes, lane width, etc. there is one additional tunnel dependent setting. The other tunnel dependent model setting is the percentage of freight traffic. These percentages can be seen in Table 5.3.

Table 5.3 Percentage of freight traffic for the different tunnels (Rijkswaterstaat, 2020) (NDW, 2020)

Tunnel	% Freight	Source
WK	7%	NDW
BL	12%	NDW
LR	11%	NDW
KWA	23%	INWEVA

Variable settings

In section 3.3 the methodology for the variable settings is explained. Here, the used settings for the calibration are shown in Table 5.4. The range of the variables is determined by a trial-and-error approach and optimised afterwards. This is the reason why the car parameter (β) does not variate for the Wijkertunnel and the Leidscherijntunnel. In earlier calibrations it turned out to be that 0 was the best value. The number of settings correspond with the number of results shown in Figure 5.2 in section 5.5.

Table 5.4 Variable settings for calibration for all tunnels

Tunnel	Lane width						Speed						
	Left			Right			Truck (α)			Car (β)			
	From	Step	To	From	Step	To	From	Step	To	From	Step	To	# settings
WK	3.1	0.2	3.7	3.1	0.2	3.7	85	5	115	0	-	-	112
BL	3.3	0.2	3.7	3.3	0.2	3.7	95	5	115	0	0.3	0.6	135
LR	2.7	0.2	3.5	2.7	0.2	3.5	90	5	105	0	-	-	100
KWA	2.8	0.2	3.4	2.8	0.2	3.4	90	5	115	0	0.3	0.3	192

5.5 Results of calibration

In this section, the chosen parameter settings are presented. Several simulations are performed with different parameter settings, as described in 5.4. After using the calibration method proposed in 3.5 (changing one factor at a time) and calculating the KPI as described in chapter 4, the best parameter setting is determined for each tunnel. These parameter settings are shown in Table 5.5. To be sure the calculated KPI creates logic results, the KPI's are plotted for each parameter setting for all tunnels. This is shown in Figure 5.2. Furthermore, to make the KPI more understandable, the absolute difference between the Vissim simulation and the NDW data is visualised for speed and intensity. In Figure 5.3, this is shown. For every location (Hm), every dot represents one intensity setting (500 - 4500 veh/h). This is an example for the Wijkertunnel, the results for the other tunnels and a more detailed example of the calibration method are shown in Appendix L.

Table 5.5 Best parameter setting per tunnel

Tunnel	Lane width		Speed	
	Left	Right	Truck (α)	Car (β)
WK	3.7 m	3.3 m	115 %	0 [-]
BL	3.7 m	3.3 m	110 %	0 [-]
LR	2.9 m	3.1 m	100 %	0 [-]
KWA	2.8 m	2.8 m	90 %	0 [-]

Figure 5.2 The normalized RMSE values for all tunnels with the best value per tunnel

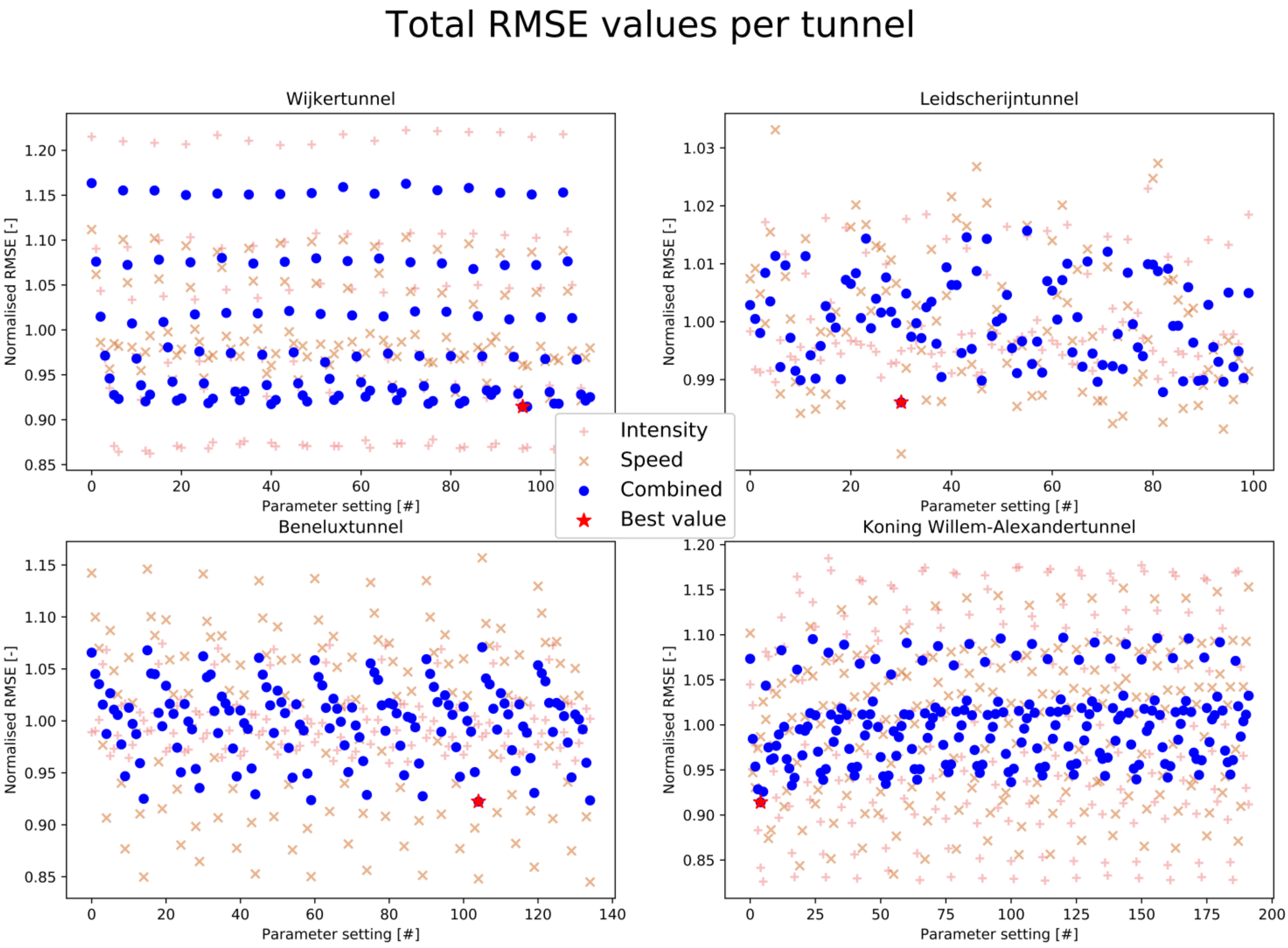
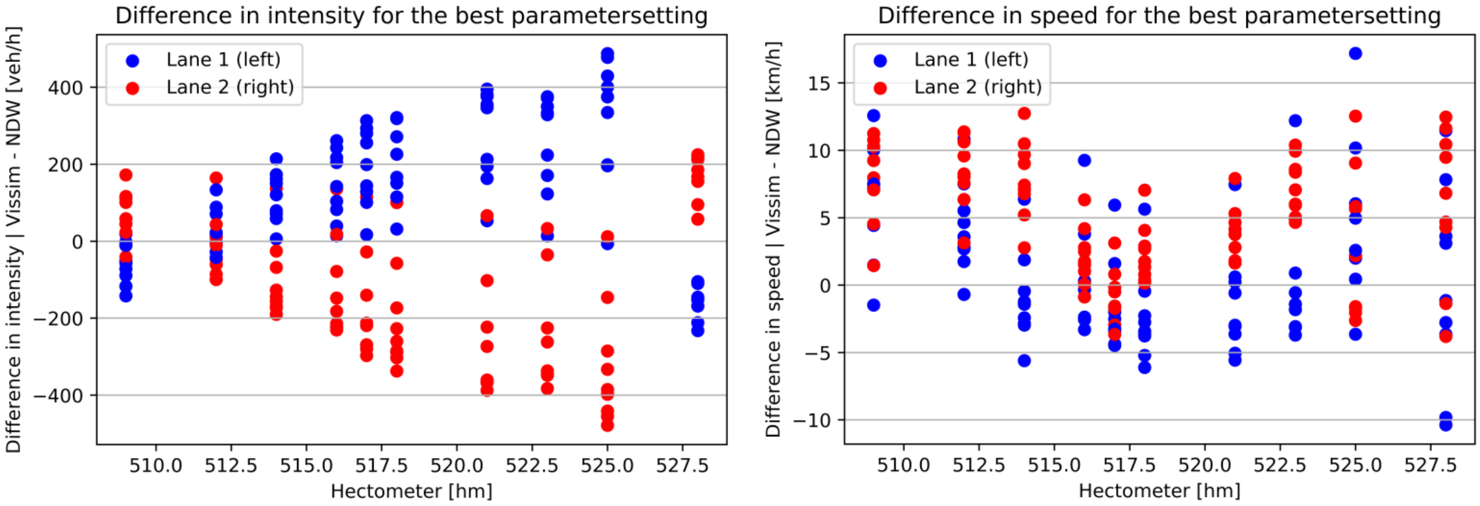


Figure 5.3 Difference in intensity (left) and speed (right) for the best parameter setting for the Wijkertunnel



6

RESULTS

With the proposed parameter settings in the previous chapter, the safety assessment is performed for the four tunnels. Besides the tunnel, a normal road stretch, without any tunnel aspects is simulated as reference, to compare with the simulated tunnels. This chapter presents the results of the safety assessments, which will be discussed in chapter 7. The safety assessment consists out of a qualitative part and a quantitative part (see 4.2) which will be presented in the following sections.

6.1 Quantitative Assessment

The quantitative assessment consists out of the 4 different KPI's to identify what the effect of the tunnel is on safety. The results for all tunnels are shown in Table 6.1. The presented 'difference' is the percentual difference of the tunnel compared to a normal road.

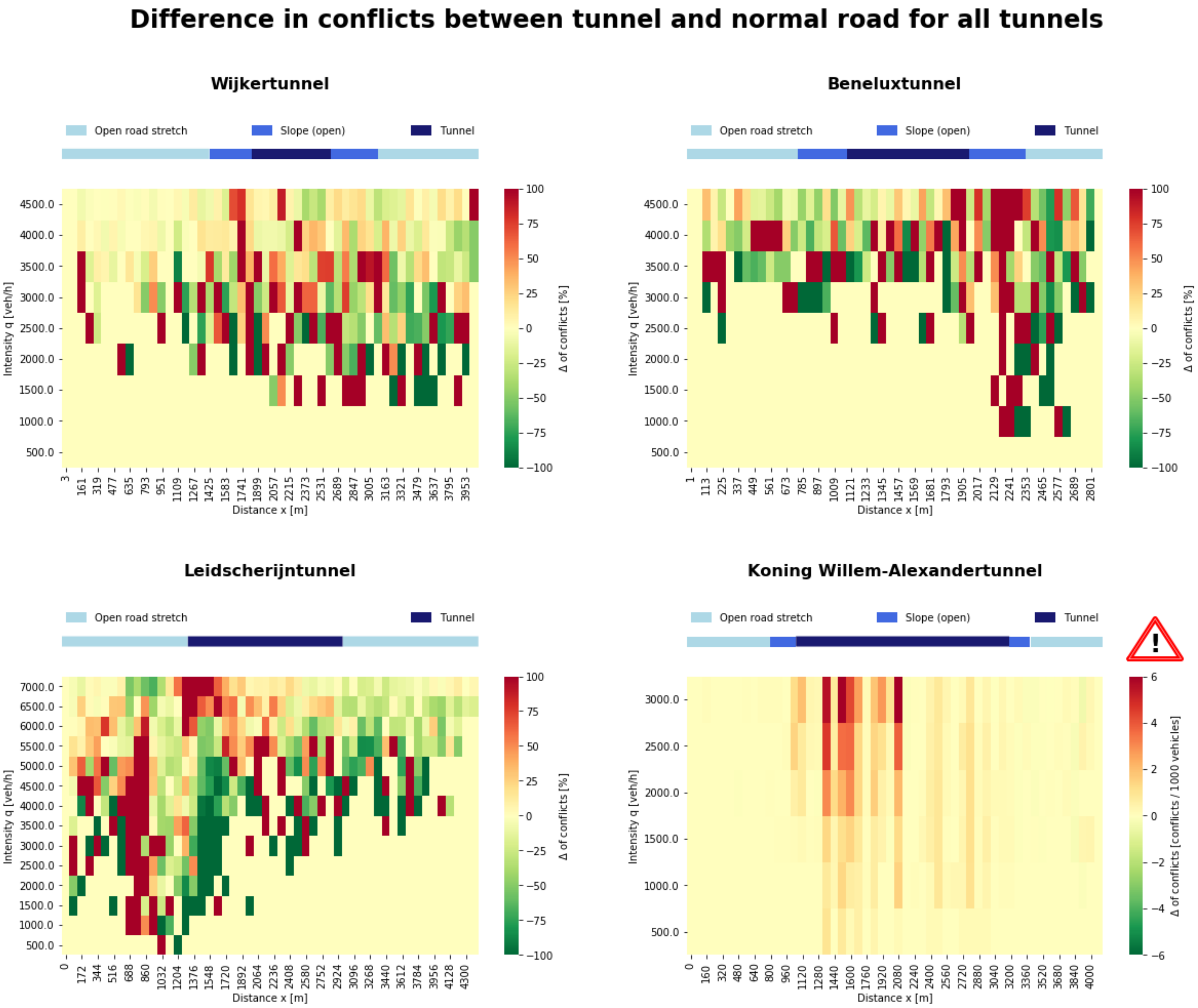
Table 6.1 Quantitative results for the 4 KPI's for all tunnels

KPI		**Nr of conflicts [#]**	**Mean TTC [s]**	**Mean PET [s]**	**Conflict Type [%]**	
					Rear end	Lane change
Wijkertunnel	Normal	11192	0.88	1.36	85	15
	Tunnel	11235	1.17	1.34	84	16
	Difference	+ 0.4 %	+ 32.9 %	- 1.5 %	-1.2%	+ 6.7 %
Beneluxtunnel	Normal	1832	0.89	1.47	82	18
	Tunnel	1803	1.17	1.45	83	17
	Difference	- 1.6 %	- 31.5 %	- 1.4 %	+ 1.2 %	- 5.6 %
Leidscherijntunnel	Normal	38780	0.95	2.00	85	15
	Tunnel	42015	1.24	2.18	86	14
	Difference	+ 8.5 %	+ 30.5 %	+ 9.0 %	+ 1.1%	- 6.7 %
Koning Willem-Alexander tunnel	Normal	360	0.15	0.17	77	23
	Tunnel	3045	0.62	0.7	82	18
	Difference	+ 745.8 %	+ 313.3 %	+ 311.8 %	+ 6.5%	- 22%

6.2 Qualitative comparison

Besides the quantitative comparison, the qualitative figures give in-depth insights in the location and number of conflicts in the tunnels. Figure 6.1 presents the difference between the reference scenarios, the normal road stretch and the tunnels. First, the conflicts are aggregated in location intervals. These figures are shown in Appendix M. Afterwards, the difference is determined by taking the number of conflicts per vehicle for the tunnel scenario and calculate the percentual difference compared to the number of conflicts per vehicle on the normal road stretch. For example, if the figure is red, there are more conflicts on that location in the tunnel compared to the normal road stretch. If the figure is green, it is the opposite.

Figure 6.1 Percentual difference in the number of conflicts between a tunnel and a normal road



Warning for Figure 6.1

The used visualisation for the Koning-Willem Alexandertunnel is different from the others. In this figure the absolute difference is shown instead of the relative difference. This is done because the reference scenario (normal road) at the KWA-tunnel does barely cause conflicts. If the relative difference is used for the visualisation, the difference will be 'infinite' and hence not show useful results.

7

DISCUSSION

In this chapter the results presented in chapter 6 are analysed and discussed. Also, a connection between the results and the literature is established. This first part is connected to research questions 1 and 4. A recap of the discussion is given in section 7.2. Afterwards, there is a discussion about the limitations and assumptions of this research and the used model. This is mainly related to research question 2 and 3. A recap is given in section 7.4.

7.1 Traffic safety with micro simulation

In this section, the results of the simulations are analysed. Remarkable observations are described and possible explanations for these observations are discussed. This discussion helps to evaluate the used quantifications as described by research question **1. What is a suitable quantification of aspects of at tunnel that affect traffic safety?** Furthermore, the discussion of the results gives an answer to research question **4. What is the traffic safety in a simulated tunnel, compared to a simulated regular road stretch?** With the answer on the last question, also a preliminary answer on the main research question **What are the safety impacts of a tunnel on traffic?** can be drawn. First, some general observations are discussed. Afterwards, the discussion of the results is done for each tunnel separately. At the end, all observations are combined in order to identify and discuss general trends.

General observation

The first observation that became clear from the results, is that the number of conflicts (in conflicts/veh) increases when the intensity increases. This effect is clearly visible for all tunnels (see Figure 9.22 in Appendix M.) as well the tunnels as on normal road stretches. This result corresponds with the findings of Nussbaumer, who stated that the higher the intensity, the more accidents occur (Nussbaumer, 2007). It also confirms the hypothesis that the findings of Amundsen and Ranes, who stated that lower intensities lead to more accidents (Amundsen & Ranes, 2000), are not valid on the Dutch highway.

In the literature, there is no compliance about the effect of tunnel length on the number of accidents. Most resources expect most accidents to occur in the tunnel entrance and therefor, the longer the tunnel, (relatively) less accidents occur (Amundsen & Ranes, 2000; Amundsen, 2009; Bassan, 2016; Allenbach, Cavegn, Hubacher, Siegrist, & Cavegn, 2004) but others state that long tunnels should be avoided because longer tunnels will cause more accidents (Martens & Kaptein, 1997). From this research, no clear effect of tunnel length can be derived. A remarkable illustration is the difference in as well total conflicts as conflicts per kilometre between the Wijkertunnel and Beneluxtunnel. The absolute number of accidents is dependent on the intensity and the relative number of accidents does differ per tunnel. An overview is presented in Table 7.1. There is also no clear increase of conflicts visible in the tunnel entrance. More discussion about the location of conflicts follows in the next paragraphs.

Table 7.1 Absolute number of conflicts and average number of conflicts for tunnels with different lengths

Tunnel	Length	Number of conflicts (abs.)	Avg. number of conflicts / 1000 veh / km (for high intensity)
WK	719 m	11235	39
BL	713 m	1803	10

Tunnel	Length	Number of conflicts (abs.)	Avg. number of conflicts / 1000 veh / km (for high intensity)
LR	1651 m	42015	8
KWA	2177 m	3045	11

From the quantitative results, some other useful results can be derived. The first result is that the conflict-type distribution between rear end and lane change, does not differ clearly between tunnels and normal roads. The results of the average TTC does not provide useful results. From the average PET however, it can be derived that in the tunnels where there is only a displacement of conflicts, the average PET value is more or less the same, while in the Koning Willem-Alexandertunnel, the average PET value is higher in the tunnel compared to the normal road stretch. This result suggests that on the normal road the conflicts that occur are more severe but the total number of conflicts is less. However, in a tunnel, the total number of conflicts is higher but the severity is less.

Results per tunnel

Wijkertunnel

Emergency lane | Slope | 2 lanes

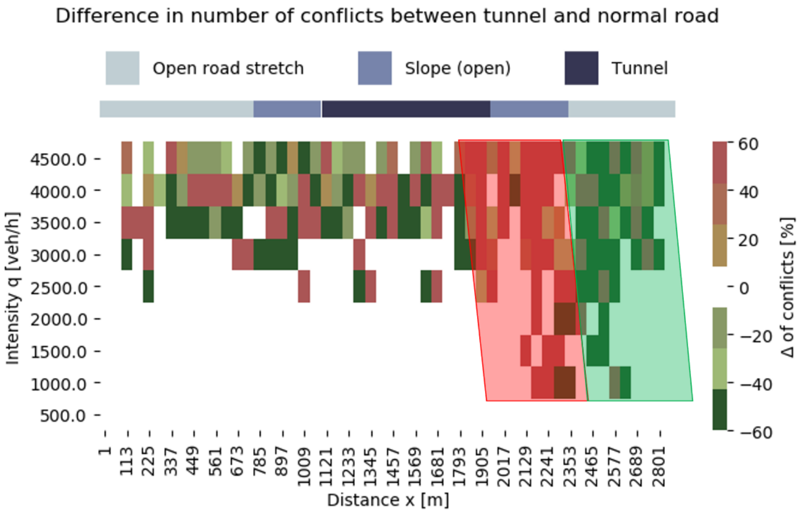
At the Wijkertunnel, the total number of conflicts does not differ between the normal road and the tunnel. Nevertheless, the location of conflicts is different. From the visualisation (see Figure 6.1), it can be derived that in the tunnel, and especially at uphill slopes, there are more conflicts than on a normal road stretch. When the road becomes flat again, the number of conflicts is less compared to the normal road stretch. This effect can easily be explained. Due to the uphill slope, vehicles (especially freight traffic) slow down, which results in smaller headways and more speed difference between vehicles. This causes an increase in conflicts, according to the findings of Martens and Kaptein (Martens & Kaptein, 1997). When there is no slope anymore, vehicles speed up again and due to reaction time, the headway increases. This explains the local decrease of conflicts. While the total number of conflicts does not differ, the effect of a slope can be described as a **displacement of conflicts**.

Beneluxtunnel

No emergency lane | Slope | 2 lanes

For the Beneluxtunnel, the effect of the uphill slope is even more visible then at the Wijkertunnel. Also, the number of conflicts is the same so also for this case, a **displacement of conflicts** describes the effect of the slope. This effect is highlighted in Figure 7.1 where the red plane covers the increase of conflicts on the uphill slope and the green plane covers the decrease in conflicts afterwards. While the Beneluxtunnel does not have an emergency lane, the hypothesis was that the lane width should have been narrower compared to a normal road. However, the calibration did not lead to narrower lanes that should simulate the lack of an emergency lane. Therefore, the effect of an emergency lane cannot be derived from this tunnel. The lack of narrower lanes also explains why there is no effect of the tunnel entrance visible. There is simply no discontinuity in the simulation model, so the negative effect of the entrance, as described by several researchers (Amundsen & Ranes, 2000; Amundsen, 2009; Bassan, 2016; Allenbach, Cavegn, Hubacher, Siegrist, & Cavegn, 2004) cannot be retrieved from this simulation.

Figure 7.1 Identification of main effect of the tunnel on the number of conflicts



Koning Willem-Alexandertunnel

No emergency lane | Slope | 2 lanes

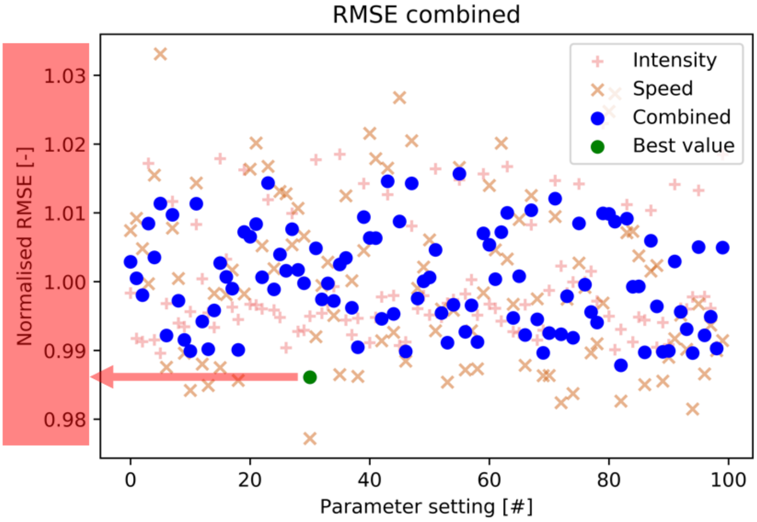
In the KWA tunnel, according to the NDW data, only low intensities (< 3250 veh/h) occur. Therefore, the number of conflicts is only determined for an input intensity till 3000 veh/h. Due to these low intensities, on the normal road stretch, almost no accidents occur. However, in the tunnel, there is a 700% increase in conflicts. These extra conflicts occur mainly in the beginning of the tunnel. The reason for these conflicts in the simulation is the narrow road, in combination with horizontal curves in the road. The, although small, curves in Vissim cause an effect that the minimum lateral distance between cars is not enough. This results in deceleration of cars which cause extra conflicts because the headway between vehicles becomes smaller. So, the effect of narrow lanes can be described by **causing extra conflicts in the narrow road parts**. This is in line with the researches that state that object distance causes a displacement to the centre of the road, which results in smaller distances between cars and hence in more accidents (Calvi & Amico, 2013; Lewis-evans & Charlton, 2006; Martens & Kaptein, 1997; Törnros, 1998; Blaauw & van der Horst, 1982). Another observation is the small increase in head tail conflicts. This can also be explained by the before mentioned theory of smaller headways.

Leidscherijntunnel

Emergency lane | No slope | 3 lanes

At the Leidscherijntunnel, some remarkable observations are made. It was not expected that the Leidscherijntunnel would have smaller lanes, because in reality, this tunnel is very ‘spacious’. There is a wide emergency lane and a normal redress lane (in Dutch: redresseerstrook). An explanation can be found in the calibration of the Leidscherijntunnel. The best parameter setting that is used, is just a fraction better than the other settings. If the KPI of the best setting of the Leidscherijntunnel is compared with the other tunnels, at the Leidscherijntunnel, it is around 99% of the average, so 1% better than the average (see Figure 7.2). For the other tunnels, the best setting lays around 90% (see Figure 5.2), so there is the difference more clear. Also, there is no clear pattern in the RMSE values of the Leidscherijntunnel. Probably, the best parameter setting used is just ‘luck’ and therefore, the results of the Leidscherijntunnel are not representing reality and hence not well explainable. For a good safety assessment, more detailed behavioural aspects should be considered, preferably using empirical trajectory data in the calibration process.

Figure 7.2 The combined RMSE for the Leidscherijntunnel with extra attention to the small difference



Combined results

Overall, interesting aspects can be derived from the results. The first observation is the effects of slopes and narrow lanes are clearly visible in the number of conflicts. This strengthens the idea to use these tunnel aspects for safety assessment of tunnels with the use of micro-simulation. However, a critical view on the input values of the simulation is needed, while the results of a simulation are directly dependent on that input. This need is confirmed by the simulation of the Leidscherijntunnel, where the results of the calibration do not correspond with reality.

7.2 Recap of the results

From the discussion, there are a few important issues that need to be pointed out. The first issue is that it turned out to be possible to assess safety out of micro-simulation and clearly see the effects of the tunnel aspects that are modelled. Nevertheless, the input of the model should be reviewed critically because wrong input will result in misleading results, as shown by the Leidscherijntunnel. Hence, there are the four main results that are derived from the results:

- Higher intensities lead to more conflicts
- Tunnel length has no remarkable influence on the number of conflicts
- Slopes cause a displacement of conflicts, not an increase in conflicts
- Narrow lanes cause an increase in conflicts in the narrow parts of the road

7.3 Assumptions & Limitations

During this research, several assumptions are made and points of discussion regarding the methodology and the model appeared, mainly because lacking literature. The discussion points are related to research question **2. How to implement the tunnel characteristics in Vissim?** and research question **3. How to calibrate the Vissim model on loop detector data?** First, the used methodology is discussed and afterwards, the used model and the major model assumptions are described. An overview of the assumptions and limitations is given in Table 7.2.

Table 7.2 Overview of described assumptions and limitations

	Assumption/ Limitation	Explanation
Simvra+ speed profiles are an underestimation of reality	Limitation	Simvra + is the only estimation of truck behaviour on slopes in the Netherlands
Only use Simvra+ profiles as input for speed profiles	Limitation	Due to programming choices, it was not possible to try another assumption within the available resources
Smaller lane width simulates the effect of small object distances	Assumption	Vissim does not have 'objects' near the road. Only the road width determines the lateral road position
The used acceptable lateral distance between vehicles in Vissim	Assumption	The effect of this parameter was discovered during the research, and there were no resources to calibrate this parameter
Set the road position of all vehicles to 'Middle of the lane'	Limitation	It is not possible to implement an empirical distribution for lateral road position in Vissim
Calibration is done based on loop detector data	Limitation	Preferably, empirical trajectory data is used for the calibration, however, this data does not exist
A one-factor-at-a-time calibration approach is used	Limitation	A mathematical optimisation approach might result in better parameter settings and can decrease the simulation time. However, the implementation will take a lot of time and probably cause more errors and/or instability of the model
The use of the parameter settings of A. Bosdikou	Limitation	There is no other literature available with an extensive calibration for safety assessment on the Dutch highway
The behaviour in the tunnel is the same as on a normal road stretch	Assumption	Due to the lack of data of behaviour in tunnels, it is assumed that the general traffic behaviour in tunnels is the same as on normal road stretches
The high number of parameters in Vissim	Limitation	The high number of parameters makes it hard to identify the effects of a parameter setting. This makes it difficult to identify if Vissim simulated the correct aspect for the wanted outcome

Tunnel Characteristics

As described in the methodology (chapter 3), the implementation of tunnel characteristics is done for two aspects: slopes and lane width. This is done using reduced speed areas and physical lane width, respectively. The two methods are discussed over here.

Reduced speed areas

According to experts, a suitable approach would be to use the Simvra+ speed profiles and verify them by apply them to tunnels. The Simvra+ speed profiles are calibrated for the Dutch roads (Bouwdienst Rijkswaterstaat, 1999) (although a long time ago, this is discussed below) and if the speed profiles of trucks in the tunnels would deviate from the Simvra+ speed profiles, the hypothesis is that this is due to other aspects of the tunnel. Unfortunately, there is no loop detector data that distinguishes vehicle types available in the tunnels, so this approach is not suitable.

Nevertheless, the speed profiles derived from Simvra+ are used as base for the used speed profiles in this research. This approach has some drawbacks. Simvra+ is a software program developed in 1998 and it is questionable if the outcomes of this program are still according to reality. Trucks have become more powerful over the last 20 years so deceleration on slopes might have become less. Normally, Simvra+ is used to determine if a slope causes speed drops for a majority of the trucks. For that use, the 'worst case scenario' is used and if the program overestimates the speed drop, this is not a problem. For the use in this research, the exact speeds are needed, so this forms problem. To overcome this, several variations on the Simvra+ speed profiles are used as input for the calibration.

The used speed profiles for cars in the calibration, which are variations on the Simvra+ output, are based on the educated guess that cars suffer speed difference on the same locations as trucks, only in less degree. It could have been useful to come up with other approaches to forecast the speed profiles of cars. However, due to programming limitations, this was not suitable for this research.

Lane width

The first assumption is that adjusting the lane width can simulate the effect of a smaller object distance in the tunnel compared to the normal road stretch. This object is the tunnel wall that is close to the road in some cases (especially the tunnels without emergency lane). The identified literature sources state that cars drive more to the middle of the road if the object distance is smaller (Calvi, Blasiis, & Guattari, 2012; Blaauw & van der Horst, 1982; Martens & Kaptein, 1997; Lewis-evans & Charlton, 2006; Törnros, 1998). While in Vissim, vehicles always drive in the middle of the lane, adjusting the lane width changes the lateral road position of vehicles more to the middle of the road. The hypothesis is that if cars drive more to the middle of the road, there are more conflicts.

The effect on safety of driving more towards the middle of the road, can be strengthened in Vissim by enable the observation of cars on other lanes. In the default settings, cars in Vissim do not observe vehicles in other lanes, however, the observation of vehicles on other lanes has effect on driving behaviour. Vehicles might make the decision not to overtake if there is not enough lateral space, which leads to deceleration. This required lateral space (or actually the minimum lateral distance to other vehicles) must be specified. The choice for these values is made, such that in ‘normal’ conditions, there is no effect of vehicles on adjacent lanes. However, more research on this parameter is advised.

Calibration

While safety assessment is the main goal of this research, the driving behaviour of vehicles is important. To calibrate a simulation model for driving behaviour parameters, preferably, empirical trajectory data is needed. From empirical trajectory data, more specific behavioural aspects might be derived. Examples are possible local speed drops (for example at the tunnel entrance or at the lowest point of a tunnel), lateral road position (to identify the effects of the tunnel wall) and gap acceptance (that might be different inside tunnels). Furthermore, the research will become stronger if the final results, so the number and location of the conflicts derived from the simulation model, correspond with the number of conflicts derived from empirical trajectory data. Unfortunately, there is no empirical trajectory data in tunnels available and it is quite hard to derive this data.

The second discussion point is the calibration methodology. The used ‘one factor at a time approach’ is very useful to obtain the results for all different parameter settings but it also takes a lot of time to gain them. A traffic simulation model requires a long running time, so a limited number of parameter settings can be simulated. A more sophisticated calibration method by using mathematical optimisation might create more insight and possibly results in a better parameter setting. However, implementing mathematical optimization into the used model, would take a lot of effort and would increase the instability of the model.

Model

Next to the tunnel aspects and calibration, also the used model has its limitations and assumptions.

Driving behaviour parameters

A very important assumption that is made for this research, is that the driving behaviour parameters in Vissim that are calibrated by A. Bosdikou (Bosdikou, 2017) for weaving sections in the Netherlands, are also valid in tunnels. It is justified to doubt this assumption, while it can be expected that several behavioural parameters, such as minimum longitudinal distance, maximum accelerations, maximum deceleration and gap acceptance are different in tunnels compared to normal road stretches. Preferably, before calibrating the tunnel aspects, the behavioural parameters should be calibrated on the specific driver behaviour in tunnels. Unfortunately, there is no empirical trajectory of tunnels available to perform this calibration. Therefore, it is assumed that the driving behaviour in tunnels is the same as on the normal road stretch and the difference between tunnels and normal road stretches is caused by the tunnel aspects.

Vissim

Vissim is a very sophisticated simulation software program that tries to represent as much effects of vehicles as possible. If all parameters are calibrated correctly, this results in an accurate representation of reality.

However, this approach also causes some limitations. Because the high number of parameters (> 50, (van Beinum, 2018)), it is very difficult to choose an appropriate parameter setting to represent the reality for the exact goal of a research (in this case the number of conflicts). Besides the difficult parameter choice, also the individual effect of certain parameters is hard to determine. To identify these exact effects, a big number of simulations are needed, which requires a lot of calculation power. This power, or the corresponding calculation time, was not available and therefore parameters are based on previous researches (particularly from Bosdikou (Bosdikou, 2017)) or the default settings of Vissim, without explanation.

7.4 Recap of assumptions and limitations

Because of the lack of literature assumptions are made and limitations are present in the used model and methodology. To overcome or improve these assumptions and limitations some important recommendations are presented in section 8.3.

This chapter also discussed the answers on research question **2. How to implement the tunnel characteristics in Vissim?** and **3. How to calibrate the Vissim model on loop detector data?** The most important issues are written in bold. The main discussion points regarding research question 2 are:

- It is questionable if the main driving behaviour in tunnels is the same as on a normal road stretch
- **The reduced speed areas create the effect that represents reality**. Individual vehicle based calibration might improve the results
- **Implementing smaller object distances as smaller lanes creates the expected effect**, however if the result of this effect represents reality is questionable

The main discussion points regarding research question 3 are:

- Preferably, driving behaviour parameters are calibrated based on empirical trajectory data, not solely on loop detector data
- However, **the used technique for calibration on loop detector data resulted in logic outcomes**
- For small effects of the tunnel, like in the Leidscherijntunnel, loop detector data is not sufficient
- A one-factor-at-a-time approach is sufficient to retrieve an acceptable result, however mathematical optimisation might improve the results

8

CONCLUSION & RECOMMENDATION

In this chapter first an answer to the sub questions is given. Secondly, a general conclusion is drawn and the main research question is answered. The third part of this chapter contains several recommendations for further research. The last section contains a personal reflection on this research with suggestions for improvements.

8.1 Answer to research questions

In this section, the research questions are answered briefly. This is done based on the discussions in the previous chapter.

1. What aspects are suitable and quantifiable for traffic safety assessment in tunnels?
There are several aspects of tunnels that affect traffic safety. The aspects that can be quantified are lane width/object distance, intensity, slopes and tunnel length. All mentioned tunnel aspects lead to variations in traffic safety in simulated tunnels, except for the tunnel length.

2. How to implement the tunnel characteristics in Vissim?
The two tunnel characteristics that are implemented explicit in Vissim are the slopes and the lane width/object distance. The first mentioned is implemented using reduced speed areas. This approach was useful to simulate speed differences in the tunnel. The second aspect was implemented by adjusting the lane width. The effect of this measure is also clearly visible in the simulation but if it represents reality is questionable.

3. How to calibrate the Vissim model on loop detector data?
The used approach by calculating the root mean squared error (RMSE) of the speed and intensity makes it possible to compare different parameter settings with the loop detector data and choose the parameter setting that represents reality the best. However, the acceptance of a parameter setting is ambiguous when using this approach.

4 What is the traffic safety in a simulated tunnel, compared to a simulated regular road stretch?
There are two important issues that became clear with respect to the traffic safety in tunnels. The first impact is that slopes cause a displacement of conflicts, but no increase in the number of conflicts. The second impact is that narrow lanes cause an increase in conflicts in the narrow part of the tunnel.

8.2 Overall conclusion

After the discussion of the results and answering the research questions, the main research question can be answered.

Main research question
What is the safety impact of a tunnel on traffic?

From the results, four main results can be derived. The first one is that **the slopes of tunnel, leads to a displacement of the conflicts**, but has no effect on the number of conflicts. The second result is that **narrower lanes cause an increase in conflicts** on that narrow place. These narrower lanes are simulating the lack of an emergency lane and/or a close object distance in the tunnel. The increase of conflicts can therefore be seen as the impact of the closer object distances.

The other result is that it became clear **that higher intensities cause more conflicts**. This is in line with the hypothesis derived from the literature. However, the **tunnel length caused no logic or explainable effect**, what is not in line with the hypothesis derived from the literature.

The first part of the goal of this research wat to investigate if the traffic safety assessment in tunnels with micro-simulation software is possible. The overall conclusion is that the assessment of traffic safety in tunnels with the use of micro-simulation is possible. The safety assessment produces logical and explainable results. However, more research is necessary and more empirical data is required. Hence, in the end, an assessment tool to assess safety will create more insight in traffic safety issues in tunnels and provides a quantitative method that can be standardized.

8.3 Recommendations

As mentioned in the research gap (see 1.2), extensive research is done about traffic safety in tunnels and assessing traffic safety with micro-simulation, but about a combination, assessing traffic safety in tunnels with micro-simulation, no literature or research can be found. This research provides a start in this research topic. However, there is still a lot unclear and more research is necessary to create a useful and applicable tool. The recommendations consist out of two main subjects.

Empirical trajectory data

Calibration of driver behaviour in tunnels based on empirical trajectory data would increase the reliability of this research. Now, the only empirical calibration data is the loop detector data, without distinguishing vehicle classes. By using only loop detector data, driving aspects as speed and headway are only on specific locations. This leaves gaps in between the detector locations where unknown effects could take place.

When researching empirical trajectory data, interesting aspects would be lane changing behaviour around tunnels, gap acceptance for lane changing, lateral road position and the adjustment of speed in for example the beginning of the tunnel. With this data, it would be possible to identify more specific effects of the tunnel on driving behaviour. An example is the effect of the tunnel entrance on driving speed. With only loop detector data, such effect is not identifiable.

The presence of empirical trajectory data also makes it possible to identify conflicts from that data with the use of SSM. This give the opportunity to make a comparison and do a validation of the number and location of conflicts of the simulation model and reality. It is recommended to perform this comparison if there is more data available, to check if the simulation output represents reality.

Mathematical optimisation

As stated above, empirical trajectory data would improve the reliability of this research. However, this has as result that variating more parameters in Vissim might be necessary to reach a good result. The increase of variable parameters leads to more calculation time and in that case, a one-factor-at-the-time approach is not suitable anymore. Mathematical optimisation should be implemented to reach the optimal parameter setting. However, the implementation of mathematical optimisation takes plenty of time, basically due to two reasons. First, the model is very complex, with a lot of communication between scripts and software programmes, which makes it unstable. Second, the calibration data in this research was full of data errors, which are removed or repaired manually. This makes it difficult to automate programming parts without causing errors.

8.4 Reflection

During this research, I faced minor setbacks or issues that I shall approach differently when I would deepen this research. In this section, some important issues that I faced are described and reflected on.

First, there are two issues that I did not do due to programming difficulties. When I should start over, I would have designed a more flexible simulation model. Although, most parts of the process were very well adjustable, it was difficult and took a lot of time to implement a mathematical optimisation approach and to use another speed profiles approach. If I would have more time, I could have implemented these adjustments. A good lesson for programming is to first complete the whole technical model and build the user interface afterwards instead of doing it together. This would have prevented doing work that in the end turned out to be useless.

A second aspect that could have been improved, was the lateral road position. A better approach would be to implement the lateral road position of vehicles in Vissim according to an empirical derived distribution. Unfortunately, in Vissim, it is not possible to change the lateral road position manually. To use this approach, the software manufacturer should allow users to change this setting.

Furthermore, the research scope could have been adjusted. It turned out that there are a lot of factors that have influence on traffic safety in tunnels. Of course this was known beforehand, however, I underestimated the difficulty to implement all aspects correctly in the micro-simulation software with the result that for some aspects, assumptions or simplifications are used. The main reason for this is the limited research available in this knowledge field. More research will gain new and better knowledge and can bring the academic strength of this research topic to a higher level. I expect that for a complete implementation and the development of a tool that can assess traffic safety in tunnels based on micro-simulation, several years of research is needed, preferably with a sub research for different tunnel aspects that affect safety.

A third aspect is the relatively long simulation time that is needed for the calibration. Of course, it is not easy to speed up the simulation time, however, the long simulation time caused a few drawbacks. First, I was very conservative with the number of variable parameters as well as the used range of parameters. Otherwise, simulations would take several days or even weeks and besides the waiting time, this also increases the risk of model failures. When I could do the research again, I would look closer into the tunnel choice and limit the scope to less tunnels and may focus on a single aspect. I think, in that way, the effect of one aspect could be pointed out. However, the current research compares multiple tunnel aspects and identify the effects.

On beforehand, I thought a tool that can assess traffic safety in tunnels would be a valuable addition to the work field. I still believe that such a tool would be useful, if such a tool is researched extensively and the results represent reality. However, I doubt if the benefits of developing such a tool will exceed the costs. On the other hand, if a tool prevent deadly accidents, the benefits (as well monetary as emotionally) will probably exceed the costs quite fast.

9

REFERENCES

AHN. (2020). *Actueel Hoogtebestand Nederland*. Retrieved from https://www.ahn.nl/ahn-viewer

Allenbach, R., Cavegn, M., Hubacher, M., Siegrist, S., & Cavegn, M. (2004). *Verkehrssicherheit in Autobahn und Autostrassentunneln des Nationalstrassennetzes* (1st Editio ed.). Bern: BFU (Schweizerische Beratungsstelle für Unfallverhütung).

Amundsen, F. (2009). *Studies on Norwegian Road Tunnels II.* Vegdirektoratet, Oslo.

Amundsen, F., & Ranes, G. (2000). Studies on traffic accidents in Norwegian road tunnels. *Tunnelling and Underground Space Technology, 15*(1), 3-11.

Bassan, S. (2016). Overview of traffic safety aspects and design in road tunnels. *IATSS Research, 40*(1), 35-46.

Bijlsma, W., Boonstoppel, W., Proper, T., Rundberg, J., Wilschut, M., van Oers, I., & Will, M. (1999). *2de Beneluxtunnel.* (V.-d. BNO, Ed.)

Blaauw, G., & van der Horst, A. (1982). *Lateral postitioning behaviour of car drivers near tunnel walls.* TNO, Soesterberg.

Boon, W., Van Wee, B., & Geurs, K. (2003). *Barrièrewerking van infrastructuur: A2 en Amsterdam-Rijnkanaal barrière voor inwoners van Utrecht-Leidsche Rijn?*

Bosdikou, A. (2017). *Safety analysis in Dutch weaving sections Afroditi Bosdikou.* TU Delft.

Bouwdienst Rijkswaterstaat. (1999). *Advies betreffende Vermindering van gronddekking op Velsertunnels en Wijkertunnel.* Bouwdienst Rijkswaterstaat, Utrecht.

Bouwdienst Rijkswaterstaat. (1999). *Handleiding SimVra +.* Bouwdienst Rijkswaterstaat, Apeldoorn.

Caliendo, C., & De Guglielmo, M. (2012). Accident Rates in Road Tunnels and Social Cost Evaluation. *Procedia - Social and Behavioral Sciences, 53*, 166-177.

Calvi, A., & Amico, F. (2013). A study of the effects of road tunnel on driver behavior and road safety using driving simulator. *Advances in Transportation Studies, Section B*(30), 59-76.

Calvi, A., Blasiis, M., & Guattari, C. (2012). An Empirical Study of the Effects of Road Tunnel on Driving Performance. *Procedia - Social and Behavioral Sciences, 53*, 1100 - 1110.

Carmody, J. (1997). *Design issues related to road tunnels (Technical Report No. CTS 97-05).* Universtity of Minnesota, Minneapolis.

CBS. (2019). *80 procent volwassenen heeft rijbewijs*. Retrieved from https://www.cbs.nl/nl-nl/nieuws/2019/09/80-procent-volwassenen-heeft-rijbewijs

Cunto, F. (2008). *Assessing Safety Performance of Transportation Systems using Microscopic Simulation.* Waterloo Universitiy, Civil Engineering.

Cunto, F., & Saccomanno, F. (2008). Calibration and validation of simulated vehicle safety performance at signalized intersections. *Accident Analysis and Prevention, 40*(3), 1171-1179.

Dijkstra, A., Marchesini, P., Bijleveld, F., Kars, V., Drolenga, H., & Maarseveen, M. (2010). Do calculated conflicts in microsimulation model predict number of crashes? *Transportation Research Record*(2147), 105-112.

Esri Nederland. (2019). Provinciegrenzen 2019. ArcGIS - Esri Nederland.

Fellendorf, M., & Vortisch, P. (2001). Validation of the Microscopic Traffic Flow Model VISSIM in Different Real-World Situations. *Transportation Research Board 80th Annual Meeting*(January 2001), 1-9.

FHWA. (2007). *SSAM Version 2.1.6 – Release Notes.* FHWA.

FHWA. (n.d.). *Mitigation Strategies For Design Exceptions*. Retrieved from Mitigation Stategies For Design Exceptions (Archived): https://safety.fhwa.dot.gov/geometric/pubs/mitigationstrategies/chapter3/3_lanewidth.cfm

FHWA. (n.d.). *Surrogate Safety Measures From Traffic Simulation Models Final Report.* FHWA, McLean.

Francke, J. (2018). *Trendprognose wegverkeer 2018-2023 voor RWS Kennisinstituut voor Mobiliteitsbeleid.*

Gao, Y., & Rakha, H. (2008). Calibration and Comparison of the VISSIM and INTEGRATION Microscopic Traffic Simulation Models. *Fuel*, 1-67.

Geofabrik Downloads. (2020). gis_osm_roads_free_1. Geofabrik.De.

Gettman, D., Pu, L., Sayed, T., & Shelby, S. (2008). Surrogate Safety Assessment Model and Validation: Final Report. *Publication No. FHWA-HRT-08-051*(June), 1-324.

Google. (2020, Mei 24). *Google Maps*. Retrieved from Google Maps: https://www.google.nl/maps/preview

Hauer, E. (1982). Traffic conflicts and exposure. *Accident Analysis and Prevention, 14*(5), 359-364.

Hayward, J. (1972). Near miss determination through use of a scale of danger. *Highway Research Board*(384), 24-35.

Heikoop, H. (2015). *Capaciteitswaarden Infrastructuur Autosnelwegen.* Rijkswaterstaat.

Higgs, B., Abbas, M., & Medina, A. (2011). Analysis of the Wiedemann Car Following Model over Different Speeds using Naturalistic Data. *3rd International Conference on ...*, 1-22.

Kircher, K., & Ahlstrom, C. (2012). The impact of tunnel design and lighting on the performance of attentive and visually distracted drivers. *Accident Analysis and Prevention, 47*, 153-161.

Kirytopoulos, K., Kazaras, K., Papapavlou, P., Ntzeremes, P., & Tatsiopoulos, I. (2017). Exploring driving habits and safety critical behavioural intentions among road tunnel users: A questionnaire survey in Greece. *Tunnelling and Underground Space Technology, 63*, 244-251.

KNMI. (2019). *Tijden van zonopkomst en -ondergang 2020*. Retrieved from https://www.knmi.nl/kennis-en-datacentrum/achtergrond/klimatologische-brochures-en-boeken

KNMI. (2020). *Daggegevens van het weer in Nederland*. Retrieved from https://www.knmi.nl/nederland-nu/klimatologie/daggegevens

Lan, S., Liu, Y., Liu, B., Sheng, P., Wang, T., & Li, X. (2011). Effect of slopes in highway on traffic flow. *International Journal of Modern Physics C, 22*(4), 319-331.

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

Law, A. (2015). *Simulation Modeling and Analysis* (5th ed.). New York: McGraw-Hill Education.

Lewis-evans, B., & Charlton, S. (2006). Explicit and implicit processes in behavioural adaptation to road width. *Accident Analysis and Prevention, 38*(September 2005), 610-617.

Ma, Z., Shao, C., & Zhang, S. (2009). Characteristics of traffic accidents in Chinese freeway tunnels. *Tunnelling and Underground Space Technology, 24*(3), 350-355.

Martens, M., & Kaptein, N. (1997). *Effects of tunnel design characteristics on driving behaviour and traffic safety : a literature review.* TNO Human Factors, Soesterberg.

Mullakkal-Babu, F., Wang, M., Farah, H., van Arem, B., & Happee, R. (2017). Comparative assessment of safety indicators for vehicle trajectories on highways. *Transportation Research Record, 2659*(1), 127-136.

National Government. (2006). Wet aanvullende regels veiligheid wegtunnels.

NDW. (2020). *Data Exploration + Exporter (DEXTER)*. Retrieved from Data Exploration + Exporter (DEXTER): https://dexter.ndwcloud.nu/home

Nussbaumer, C. (2007). Comparative analysis of safety in tunnels. *Young Researchers Seminar 2007*, (pp. 1-9). Brno.

Oud, M. (2016). *Performance of Existing Integrated Car Following and Lane Change Models around Motorway ramps.* TU Delft.

Peng, Y., Abdel-Aty, M., Shi, Q., & Yu, R. (2017). Assessing the impact of reduced visibility on traffic crash risk using microscopic data and surrogate safety measures. *Transportation Research Part C: Emerging Technologies, 74*(January 2008), 295-305.

Pirdavani, A., Brijs, T., Bellemans, T., & Wets, G. (2010). Evaluation of traffic safety at un-signalized intersections using microsimulation: A utilization of proximal safety indicators. *Advances in Transportation Studies*(22), 43-50.

Rijksoverheid. (2020). Verkeersongevallen - Nederland 2009-2018 - download.

Rijkswaterstaat. (2020). *DTB data*. Retrieved from https://geoservices.rijkswaterstaat.nl/geoweb53/index.html?viewer=DTB_Bladindeling.Webviewer

Rijkswaterstaat. (2020). *INWEVA*. Retrieved from INWEVA: https://geoservices.rijkswaterstaat.nl/ext/geoweb51/index.html?viewer=Inweva.Webviewer

Rijkswaterstaat. (2020). *Kader Verkeersveiligheid.*

Rijkswaterstaat. (2020). Kunstwerken in Weg.

Rijkswaterstaat. (2020). maximumsnelheden-avond-nacht-va-16mrt2020.

Rijkswaterstaat. (2020). *Tunnels*. Retrieved from https://www.rijkswaterstaat.nl/wegen/wegbeheer/tunnels/index.aspx

Rijkswaterstaat GPO m.m.v. Witteveen + Bos. (2017). *Richtlijn Ontwerp Autosnelwegen 2017.* Rijkswaterstaat.

Robinson, S. (2014). *Simulation - The practice of model development and use* (2nd ed.). Hampshire / New York: Palgrave Macmillan.

Rossen, V. (2018). *Autonomous and Cooperative Vehicles & Highway Capacity.*

Stichting Incident Management Nederland. (2020). *Krakeel in de Coentunnel*. Retrieved from Stichting Incident Management Nederland: https://www.stichtingimn.nl/200131-krakeel-in-de-coentunnel.php

SWOV. (2011). SWOV Fact sheet. *SWOV Fact sheet*.

SWOV. (2020). *Kosten Verkeersongevallen - Hoeveel kosten verkeersongevallen de maatschappij?* Retrieved from https://www.swov.nl/feiten-cijfers/fact/kosten-verkeersongevallen-hoeveel-kosten-verkeersongevallen-de-maatschappij

Törnros, J. (1998). Driving behaviour in a real and a simulated road tunnel - A validation study. *Accident Analysis and Prevention, 30*(4), 497-503.

Unknown. (2013). *NDW Interface beschrijving.*

van Beek, J., Ceton-O'Prinsen, N., & Tan, G. (2003). *Tunnels in Nederland - Een nieuwe generatie* (1st Editio ed.). Amsterdam.

van Beinum, A. (2018). *Turbulence in traffic at motorway ramps and its impact on traffic operations and safety.* TU Delft, Civiele Techniek en Geowetenschappen.

van den Bos, M. (2002). *De verkeersafwikkeling op hellingen.* TU Delft, Civiele Techniek en Geowetenschappen, Delft.

van der Hoeven, F. (2010). Landtunnel Utrecht at Leidsche Rijn: The conceptualisation of the Dutch multifunctional tunnel. *Tunnelling and Underground Space Technology, 25*(5), 508-517.

van der Horst, A. (1990). A time-based analysis of road user behaviour in normal and critical encounters.

van Driel, C., Davidse, R., & van Maarseveen, M. (2004). The effects of an edgeline on speed and lateral position : a meta-analysis. *Accident Analysis and Prevention, 36*, 671-682.

Wu, K., & Jovanis, P. (2013). Defining and screening crash surrogate events using naturalistic driving data. *Accident Analysis and Prevention, 61*, 10-22.

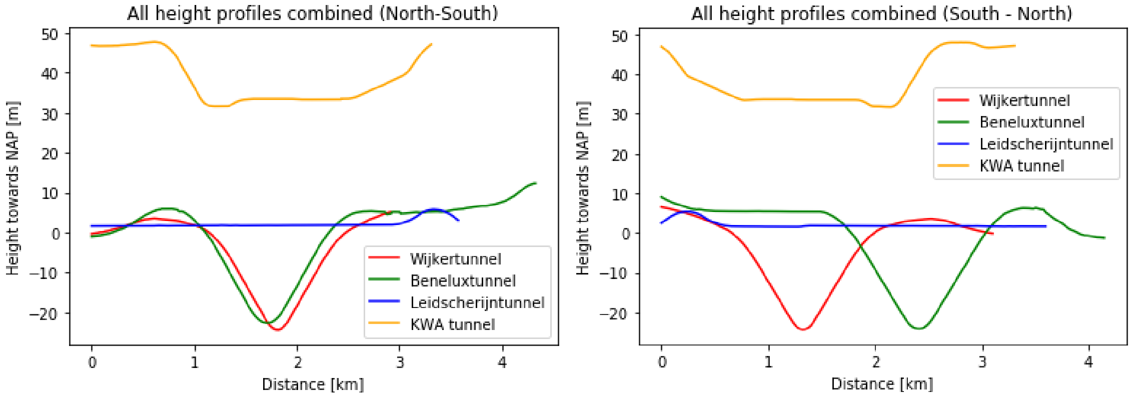
Yeung, J., & Wong, Y. (2013). Road traffic accidents in Singapore expressway tunnels. *Tunnelling and Underground Space Technology, 38*, 534-541.

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

Appendices

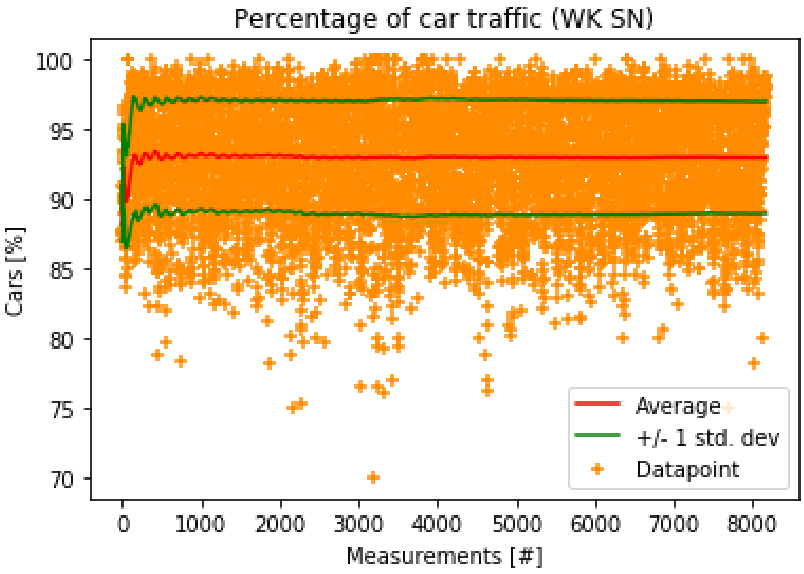
A. Height profiles of tunnels

Figure 9.1 Height profiles for the used tunnels in 1 graph per direction



B. Determining freight traffic

Figure 9.2 Example of car traffic for the Wijkertunnel South-North



C. Behavioural parameters

Table 9.1 Parameter settings from different literature sources (Bosdikou, 2017) (Oud, 2016)

1. Car following model

Parameter	Unit	Type	Remark	Default	Bosdikou	Oud
Maximum look ahead distance	m	number		250	263	-
Number of observed vehicles	#	number		2	8	-
CC0 - Standstill Distance	m	number		1.5	2.36	-
CC1 - Headway Time	s	drop-down		0.9	0.5	1.2 - 1.5
CC2 - 'Following' variation	m	number		4	3.91	-
CC3 - Threshold for Entering 'Following'	s	number		-8	-9.87	-
CC4 - Negative 'Following' Threshold	m/s	number		-0.35	-1.21	-
CC5 - Positive 'Following' Threshold	m/s	number		0.35	1	-
CC6 - Speed dependency of Oscillation	1/(m*s)	number		11.44	-	-
CC7 - Oscillation Acceleration	m/s^2	number		0.25	0.24	-
CC8 - Standstill Acceleration	m/s^2	number		3.5	-	-
CC9 - Acceleration with 80 km/h	m/s^2	number		1.5	-	-

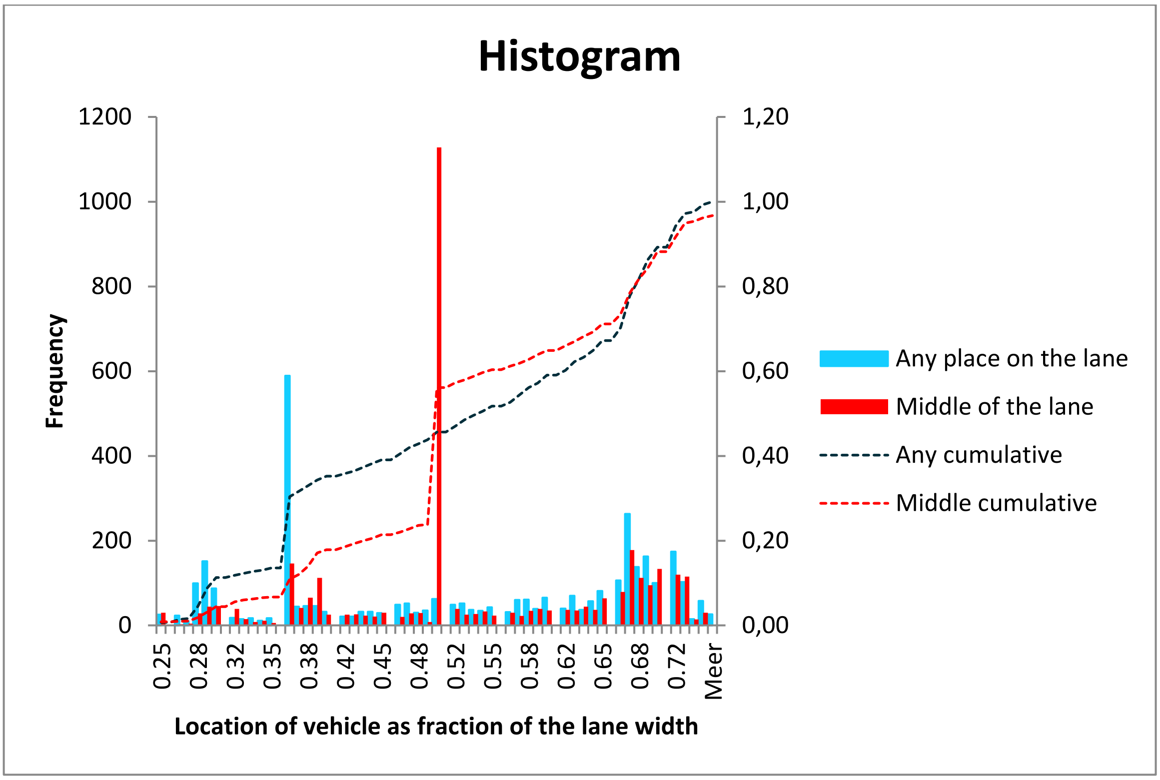
2. Lane change

Parameter	Unit	Type	Remark			
General behavior	-	drop-down		Free lane selection	Slow lane rule	
Max deceleration (Trailing vehicle)	m/s^2	number		-3	-2.35	-
Minimum headway (front/rear)	m	number		0.5	0.83	-
Free driving time	s		Not in Vissim 2020	11	13.88	40
Safety distance reduction factor	-	number		0.6	0.43	0.9 - 1.0
Cooperative behavior	-	checkbox	Not in Vissim 2020	false	true	-

D. Analysis ‘Any’ lateral road position

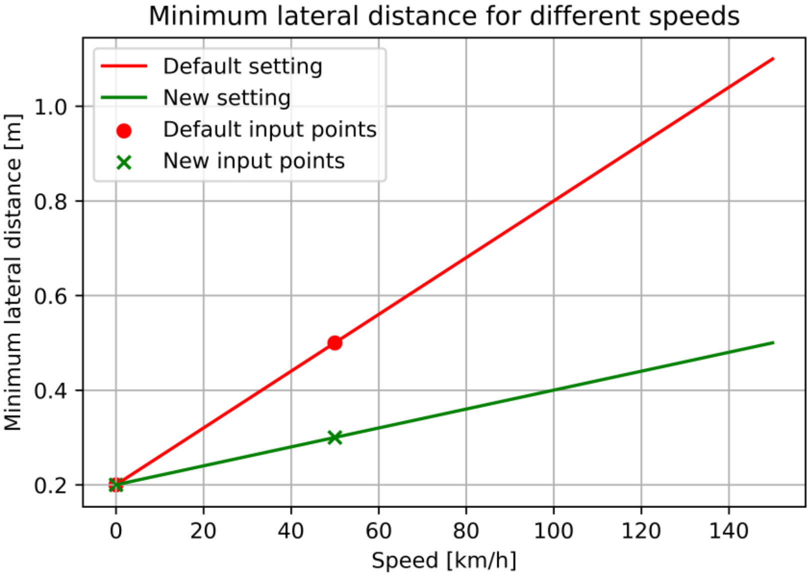
In Figure 9.3 the histogram for 2 different lateral road positions is shown. As can be seen, the middle of the lane setting has a clear peak at 0.5, what is the middle of the lane. For the ‘Any’ place on the lane, a clear distribution was expected, however there is no clear distribution.

Figure 9.3 Histogram of road positions for different settings



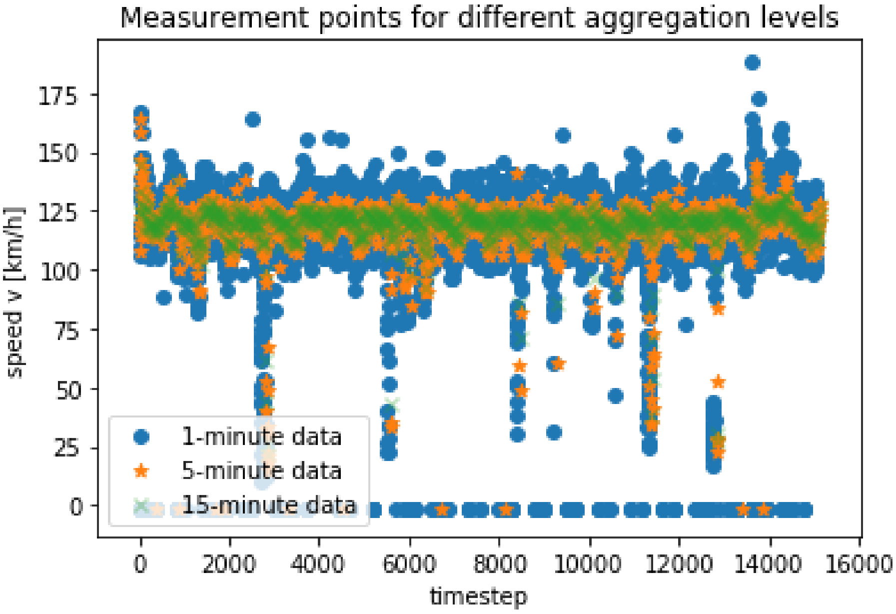
E. Minimum lateral distance

Figure 9.4 Minimum lateral distance for different speeds with the default setting and the new setting



F. Aggregation levels

Figure 9.5 Aggregation levels and the speed measurements for those levels (A9, hm 51.6, Re, Lane 1 - April 2018) (NDW, 2020)



G. Processing NDW-data

In this appendix the processing method of the NDW-data is explained. This is done with an example of the Wijkertunnel S-N.

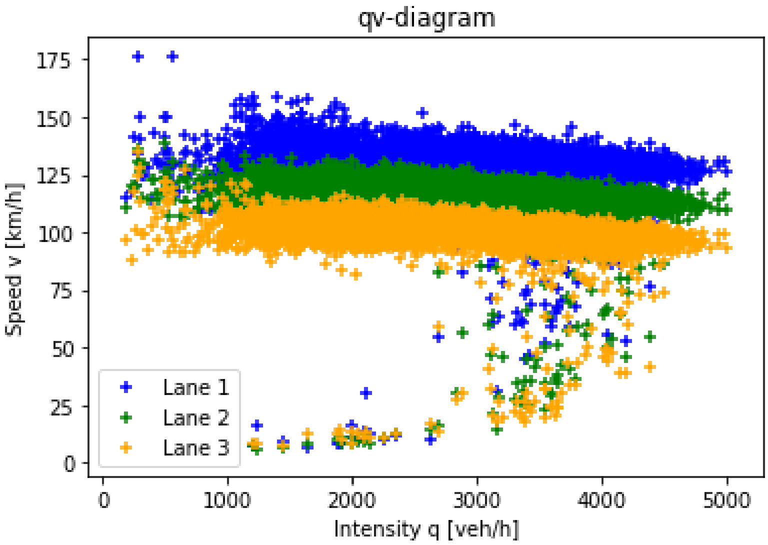
In order to create good plots and do correct transformations, the first step is to sum the intensity for all lanes on a timestep, according to equation (9.1).

$$q_t = \sum_{n=1}^{N} q_{t,n} \qquad (9.1)$$

where: N is the number of lanes

After this summation, the speed per lane is plot against the total intensity on that timestep. An example is given in Figure 9.6. The recognizable shape of a qv-diagram can be observed.

Figure 9.6 Intensity-speed plot after summation of the intensities on all lanes

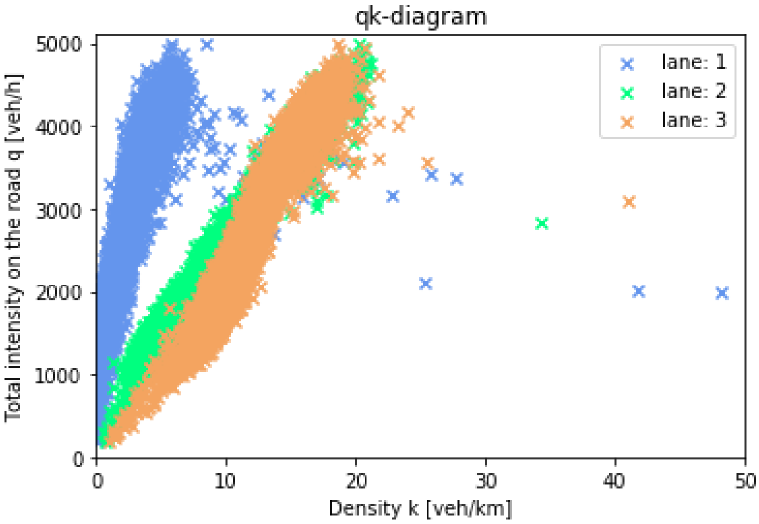


However, for the calibration process, congested datapoints are removed. To perform this removal, first the density per lane per timestep is calculated and plotted. The calculation is done by using equation (9.2). The result of this calculation is shown in Figure 9.7.

$$k_{t,n} = q_{t,n} / v_{t,n} \quad (9.2)$$

where: n is the number of lanes
t is the time step

Figure 9.7 Intensity-density plot



With this data, it is possible to apply a filter, such that congested datapoints are removed from the data. This filter is based on two boundary values. The first value is the moving average minus a bandwidth, described by equation (9.3) . The second value is maximum density value defined by the maximum moving average value plus an amount of datapoints, as described by equation (9.4). An example of the boundaries for 1 lane is shown in Figure 9.8. An example for all lanes is shown in Figure 9.9. Parameters b, c and d are visually determined for each tunnel tube.

$$LB(m) = \frac{\sum_{i=m-b}^{m+b} q_i}{2b+1} - c \quad \forall\, m \in (0,1,\dots,M) \quad (9.3)$$

where: LB(m) is the lower bound value for measurement m

b the width of the moving average
c the bandwidth of the datapoints

$$VB = k(\max(LB(m)) + d) \tag{9.4}$$

where: *VB is the vertical boundary*
k is the density
m is a measurement
d is a parameter that includes d extra measurement points

Figure 9.8 Filter by density for 1 lane with the boundaries

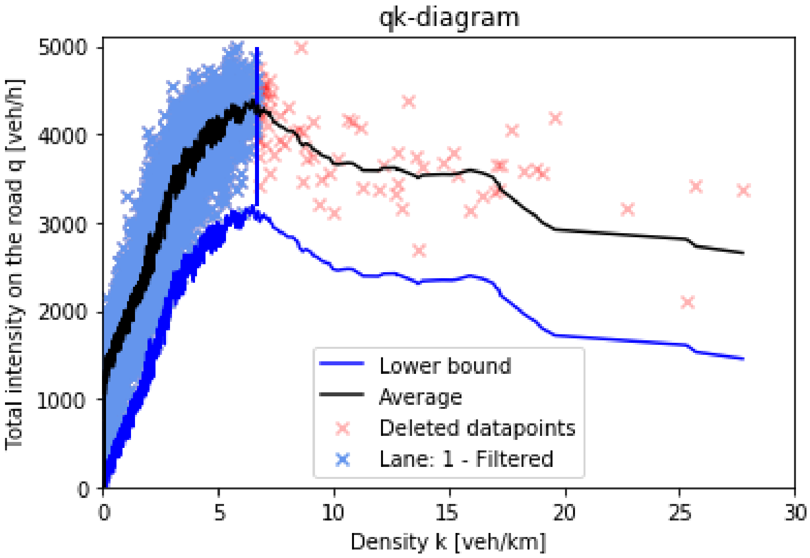
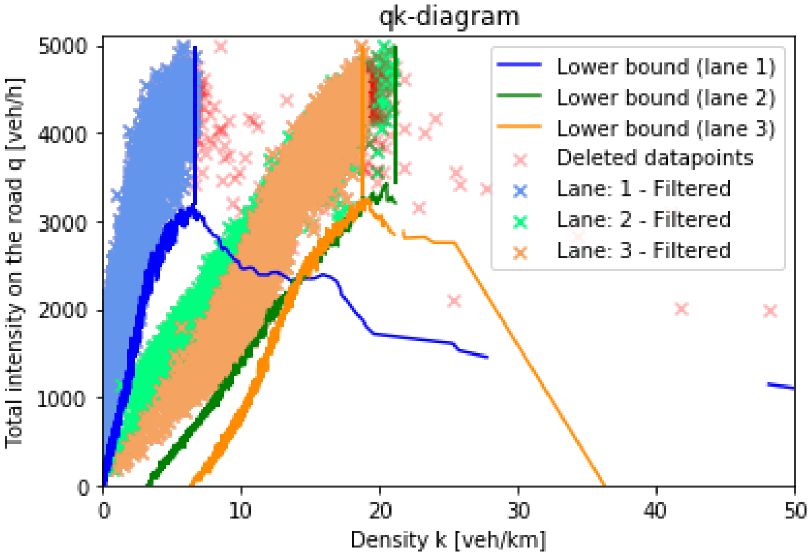
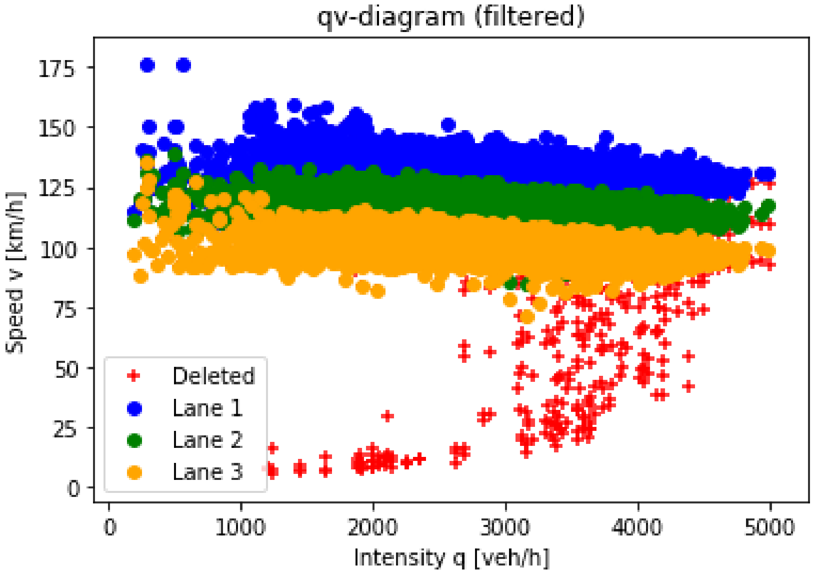


Figure 9.9 Filter by density for all lanes with the boundaries



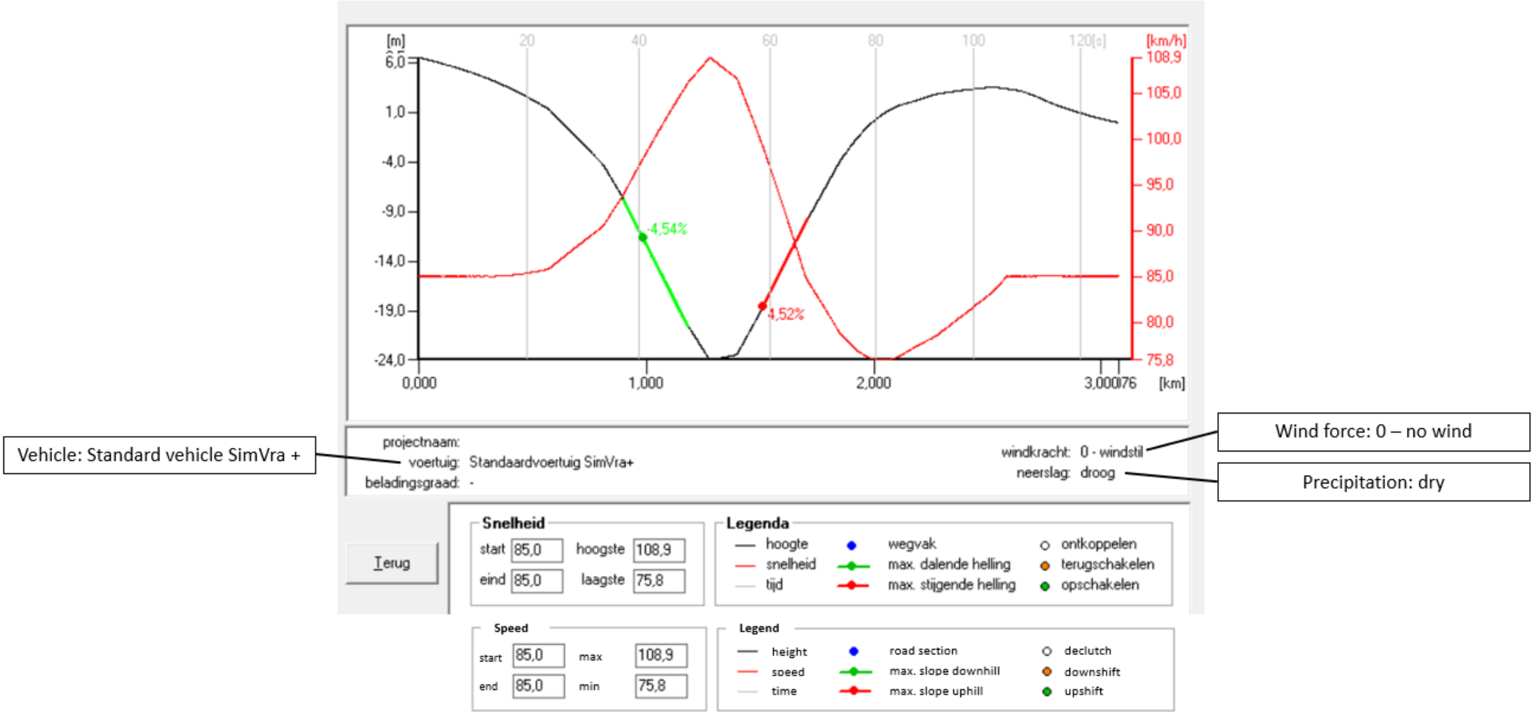
After subtracting all non-feasible data points, a new qv-diagram is plotted to check if the filter has the correct effect. The plot with the filtered data is shown in Figure 9.10. All data points that are in the congested branch of the q-v diagram are deleted from the dataset.

Figure 9.10 Intensity-speed diagram after applying the density filter



H. Translation of SimVra+ output

Figure 9.11 Translation of SimVra+ output



projectnaam:
voertuig: Standaardvoertuig SimVra+
beladingsgraad: -

windkracht: 0 - windstil
neerslag: droog

Vehicle: Standard vehicle SimVra +

Wind force: 0 – no wind

Precipitation: dry

Snelheid
start 85,0 hoogste 108,9
eind 85,0 laagste 75,8

Legenda
hoogte
snelheid
tijd
wegvak
max. dalende helling
max. stijgende helling
ontkoppelen
terugschakelen
opschakelen

Speed
start 85,0 max 108,9
end 85,0 min 75,8

Legend
height
soeed
time
road section
max. slope downhill
max. slope uphill
declutch
downshift
upshift

I. Warm-up Period

The warmup period is determined with the graphical method described by Robinson. (Robinson, 2014) Also, the MSER method is tried, but it turned out to be that the graphical method was more conservative and therefor considered more reliable. The used method is to do a simulation for an average intensity (2500 veh/h) and obtain the two KPI values: speed and intensity. These KPI's are saved for all loop detectors every 60 seconds and the moving average is plotted. The results can be seen in Figure 9.12 and Figure 9.13. This example is for the Wijkertunnel. All lines become stable after 600 seconds. So, the warmup time for the Wijkertunnel is set to 600 seconds.

Figure 9.12 The moving average of the speed for all loop detectors for 60 s intervals

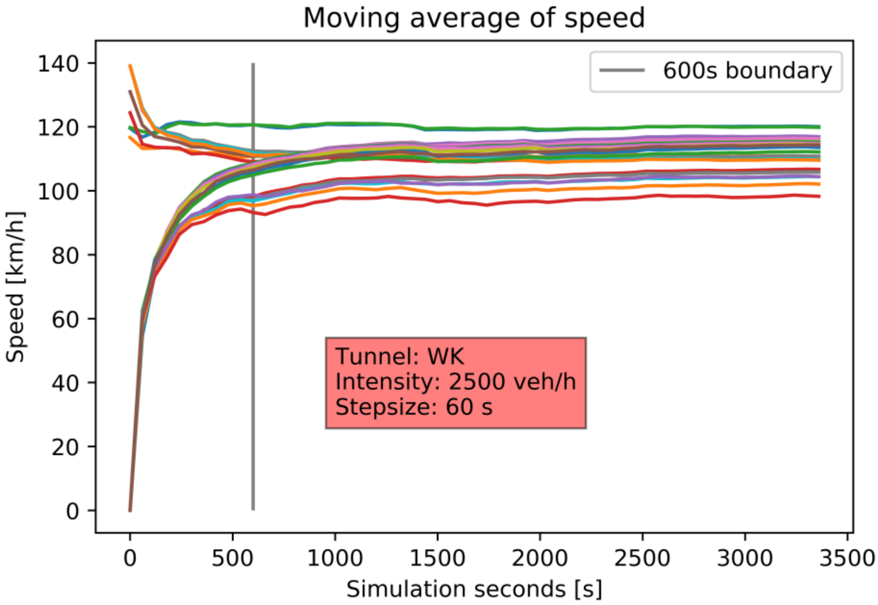
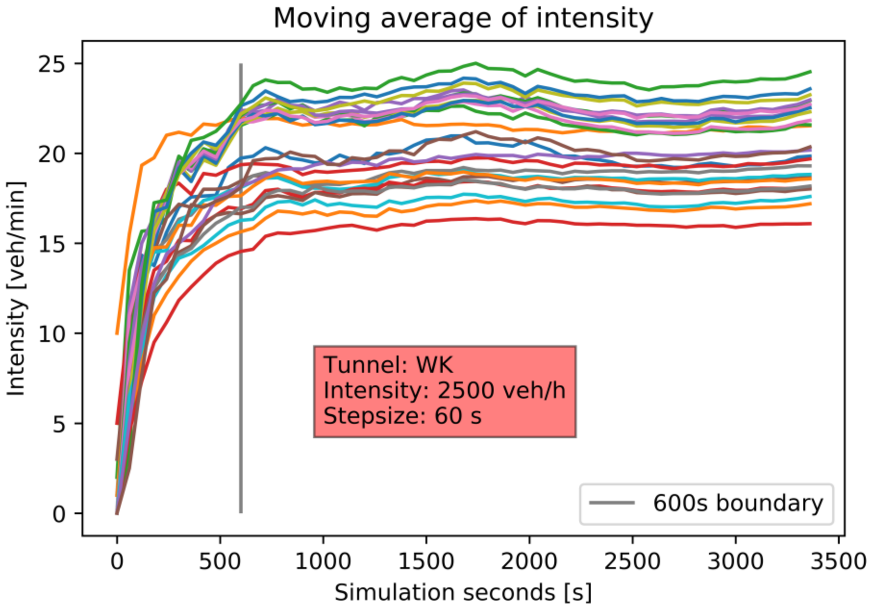


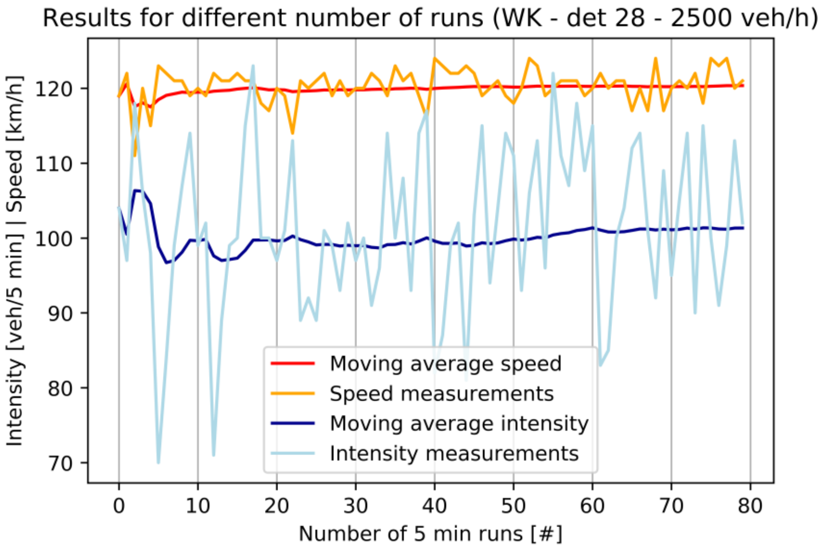
Figure 9.13 The moving average of the intensity for all loop detectors for 60 s intervals



J. Number of runs

To determine the number of runs, also the graphical approach is used, as described by Robinson. (Robinson, 2014) The results of 5-minute periods (the warm-up time is excluded) are plotted and the moving average is also plotted. From the point where the line becomes more or less flat, there is no remarkable change anymore. As can be seen, from 20 runs, the line becomes flat, so for the Wijkertunnel, 20 runs are performed.

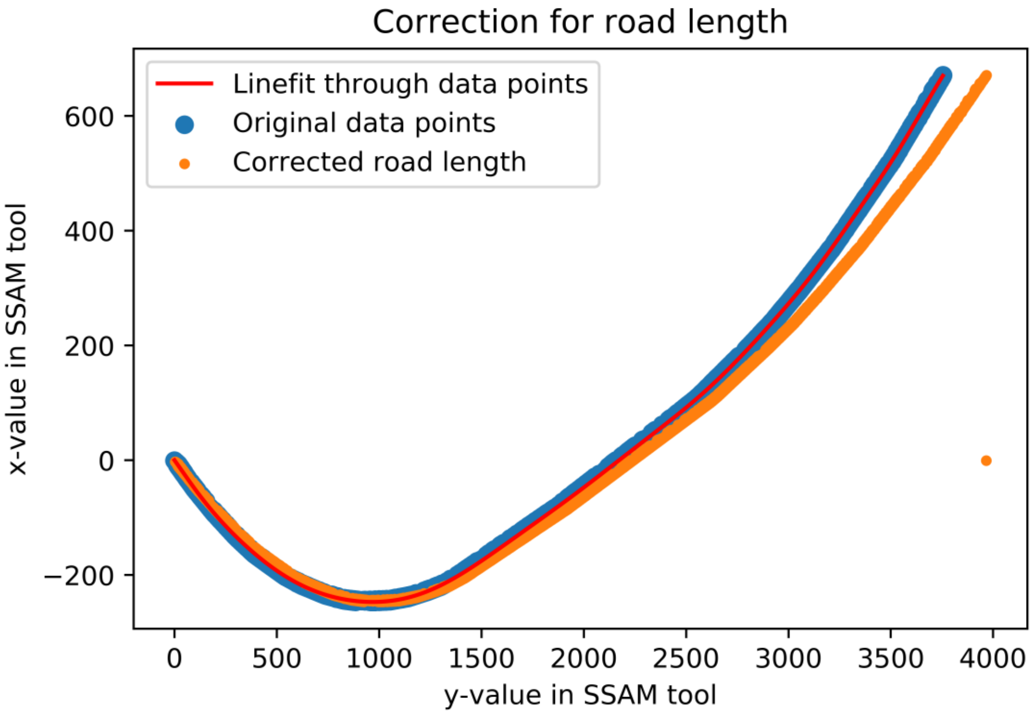
Figure 9.14 Moving averages for speed and intensity for different number of runs.



K. Road length correction

While the SSAM tool projects conflicts on a specific point, but for this research, a classification per road stretch with a certain length is favourable, a correction has to take place. This is done in the following way. First, all datapoints out of the SSAM tool are plotted on a x-y plane. Second, a polynomial line is plotted trough these data points. The assumption is that this polynomial line is the middle of the road. With a line of the middle of the road in the x-y plane, it is possible to calculate the exact length of the road and classify the conflicts in a certain road stretch. In Figure 9.15 this is visualised.

Figure 9.15 Visualisation of the correction of the road length

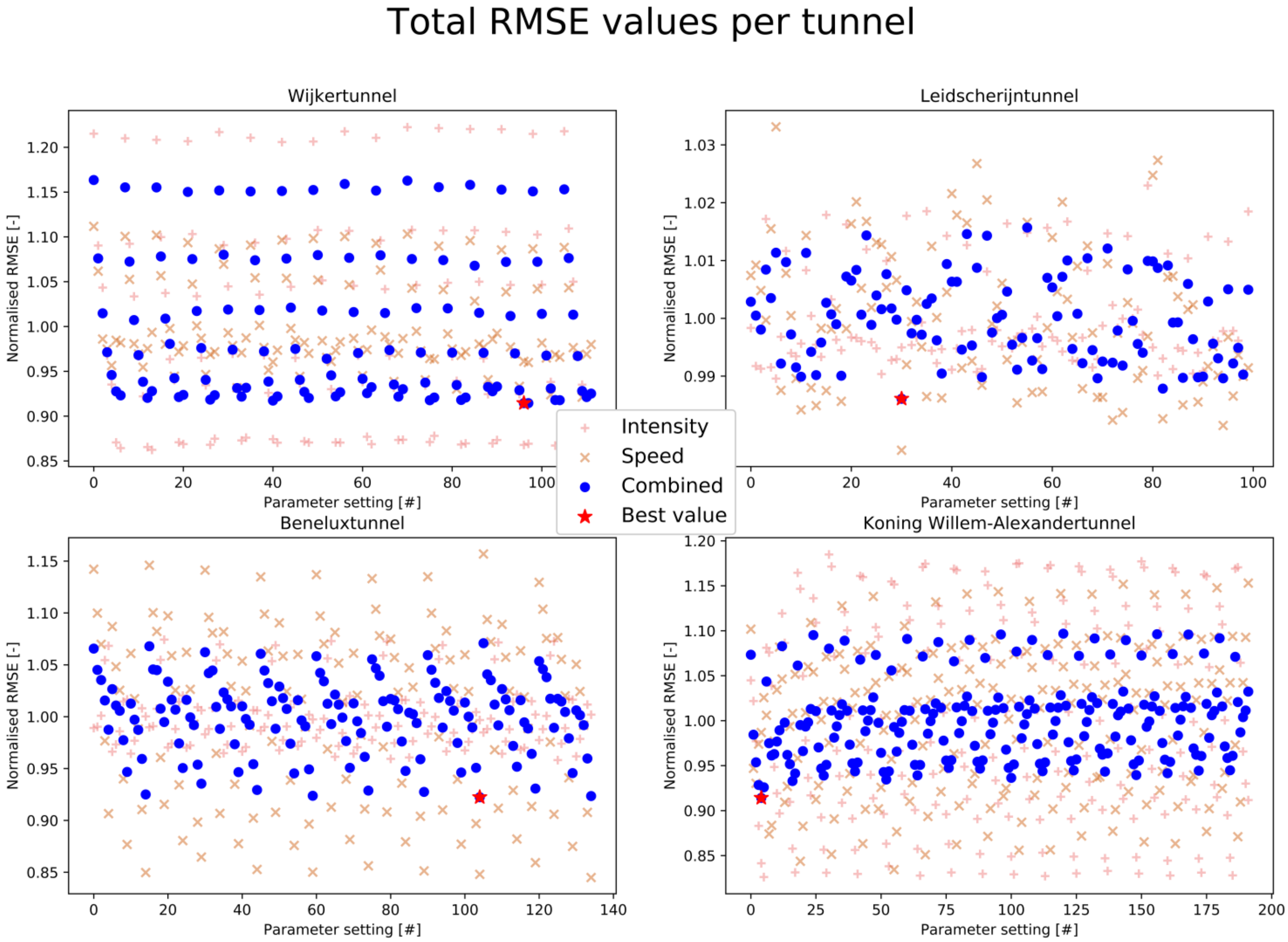


L. Results of Calibration

In this appendix, the exact procedure of the calibration process is described. First, the overall results (total RMSE values per tunnel) are shown in Figure 9.16. Afterwards, for the Wijkertunnel, the complete process from simulation output to final KPI is described.

Figure 9.16 Total RMSE values per tunnel

The output of Vissim consists out of average values of speed and intensity of ‘x’ 5-minute time intervals, where ‘x’ is the number of batches (normally around 20). This is done for all loop detectors and for all lanes in Vissim, which are in the same location as the detectors which generate the NDW data. This is visualized in Figure 9.17.

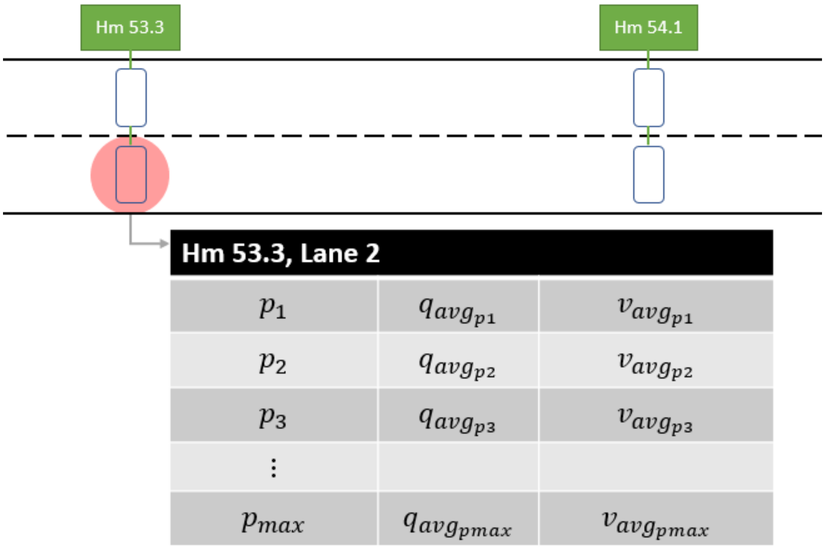


After the generation of output data, the data is used for the calculation of the KPI. The RMSE is calculated by using all loop detectors on all lanes. After taking the square root of the summed Mean Square Error, the total RMSE for a parameter setting is determined. This is the sum of all intensities with the same parameter setting, divided by the number of intensities. This step is visualized in Figure 9.18.

While the total KPI is a combination of speed and intensity, some more steps are needed. While both factors count equally, both RMSE values are normalized by divide them by the average RMSE of that factor. So, the RMSE of speed, is divided by the average RMSE of all speed values. The same is done for the intensity. By taking the average of these two values, Figure 9.16 is created.

From this figure, the best solution (the lowest RMSE) parameter setting is determined. By plotting the real differences of this parameter setting, more insight is the results is created. The differences between the NDW-data and Vissim-data are visualised in Figure 9.19 and Figure 9.20.

Figure 9.17 Visualisation of the generated data for one loop detector



Hm 53.3, Lane 2		
p_1	$q_{avg_{p1}}$	$v_{avg_{p1}}$
p_2	$q_{avg_{p2}}$	$v_{avg_{p2}}$
p_3	$q_{avg_{p3}}$	$v_{avg_{p3}}$
⋮		
p_{max}	$q_{avg_{pmax}}$	$v_{avg_{pmax}}$

Figure 9.18 RMSE values for different parameter settings per intensity (different blue colour is different intensity)

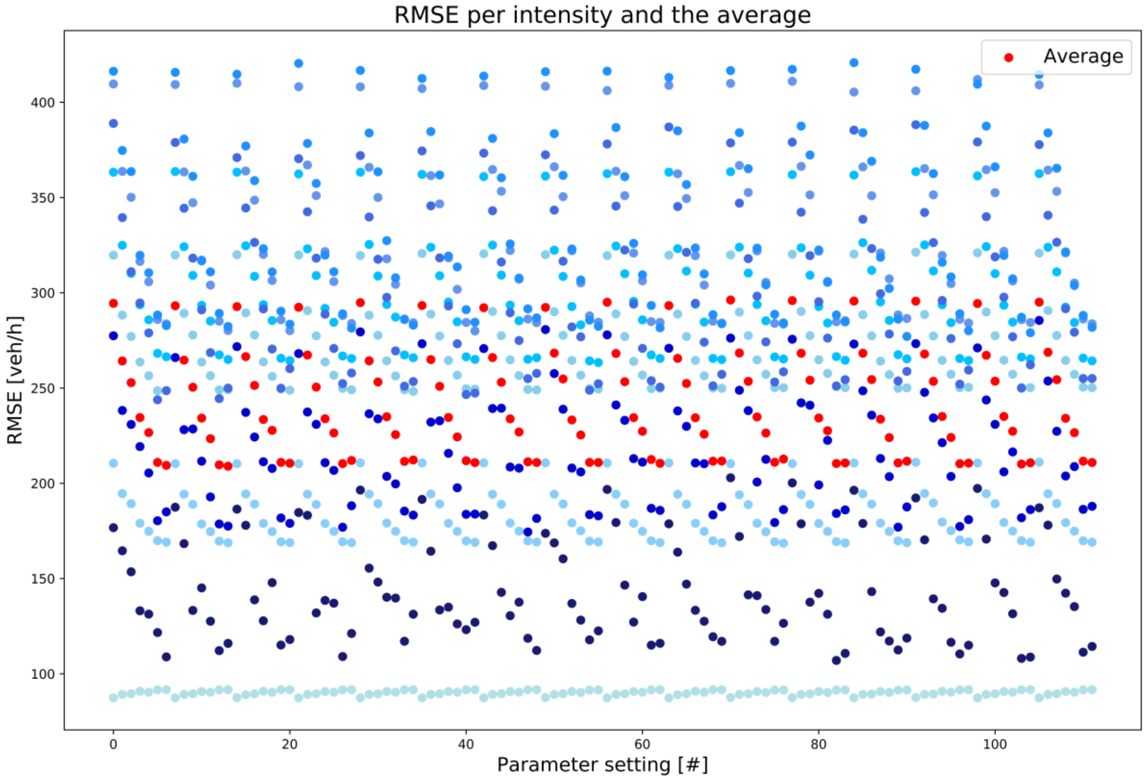


Figure 9.19 Difference in intensity (left) and speed (right) for the best parameter setting for the Beneluxtunnel

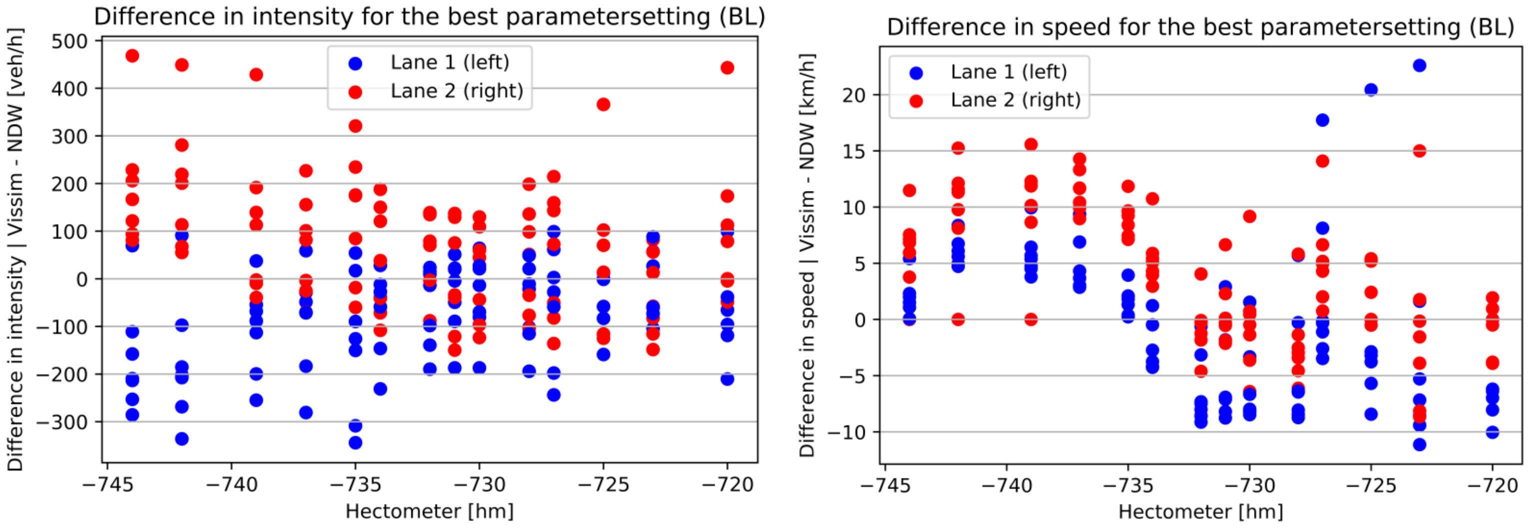


Figure 9.20 Difference in intensity (left) and speed (right) for the best parameter setting for the Leidscherijntunnel

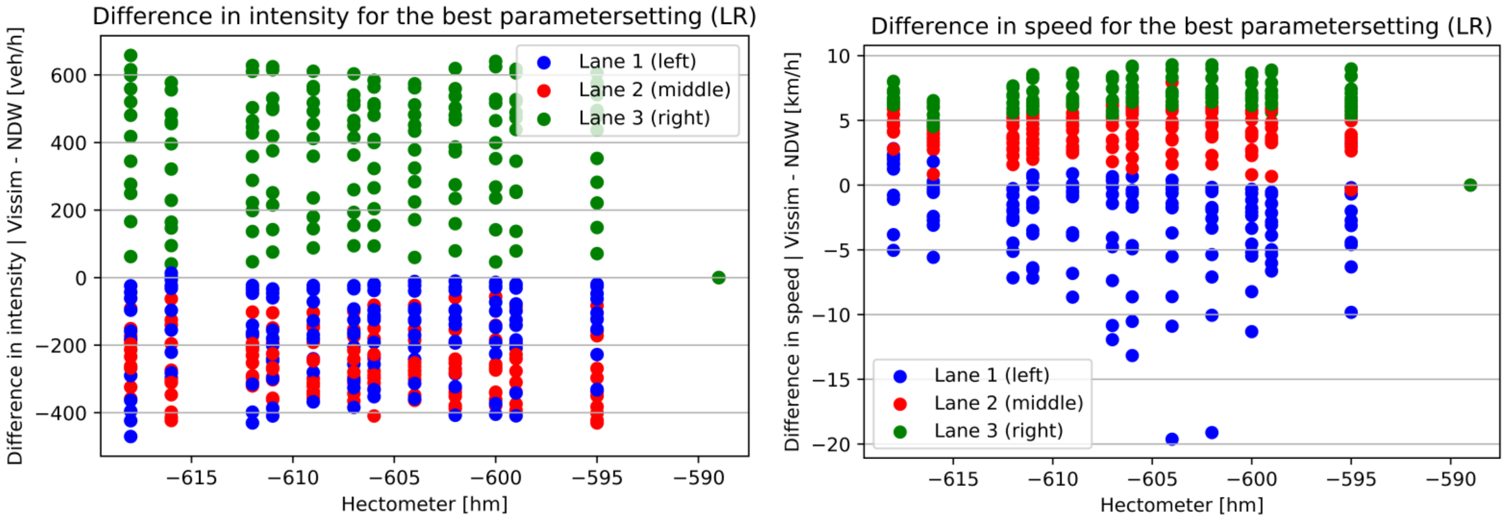
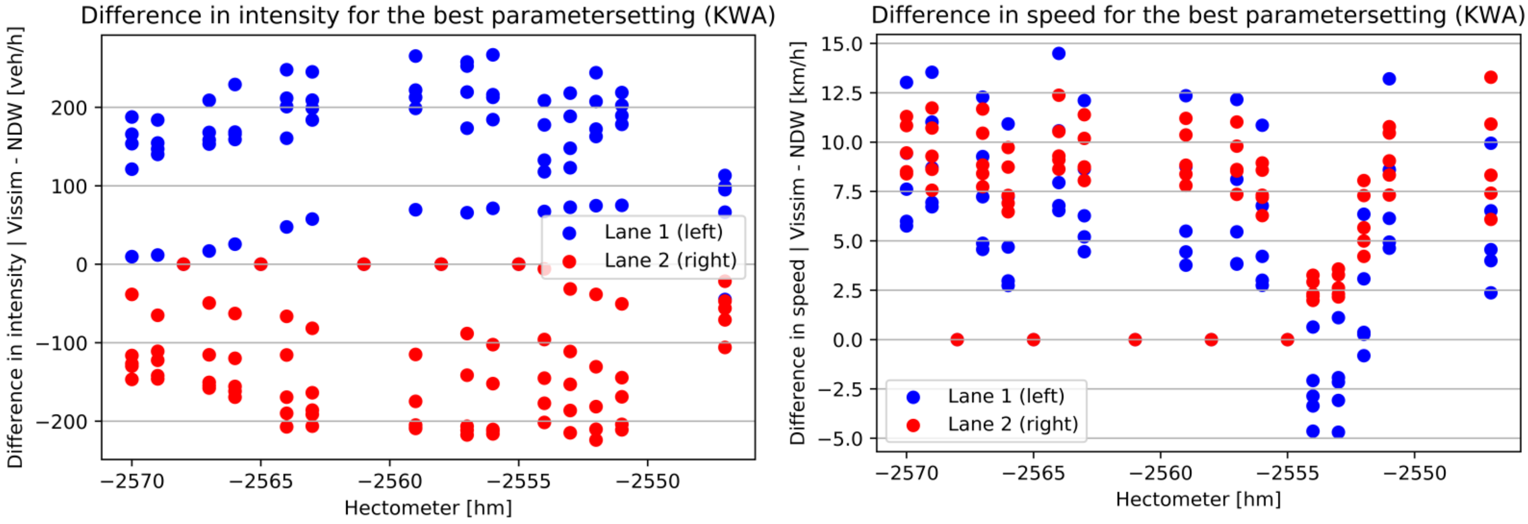
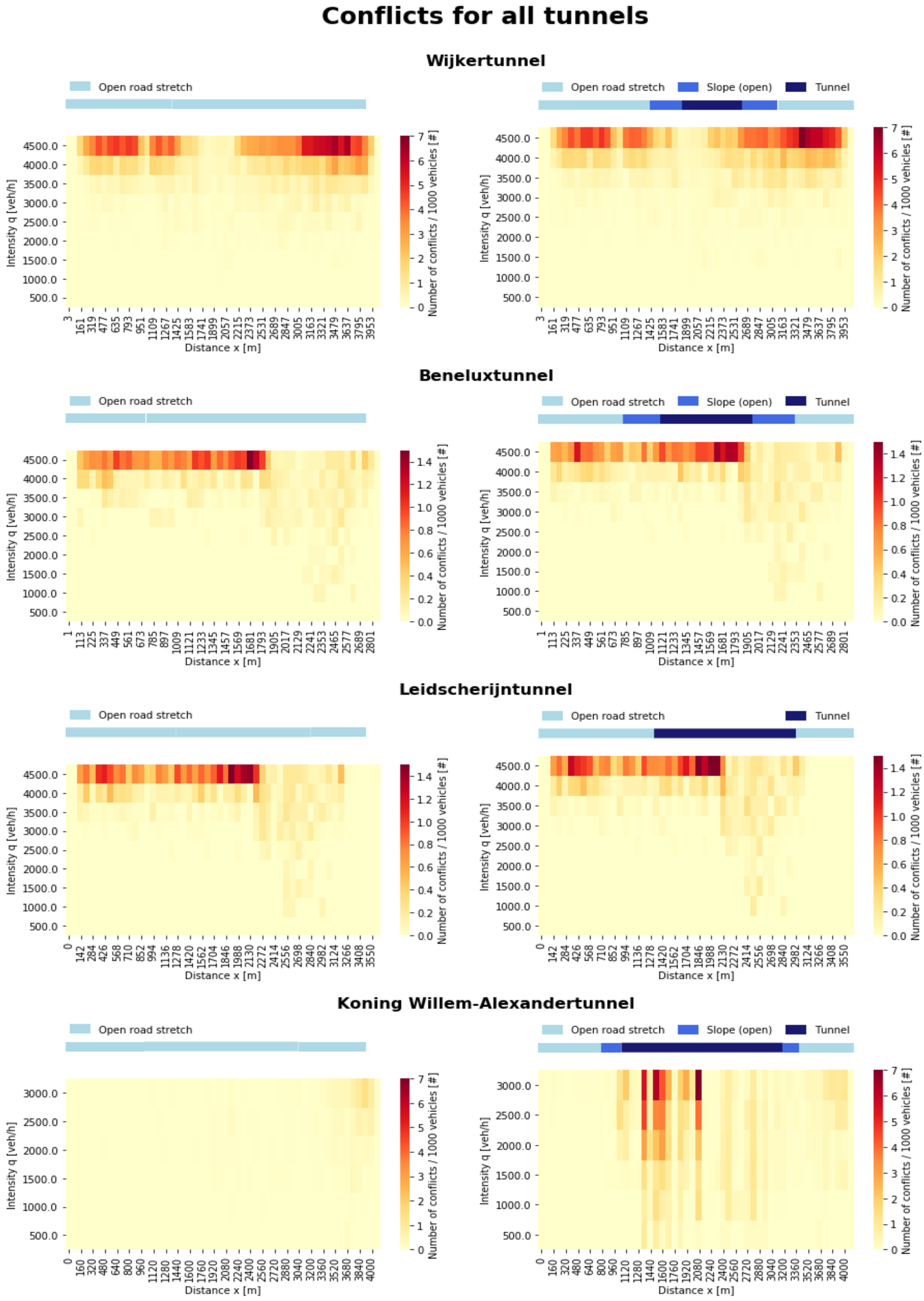


Figure 9.21 Difference in intensity (left) and speed (right) for the best parameter setting for the Koning Willem-Alexandertunnel



M. Results - Number of conflicts

Figure 9.22 Conflicts (in #/1000 veh) for all tunnels and corresponding normal road stretches



N. Tunnel Choice

The choice of tunnels that can be used for this research is divided into 3 different parts:

1 Exclusion of tunnels
2 Classification of accepted tunnels
3 Choice of tunnels

Step 1: Exclusion of tunnels

In the first step, tunnels that are not appropriate for this research, due to several reasons are excluded from the further process. This exclusion is done by following the diagram shown in Figure 9.23. The number of datapoints are derived from the NDW data exporter Dexter (NDW, 2020). The length of the tunnels is derived from Google maps. (Google, 2020) The last step is about irregularities. These irregularities concern several issues. Some examples are ramp metering just in front of the tunnel or non-regular road configurations.

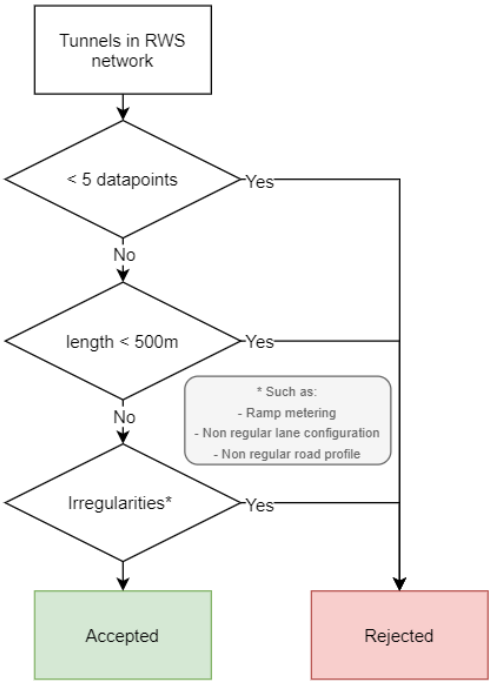
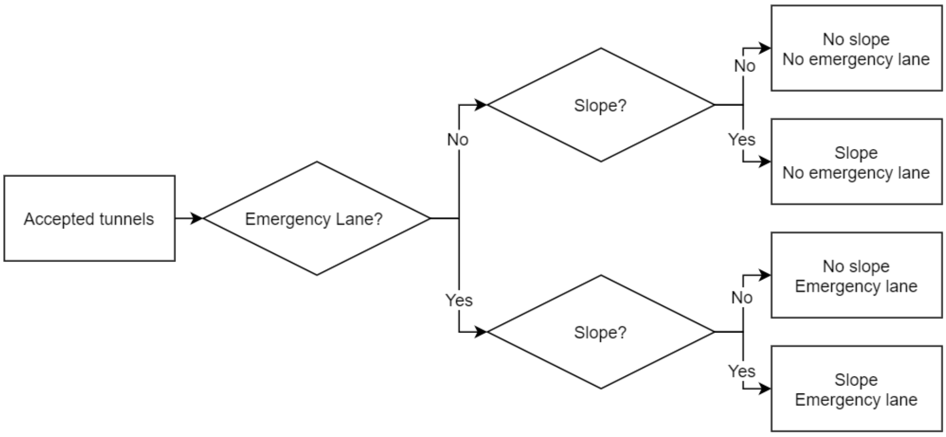


Figure 9.23 The exclusion process of tunnels (step 1)

Step 2: Classification of accepted tunnels

The second step concerns the classification of the tunnels. From the literature it became clear that the presence of an emergency lane and the presence of slopes are important factors of a tunnel. Therefore, the accepted tunnels from step 1 are divided over 4 classes. This process is shown in Figure 9.24.

Figure 9.24 The classification process of the tunnels (step 2)



Step 3: Choice of tunnels

From the accepted and classified tunnels, four tunnels are chosen such that it is possible to compare those tunnels to each other. This will be done by comparing several aspects, like length, the number of lanes and the presence of a crawler lane (in Dutch: 'Kruipstrook'). In section 5.1 this choice is elaborately explained.

Table 9.2 Choice process (from left to right) with reason for objection

Name	Datapoints	Reason of objection
Koning Willem-Alexandertunnel	20	
Ketheltunnel	11	Non-regular lane configuration (4 + 2 + 1)
Leidscherijn Tunnel	9	
Beneluxtunnel	9	
Drechttunnel	8	
Coentunnel	7	No height profile
Velsertunnel	7	Ramp metering
Heinenoordtunnel	7	
Botlektunnel	6	
Zeeburgertunnel	6	
Aquaduct in de Gouwe	6	
Wijkertunnel	5	
Schipholtunnel	5	
Noordtunnel	5	
Aquaduct Vechtzicht	2	Not enough data points (< 5)
Tunnel in de A5	2	Not enough data points (< 5)
Limesaquaduct in de Oude Rijn	2	Not enough data points (< 5)
Aquaduct in het Haarlemmermeer	1	Not enough data points (< 5)
Aquaduct in de Gaag	1	Not enough data points (< 5)
Roertunnel	0	Not enough data points (< 5)
Tunnel Swalmen	0	Not enough data points (< 5)
Vlaketunnel	0	Not enough data points (< 5)
Aquaduct Mid-Fryslan	0	Not enough data points (< 5)
Prinses Margriettunnel	0	Not enough data points (< 5)

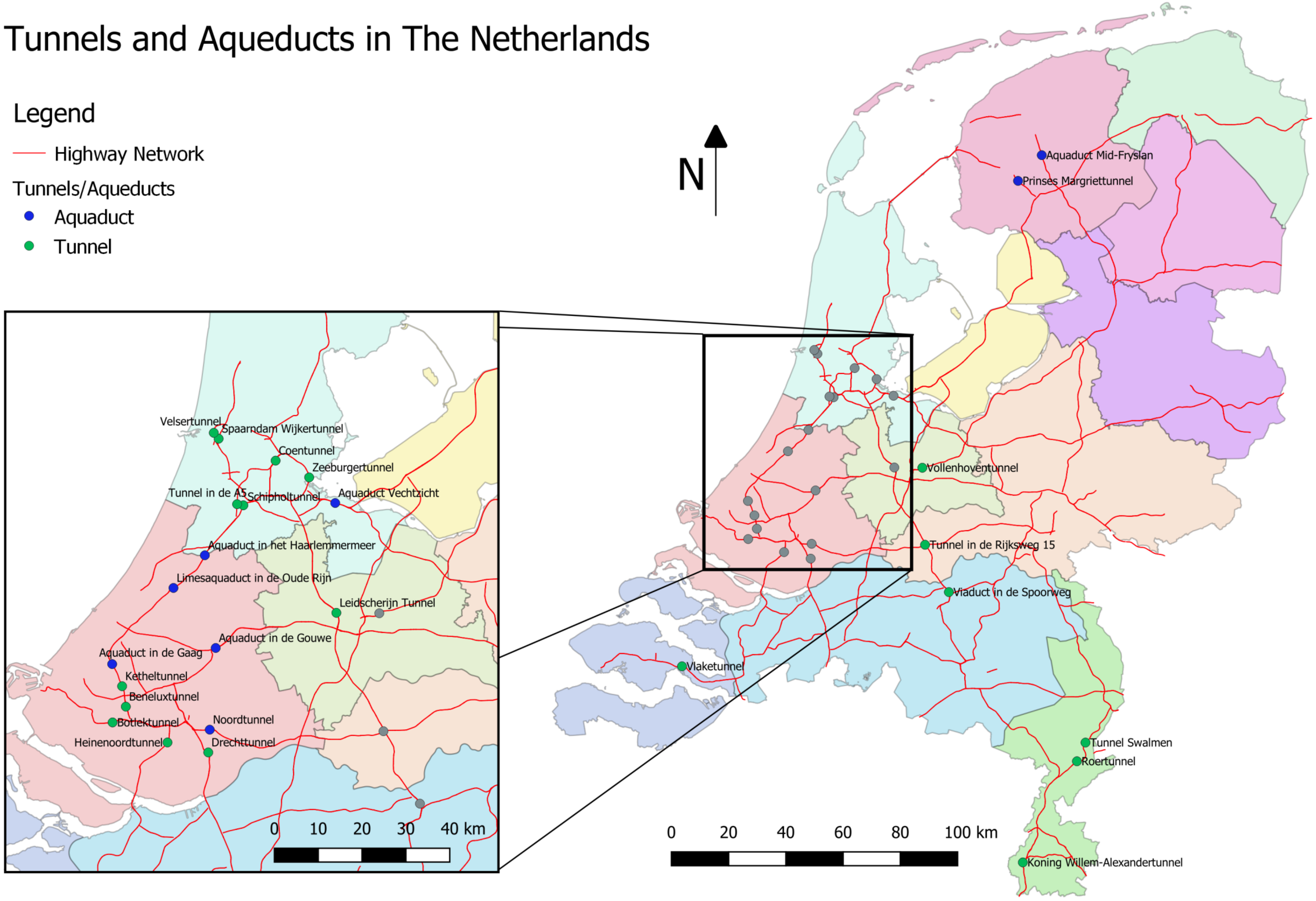
Name	Emergency lane?
Koning Willem-Alexandertunnel	No
Leidscherijn Tunnel	Yes
Beneluxtunnel	No
Drechttunnel	No
Heinenoordtunnel	No
Botlektunnel	No
Zeeburgertunnel	No
Aquaduct in de Gouwe	Yes
Wijkertunnel	Yes
Schipholtunnel	No
Noordtunnel	No

With emergency lane	Slopes?	Length	2nd reason for objection
Leidscherijn Tunnel	No	1651	
Aquaduct in de Gouwe	Yes	43	To short
Wijkertunnel	Yes	719	
Without emergency lane			
Koning Willem-Alexandertunnel	No	2177	
Beneluxtunnel	Yes	713	
Drechttunnel	Yes	570	Very narrow road profile, and sharp curve
Heinenoordtunnel	Yes	603	
Botlektunnel	Yes	541	
Zeeburgertunnel	Yes	540	
Schipholtunnel	No	554	Non comparable road configuration
Noordtunnel	Yes	553	

With emergency lane	Slopes?
Leidscherijn Tunnel	No
Wijkertunnel	Yes
Without emergency lane	
Koning Willem-Alexandertunnel	Yes
Beneluxtunnel	Yes
Heinenoordtunnel	Yes
Botlektunnel	Yes
Zeeburgertunnel	Yes
Noordtunnel	Yes

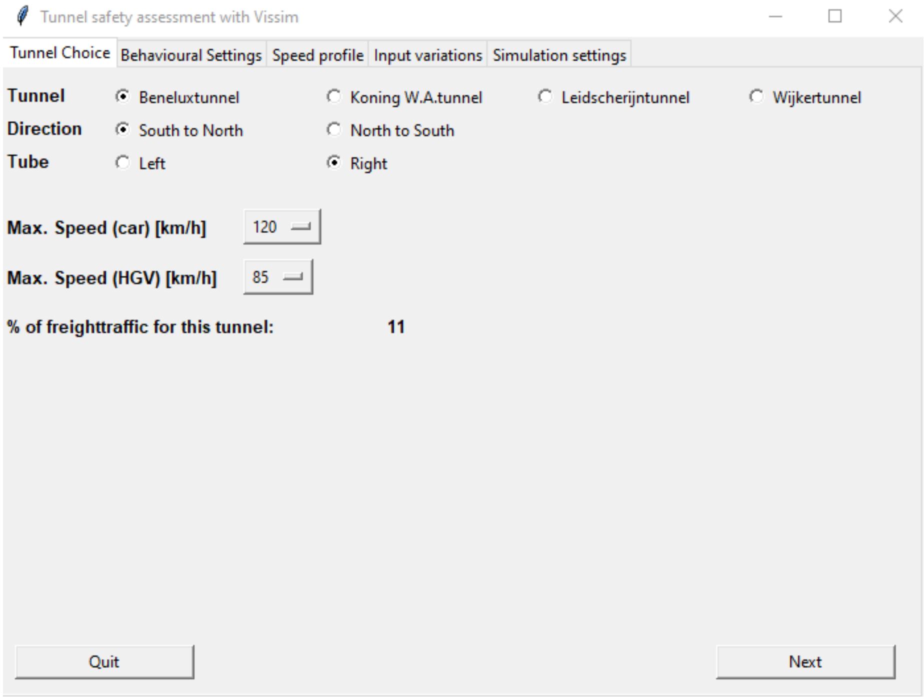
O. Overview of tunnels in the Netherlands

Figure 9.25 An overview of the tunnels in the Netherlands



P. Screenshots of the user interface

Figure 9.26 Screenshots of the user interface with all the parameters that are needed



Tunnel ● Beneluxtunnel ○ Koning W.A.tunnel ○ Leidscherijntunnel ○ Wijkertunnel

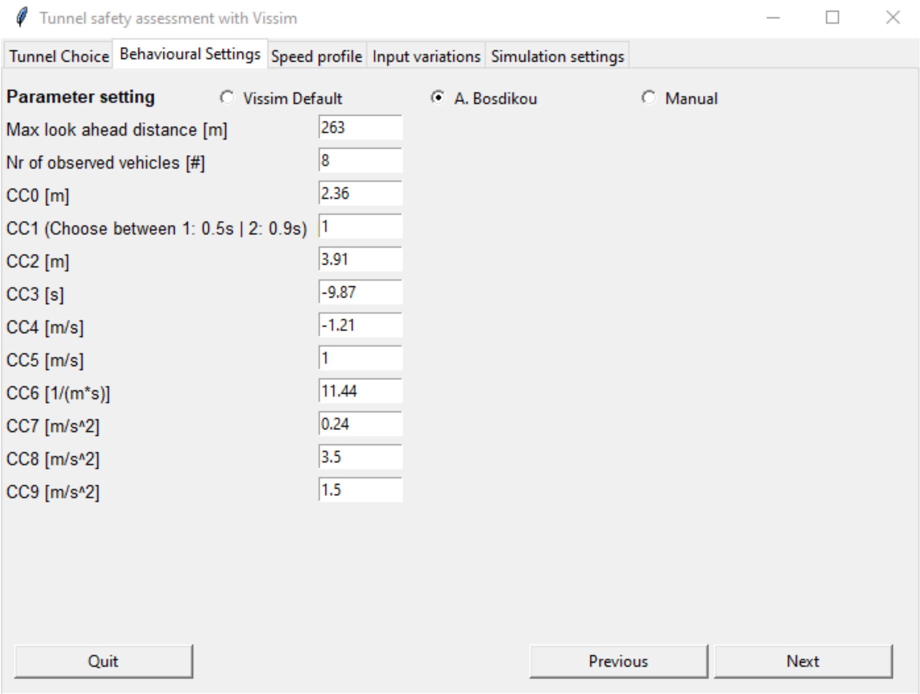
Direction ● South to North ○ North to South

Tube ○ Left ● Right

Max. Speed (car) [km/h] 120

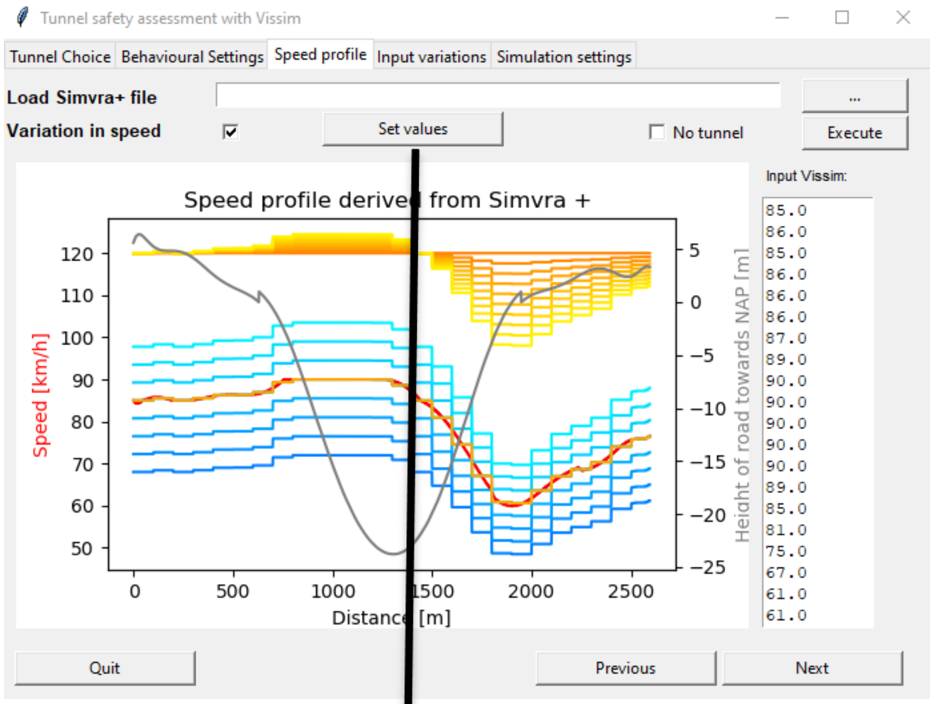
Max. Speed (HGV) [km/h] 85

% of freighttraffic for this tunnel: 11



Parameter setting ○ Vissim Default ● A. Bosdikou ○ Manual

Max look ahead distance [m]	263
Nr of observed vehicles [#]	8
CC0 [m]	2.36
CC1 (Choose between 1: 0.5s | 2: 0.9s)	1
CC2 [m]	3.91
CC3 [s]	-9.87
CC4 [m/s]	-1.21
CC5 [m/s]	1
CC6 [1/(m*s)]	11.44
CC7 [m/s^2]	0.24
CC8 [m/s^2]	3.5
CC9 [m/s^2]	1.5

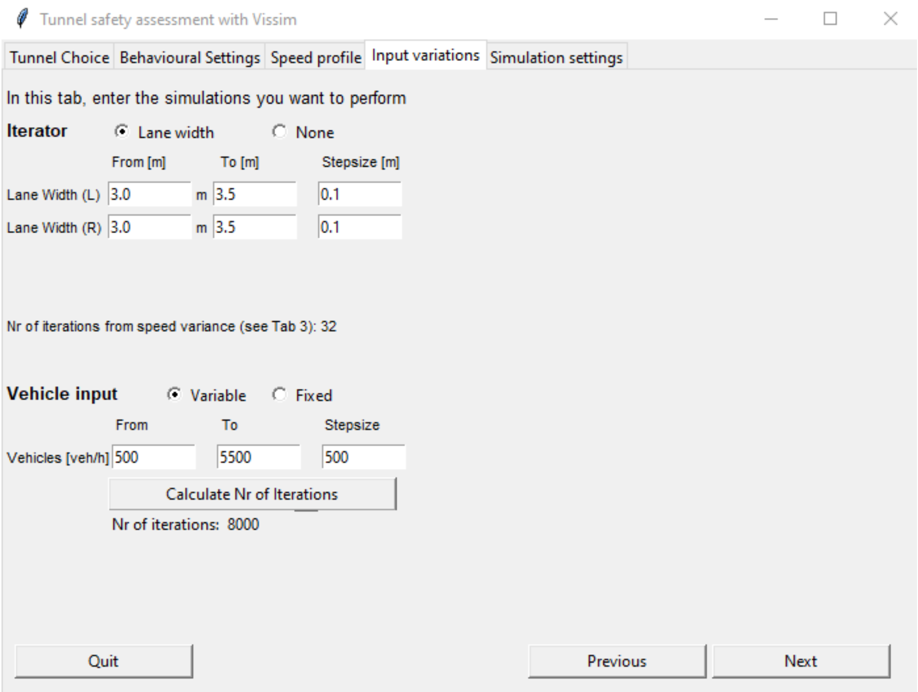


Load Simvra+ file

Variation in speed ☑ ☐ No tunnel

Input Vissim:

```
85.0
86.0
85.0
86.0
86.0
86.0
87.0
89.0
90.0
90.0
90.0
90.0
90.0
89.0
85.0
81.0
75.0
67.0
61.0
61.0
```



In this tab, enter the simulations you want to perform

Iterator ● Lane width ○ None

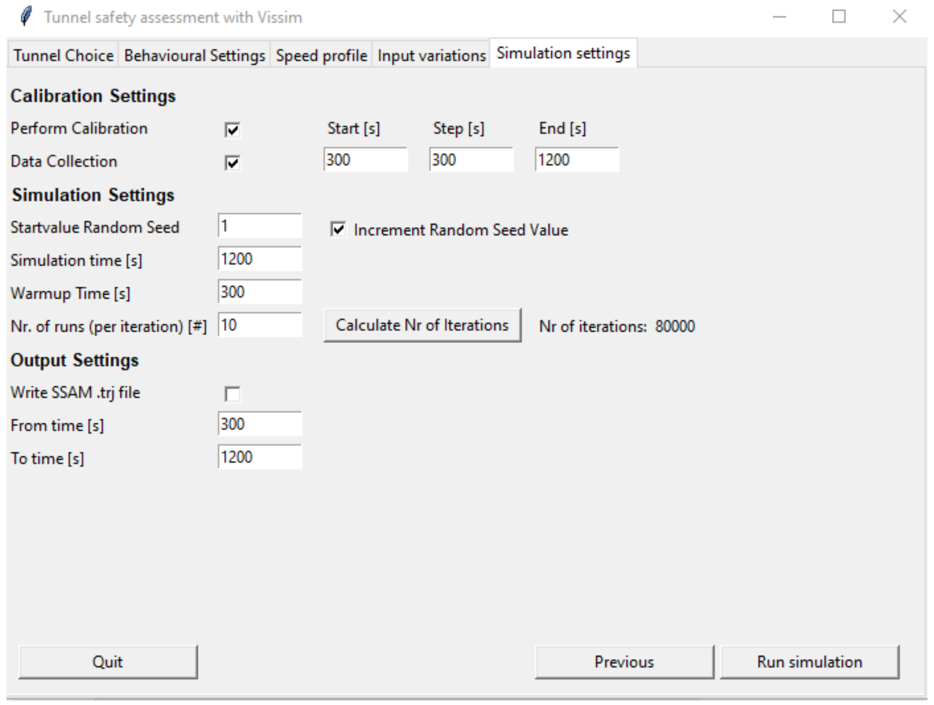
	From [m]	To [m]	Stepsize [m]
Lane Width (L)	3.0 m	3.5	0.1
Lane Width (R)	3.0 m	3.5	0.1

Nr of iterations from speed variance (see Tab 3): 32

Vehicle input ● Variable ○ Fixed

	From	To	Stepsize
Vehicles [veh/h]	500	5500	500

Nr of iterations: 8000



Calibration Settings

Perform Calibration ☑

Data Collection ☑ Start [s] 300 Step [s] 300 End [s] 1200

Simulation Settings

Startvalue Random Seed 1 ☑ Increment Random Seed Value

Simulation time [s] 1200

Warmup Time [s] 300

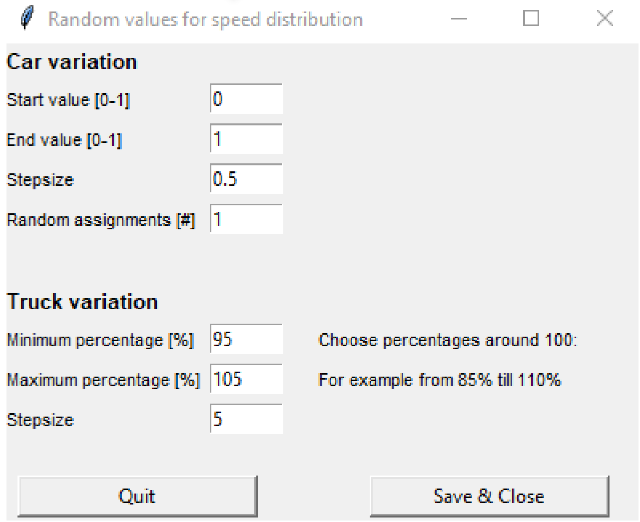
Nr. of runs (per iteration) [#] 10 Nr of iterations: 80000

Output Settings

Write SSAM .trj file ☐

From time [s] 300

To time [s] 1200



Car variation

Start value [0-1] 0

End value [0-1] 1

Stepsize 0.5

Random assignments [#] 1

Truck variation

Minimum percentage [%] 95 Choose percentages around 100:

Maximum percentage [%] 105 For example from 85% till 110%

Stepsize 5