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Performance of rush-hour lanes and pluslanes

A study to behavioral factors and design factors

FINAL REPORT

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Colophon

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Summary

Rush-hour lanes and pluslanes have been operational in the Netherlands since 1996. They are intended as a measure to increase capacity without the need to add an extra lane to the cross section. Individually, rush-hour lanes and pluslanes have been evaluated. However, not much research, however, compares rush-hour lane or pluslane designs with each other. In this research, long-term data will be used to get detailed information about the performance of different rush-hour lane and pluslane designs. Also, a driving simulator study is performed to gain insight in the underlying behavioral factors and to analyze the performance of changes in rush-hour lane designs.

The main question for the research is:
What is the performance of rush-hour lanes and pluslanes, what are the behavioral factors and design factors causing differences in performance and what changes can be made to the design of rush-hour lanes to improve the performance?

In the ex-post evaluation of performance, data is used for a period of 120 days of 5 highway sections with a rush-hour lane and 5 highway sections with a pluslane. The sections are compared using lane flow distributions that show the occupation of the lanes and intensity-speed relations that show the differences in free-flow speeds driven on the sections. In the first analysis, rush-hour lanes are compared with regular right lanes and pluslanes are compared with regular left lanes. The rush-hour lane section at the A50 between junction Ewijk and junction Valburg is designed in the driving simulator to analyze the behavioral factors that underlie the results from this first comparison.
Also, a comparison is made between the occupation of different locations at rush-hour lanes and pluslanes. For this purpose, the start section and the end section are compared with a turbulence-free section.
As a final analysis, the design factors that are researched for their influence on performance are: the lane width, the speed limit and the total number of lanes. A lot of variation in these design factors can be found on the rush-hour lane and pluslane sections that have been implemented today. However, some designs have not been implemented yet. The driving simulator provided the perfect opportunity to test new designs of rush-hour lanes. The simulator is used to test the influence of reducing the signaling by 50% and the influence of changing the markings from continuous to broken on the occupation of rush-hour lanes.

Regarding the design factors, it can be concluded from this research that a high speed limit of 120 km/h has a negative effect on the occupation of rush-hour lanes and also on the speeds driven at rush-hour lane sections. The car-following behavior of vehicles on a rush-hour lane section with such speed limit is researched in the driving simulator study. It shows that the incentive of using the rush-hour lane at this speed limit is low.

Changing the markings from continuous to broken in the driving simulator does not affect the occupation of the rush-hour lane at 120 km/h. Also, reducing the signaling by half does not affect the occupation. Further research needs to show if these design factors have an influence on the occupation of rush-hour lanes at lower speed limits. The models that are implemented in the simulator at the Delft University of Technology are not realistic enough for this kind of research, as the behavior of virtual traffic influences the results too much.

Smaller lane widths appear to have a negative effect on the occupation of rush-hour lanes and on the speeds driven at rush-hour lane sections. This could, however, not be concluded from this research alone. At pluslane sections with a combination between a high speed limit (100 km/h) and a small lane width (< 2,80 m) the occupation of the pluslane becomes significantly less.

Adding an extra lane to the section (making it 3+1) lowers the intensity shares at low intensity levels for that section for both rush-hour lanes and pluslanes. At higher intensity levels, no significant differences were found.

Quantifying the influence of the design factors on the performance of rush-hour lanes and pluslanes is an interesting subject for further research. The performance of managed lanes to be implemented in the future can then be predicted by a model before realization. The differences between start sections and end sections also need to be analyzed in more detail for this purpose. The combination between an ex-post evaluation and a driving simulator study as is used in this research can also be well-suited for that new research.

Samenvatting

Spitsstroken en plusstroken zijn vanaf 1996 operationeel in Nederland. De capaciteit van een wegvak wordt uitgebreid zonder een extra rijstrook toe te voegen. Spits- en plusstroken zijn individueel geëvalueerd in verschillende onderzoeken. Echter, niet veel onderzoek vergelijkt verschillende ontwerpen van spits- en plusstroken met elkaar. In dit onderzoek wordt lange-termijn data gebruikt om gedetailleerde informatie te verkrijgen over prestatie-indicatoren van verschillende spits- en plusstrook ontwerpen. Ook is een rijsimulatorstudie uitgevoerd om inzicht te krijgen in de onderliggende gedragsfactoren en om de prestatie van niet bestaande ontwerpen van spitsstroken te onderzoeken.

De hoofdvraag van dit onderzoek is:
Wat is de prestatie van spitsstroken en plusstroken, welke gedragsfactoren en ontwerpfactoren veroorzaken verschillen in prestatie en welke veranderingen kunnen in het ontwerp worden toegepast om de prestatie van spitsstroken te verbeteren?

In de ex-post evaluatie naar prestatie, is 120 dagen aan data verzameld van 5 snelwegsecties met spitsstrook en 5 snelwegsecties met plusstrook. Rijstrookverdelingen zijn gebruikt om de verschillen in bezetting aan te tonen en intensiteit-snelheidrelaties zijn gebruikt om de verschillen in vrije snelheden aan te tonen. In de eerste analyses wordt een vergelijk gemaakt tussen een spitsstrook en een reguliere rechter rijstrook en tussen een plusstrook en een reguliere linker rijstrook. De spitsstrooksectie op de A50 tussen knooppunt Ewijk en knooppunt Valburg is ontworpen in de rijsimulator om de gedragsfactoren te onderzoeken die ten grondslag liggen aan de resultaten van deze eerste vergelijking.
Ook is een vergelijk gemaakt tussen de bezetting van verschillende locaties op spits- en plusstrooksecties. Hiervoor zijn begin- en eindsecties vergeken met een turbulentie-vrije sectie.
In de laatste analyse wordt onderzoek gedaan naar de ontwerpfactoren die van invloed zijn op de prestatie. De ontwerpfactoren die onderzocht worden zijn: de rijstrookbreedte, de snelheidslimit en het totaal aantal rijstroken. De bestaande ontwerpen van spits- en plusstroken laten veel variatie zien in deze ontwerpfactoren. Sommige ontwerpen zijn echter nog niet uitgevoerd. De rijsimulator is zeer geschikt om toekomstige ontwerpen te onderzoeken. De simulator wordt in dit onderzoek gebruikt om de invloed van het halveren van signalering en de invloed van onderbroken markering in plaats van doorgetrokken markering op de bezetting van spitsstroken te onderzoeken.

Wanneer gekeken wordt naar de ontwerpfactoren, kan uit dit onderzoek geconcludeerd worden dat een hoge snelheidslimiet van 120 km/h een negatieve invloed heeft op de bezetting en op de vrije snelheden van spitstroken. Het voertuig-volggedrag op een spitsstrooksectie met deze snelheidslimiet is onderzocht in de rijsimulatorstudie. Hier wordt aangetoond dat de prikkel om gebruik te maken van de spitsstrook bij deze snelheidslimiet laag is.

Het veranderen van de markering van doorgetrokken naar onderbroken en het halveren van de signalering heeft in beide gevallen geen effect op de bezetting van een spitsstrook bij 120 km/h. Toekomstig onderzoek moet aantonen of deze ontwerpfactoren wel van invloed zijn op de bezetting van spitsstroken bij lagere snelheidslimieten. De verkeersmodellen in de simulator van de TU Delft zijn niet realistisch genoeg voor dit onderzoek, aangezien het gedrag van het ingeprogrammeerde verkeer teveel invloed heeft op de resultaten.

Versmalde rijstroken lijken een negatief effect te hebben op de bezetting van een spitsstrook en op de gereden vrije snelheden op een spitsstrooksectie. Dit kon echter niet uit dit onderzoek geconcludeerd worden. Bij plusstrooksecties is een combinatie van een smalle plusstrook (< 2,80 m) met een hoge snelheidslimiet (100 km/h) van grote negatieve invloed op de bezetting van de strook.

Wanneer een sectie met 3 bestaande stroken uitgebreid wordt met een spitsstrook of een plusstrook, dan wordt deze strook minder bezet bij lage intensiteiten. Bij hoge intensiteiten zijn geen significante verschillen gevonden.

Een interessant onderwerp voor toekomstig onderzoek is het kwantificeren van de invloed van de ontwerpfactoren op de prestatie van spits- en plusstroken. De prestatie van spits- en plusstroken kan dan vóór de realisatie ingeschat worden met een model. Ook dient het verschil tussen begin- en eindsecties voor dit model beter geanalyseerd te worden. De combinatie van de ex-post evaluatie met een rijsimulatorstudie zoals dat in dit onderzoek is uitgevoerd, is voor dat toekomstig onderzoek zeer geschikt.

Preface

This report marks the end of my Master track Transport & Planning at the faculty of Civil Engineering & Geosciences at the Delft University of Technology. The research is commissioned by Rijkswaterstaat and performed at the ITS Edulab, a cooperation between Rijkswaterstaat Centre of Transport and Navigation and the Delft University of Technology.

First and foremost I would like to thank my graduation committee for their guidance throughout the project: My professor Serge Hoogendoorn, my daily supervisor Hans van Lint, the graduation coordinator Paul Wiggenraad, my external supervisor Victor Knoop, the coordinator of ITS Edulab Henk Taale and my supervisor at Rijkswaterstaat Henk Heikoop. They all provided the support I needed throughout my research.

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Robbert Beentjes,
Delft, Oktober 2012

Contents

Introduction

1.1 Background

Managed lanes* have been operational in the Netherlands since 1996. They are intended as a measure to increase capacity without the need to add an extra lane to the cross section. Managed lanes are designed in many forms. This research, however, is only focused on two main forms: the so called rush-hour lane and the so-called pluslane.

A rush-hour lane is, within this research, defined as:

A hard shoulder on the right side of a highway section that can be managed by opening it for traffic during times of day where high intensities are reached. (Vliet, 2003)

A pluslane is, within this research, defined as:

A lane on the left side of a highway section that can be managed by opening it for traffic during times of day where high intensities are reached. The hard shoulder will be maintained, as the other lanes (and possibly also the hard shoulder) will become less wide (Vliet, 2003)

Today, approximately 174 km (± 7%) of road in the Netherlands has an operational rush-hour lane and about 116 km (± 5%) of road has an operational pluslane (Helleman, 2011). These measures have been widely researched. The increase in capacity of a rush-hour lane and a pluslane is expected to be lower than the capacity increase of adding an extra lane (for a pluslane, the design capacity is 1600 veh/h) (Heikoop, 2011) . It is not yet known what the capacity-increase really is, because capacity estimators need bottlenecks for the estimation of an accurate value and no bottlenecks are yet to be found on road sections with a rush-hour lane or a pluslane operational. Individually, rush-hour lanes and pluslanes have been evaluated eg. (Bekkum, 2000) and (Van Kooten, 2000). Comparing the differences in performance of the two is interesting, because they have both similarities as differences. No known research, however, compares rush-hour lane or pluslane designs with each other. In this research, detector data of longer periods will be used to acquire clear insights into several performance indicators of rush-hour lanes and pluslanes. Focusing on different parts of the rush-hour lanes and pluslanes (at the start of the section, halfway the section and at the end of the section), the data should result in main hypotheses of the driving behavior at these managed lanes. This change in behavior is interesting. Different design factors can be the cause of these behavioral changes:

- To ‘access’ a rush-hour lane, the driver has to cross a continuous marking. This conflicts with the core idea that continuous markings may never be crossed and can lead to confusion
- The signaling system shows green arrows or red crosses. It is not known what the effect is of the green arrow in combination with the crossing of a continuous marking on the behavior of drivers
- Lane widths of pluslanes and sometimes also rush-hour lanes are smaller than the width of regular lanes and speed limits change when the lanes are opened for traffic

The link between design factors and behavioral factors is not yet made. That link will be the main focus point for this research. For Rijkswaterstaat it is important to gain more insight into these behavioral factors. They provide information for policy making at future projects.

**Managed lanes are defined as: ‘highway facilities or a set of lanes where operational strategies are proactively implemented and managed in response to changing conditions’ (FHA, 2008)*

1.2 Research objective

As mentioned in the background, no known study has compared different designs of rush-hour lanes and pluslanes with each other. Also, the link between design factors and behavioral factors is important in this research.

Problem definition

The problem is that the driving behavior probably changes at different designs of managed lanes. This change in behavior leads to a change in performance of the managed lane. It is important to gain insight in the impact of different designs on the performance of the lane. The focus for this research will therefore be on the link between design factors, behavioral factors and performance.

Main research question

What is the performance of rush-hour lanes and pluslanes, what are the behavioral factors and design factors causing differences in performance and what changes can be made to the design of rush-hour lanes to improve the performance?

It is obvious to see that 3 parts stand out in this research question: *behavioral factors*, *design factors* and *performance*. These three parts can be used to distinguish the different sub-questions. As behavioral factors and design factors are strongly related, the sub-questions about these factors are combined.

Sub-questions - Performance

A0 - How is performance defined in this research?
A1 - What is the performance of a rush-hour lane compared to a regular right lane?
A2 - What is the performance of a pluslane compared to a regular left lane?
A3 - What is the performance of different locations at rush-hour lane and pluslane sections?
A4 - What is the performance of a rush-hour lane compared to a pluslane?

Sub-questions - Behavioral factors and design factors

B1 - What are the underlying design factors causing the differences in performance?
B2 - What are the underlying behavioral factors causing the differences in performance?
B3 - What changes can be made to the design of managed lanes to improve the performance of them?

The research goal of the project is reached when all these research questions are answered. In the following chapter, a description is given of the different steps that need to be taken to achieve this research goal.

1.3 Research approach

The used research methods will be discussed in this section. As a first clarification, the research questions will be detailed even further by defining the activities needed for answering them. In the end of this chapter, the different phases of the project and the report structure will be recapped.

1.3.1 Elaboration of research questions

The questions from the previous paragraph will now be described in detail. They can be divided in different sub-questions (or sub-goals) and activities. The questions are stated in 2 different main topics: 'performance' and 'behavioral factors and design factors'. An important aspect of this research is the overlap between these 2 topics. Several aspects overlap in the questions. To keep the research organized, it is split up into 4 phases:

1. Literature review
2. Ex-post evaluation
3. Driving simulator study
4. Conclusions and recommendations

The phases of the project will be the guide in detailing the research questions.

Phase 1: literature review

Let's first discuss the sub-questions regarding performance. The most important aspect of these research questions is the word 'performance' in itself. To answer the question, it is important to know what the word performance means in the context of this research. Also, it is important to gain insight in the different aspects that influence the performance of rush-hour lanes and pluslanes (see question A0). This will be covered in the literature review. Several performance indicators will be reviewed and the most suitable for this research will be used. As another important part of the research is the study to behavioral factors (see sub-question B2), the link between macroscopic and microscopic factors is very important for this research. As a guide, finding macroscopic indicators will be the lead goal in the literature review. For each suitable macroscopic performance indicator found, the main microscopic factors that have an influence will be underpinned.

The main factor that influences the performance is the understandability of the concept of managed lanes. What makes a highway section with a managed lane present different from a regular highway section? Three aspects come to mind when thinking about this question: the lay-out, the signaling system and the differences in speed limit of sections with a managed lane present. The influence of these three behavioral factors on the performance of the managed lane will also be discussed in the literature review.

A last factor of performance is the costs. To compare the performance of rush-hour lanes with the performance of pluslanes, the costs of both measures should also be taken into account.

The goals for the literature review are:

- *To find macroscopic and microscopic performance indicators that suit the comparison between the ex-post evaluation of rush-hour lanes and pluslanes and the driving simulator study*
- *To gain insight in the understandability of the concept of rush-hour lanes*
- *To gain insight in the costs of both rush-hour lanes and pluslanes*

Phase 2: Ex-post evaluation

From the literature review, the macroscopic performance indicators are used for a data study. At first, it is important to know the existing rush-hour lanes and pluslanes in the Netherlands. A preliminary research is performed to make a summary of all rush-hour lanes and pluslanes. To research the performance of rush-hour lanes and pluslanes, first they are compared with regular right lanes and left lanes respectively. Different locations at the rush-hour lane and pluslane sections are researched after that.

To gain insight in the design factors that have an influence on the performance (see question B1), the differences in lay-outs should be identified. A selection will then be made of rush-hour lane and pluslane sections that are suitable for this research. Data of the selected sections should be compared for the different performance indicators as stated in the literature review.

The goals for the ex-post evaluation are:

- *To gain information about the existing rush-hour lane and pluslane sections in the Netherlands*
- *To compare rush-hour lane and pluslane sections with each-other, in order to answer the research questions regarding performance*

Phase 3: Driving simulator study

As macroscopic data is not suitable to derive behavioral factors, microscopic data is needed. By performing a driving simulator study, individual car data will be gathered. The rush-hour lane section on the A50 between junction Ewijk and junction Valburg forms the base design for the driving simulator and will also be analyzed in the ex-post evaluation. The microscopic factors derived in the literature review will be used in this study to explain the results from the ex-post evaluation. The driving simulator study gives insight in the behavioral factors that are the cause of differences in performance (see question B2). An absolute validation between the results from the ex-post evaluation and the driving simulator study is done to compare the macroscopic data with the microscopic data.

Another big advantage of the use of a driving simulator is the fact that non-existing designs can be tested. Both the lay-out, as well as the signaling system can be altered in the simulator to analyze the possible changes in performance (see question B3).

The goals for the driving simulator study are:

- *To recreate an existing rush-hour lane section as realistically as possible*
- *To validate the data of the created rush-hour lane with data of the existing one*
- *To analyze the underlying behavioral aspects that cause differences in performance*
- *To create alternative lay-outs of rush-hour lanes in the simulator and analyze their performance*

Phase 4: Conclusions and recommendations

This phase consists of 4 main chapters: synthesis, conclusions, implications and recommendations. The new scientific facts that came to light in the research will be described in the chapter 'synthesis'. The used methodology will be described in detail and all findings will be documented along with the connection between them.

From the findings, conclusions can be drawn. These conclusions will be focused on giving answer to the main research question.

The conclusions can be used to describe the implications of the research. In this chapter advice can be given to the choice between rush-hour lanes and pluslanes. Also, depending on the conclusions of the research, it can be recommended to reconsider the designs of rush-hour lanes and pluslanes.

Questions will still remain unanswered after the research is finished. In this chapter the recommended further research will be described. Some parts of the project may also have taken extra, unforseen time and could therefore not be finished. These should also be mentioned in this part of the final report.

1.3.2 Research setup

As a clarification, the diagram in Figure 1.1 shows the relations between the different phases of the research.

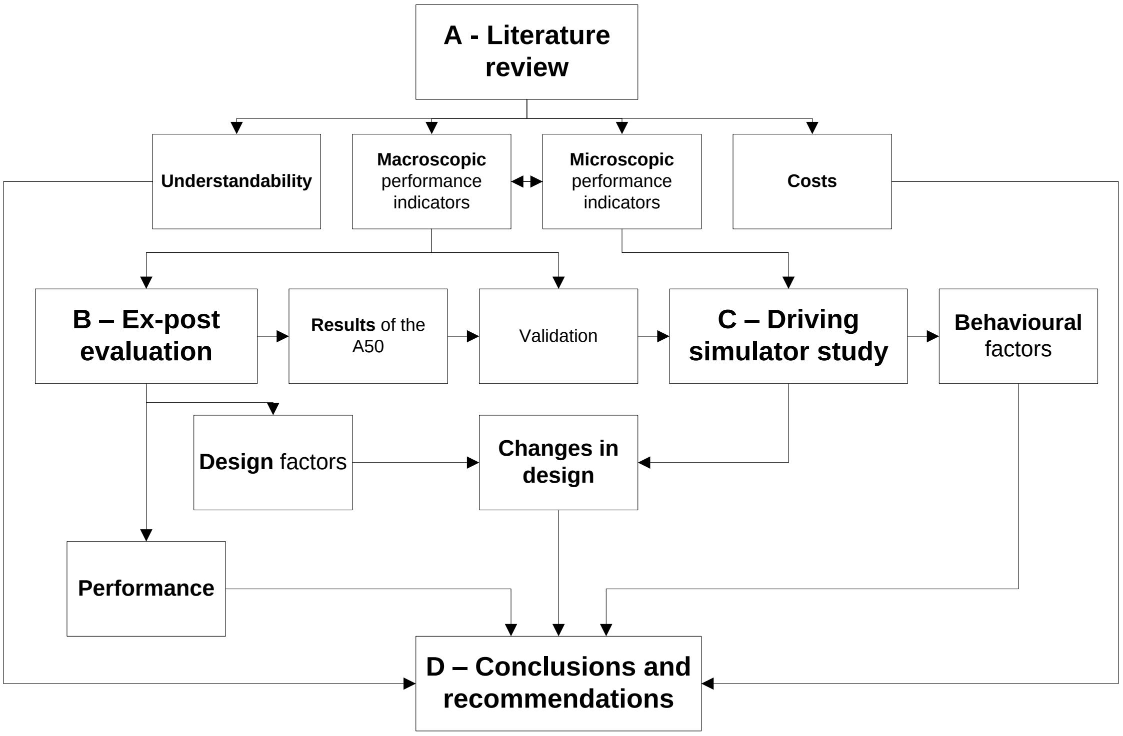


Figure 1.1: Scheme of the research structure. The main sections of the research are highlighted.

1.4 Research relevance

This research contributes to practice for Rijkswaterstaat. Rush-hour lanes and pluslanes are researched prior to this work. These researches are mainly aimed at evaluating a certain rush-hour lane or pluslane, i.e. comparing the before and after situation.

This research shows the differences in performance of different layouts. Three design factors are researched for their influence on the performance: the lane width, the speed limit and the total number of lanes. For Rijkswaterstaat, the conclusions can be used as a guide when implementing a new rush-hour lane or pluslane. It contributes to making a better ex-ante estimation of the performance.

Another important part of this research is that it provides insight in the behavioral factors that underlie differences in performance between rush-hour lanes and regular right lanes. A driving simulator study is used for this purpose. Rijkswaterstaat specifically asked for a research to behavioral factors, as it becomes increasingly important for policy makers.

As a final aspect of this research, alternative layouts are designed in the driving simulator to test for possible improvements. Two factors are changed in these alternatives designs: the markings and the signaling. For Rijkswaterstaat it is important to know the effects of changing markings from continuous to broken, as broken markings could be implemented in the future (eg. the project about the switching lane). Also, the effect of decreasing the amount of signaling at a rush-hour lane section provides important information for Rijkswaterstaat, as it can reduce the costs of the measure significantly.

1.5 Report outline

Section A: literature review

In the literature review, chapter 2 will elaborate on the link between macroscopic and microscopic performance indicators as they will be used throughout the research. Chapter 3 will cover the understandability of the rush-hour lane concept. Chapter 4, will elaborate on the cost-effectiveness of rush-hour lanes and pluslanes. Chapter 5 is the last chapter of this section and summarizes the conclusions and forms a synthesis with the other sections of this research.

Research questions that will be answered: A0

Section B: Ex-post evaluation

The section about the ex-post evaluation starts with a description of the experimental setup in chapter 6. The experimental setup is sub-divided into the preliminary research, data collection and data filtering. Chapter 7 will elaborate the results from the ex-post evaluation. Results are sub-divided into 2 parts, each elaborating different research questions: one part about the performance comparisons and the other about design factors. In the last chapter of this section, chapter 8, the conclusions will be summarized and a synthesis is made with the other sections of the research.

Research questions that will be answered: A1, A2, A3, A4 and B1

Section C: Driving simulator study

The section about the driving simulator study also starts with a description of the experimental setup in chapter 9. This chapter is sub-divided into 6 parts. At first, the driving simulator that is used for this research is described. After that, the methods of designing and programming the driving simulator environment are described. After a short paragraph about the pilot study as it is performed, the structuring of the data is mentioned last. Chapter 10 will elaborate the results from the driving simulator study. The results are sub-divided into the answering of the research questions. One is about the behavioral factors and the other one about the possible changes in the design of rush-hour lanes. In the last chapter of this section, chapter 11, the conclusions will be summarized and a synthesis is made with the other sections of the research.

Research questions that will be answered: B2 and B3

Section D: Conclusions and recommendations

This last section will give an overview of all important conclusions that can be derived from this research. It is sub-divided into 4 chapters. Chapter 12 covers the synthesis of the research, chapter 13 the conclusions, chapter 14 the recommendations and chapter 15 describes the further research that can be performed.

Section A

Literature review

1 Introduction

To gain more insight in the research that has already been performed on the subject, a literature study is carried out. In this study, the main focus will lie on the following subjects:

- Macroscopic and microscopic flow characteristics i.e. the link between the ex-post evaluation and the driving simulator study
- Clearness of the rush-hour lane concept
- Cost-effectiveness of rush-hour lanes and pluslanes

As mentioned before, the research consists of 2 main phases: the ex-post evaluation and the driving simulator study. To make sure the results from the 2 phases can be combined to conclusions, the connections between the phases need to be made. As the ex-post evaluation is focused on macroscopic, aggregated detector-loop data and the driving simulator study is focused on the individual car data of the participants, the main part of the literature study is about linking 'macro' to 'micro'. The link between macro en micro highly affects the performance indicators that will be used in this research. The first paragraph is aimed at the search for suitable performance indicators that form this link.

The performance of rush-hour lanes and pluslanes is highly affected by the clearness of the concept. If drivers don't understand the signaling system in combination with the markings, the managed lanes will not be driven. Section 2 of this chapter reviews the concept of understandability.

In the end, the performance of pluslanes will be compared to the performance of rush-hour lanes. To give a more comprehensive recommendation about the appliance of one of the two measures, it is also important to review the costs of the methods. In the last section of this chapter, the costs of both rush-hour lanes and pluslanes are reviewed. The scope for this literature review will now be described.

Scope

The definition of performance in this literature review is important to make clear prior to the analyses. Several indicators can be used to describe the performance of a highway section. The main macroscopic indicators for throughput are speeds, intensities and densities and are related to each-other with the fundamental diagram. Speeds and intensities are measured directly from the detector loop data and are used in this chapter as the two main indicators to which underlying microscopic characteristics will be linked. A third macroscopic performance indicator will be treated separately in this research, namely lane flow distributions.

In case of the rush-hour lanes and pluslanes, throughput performance can also be seen as the comparison between the before and the after situation, e.g. reduction in travel time losses. Former research already concentrated on that by evaluating the before and after situation at some time after the construction (eg. (Kusters, 1996) or, more recent (In 't Veld, 2008)) . This research is focused on the comparison of different layouts of rush-hour lanes and pluslanes and the literature review will therefore only focus on performance indicators that suit that comparison.

As only free flow data is used in this research, performance indicators regarding the length and duration of traffic jams are not included in this research. Also, only data will be used of open rush-hour lanes and pluslanes. The opening regime does therefore not play a role in this research.
As the focus will lie on throughput, also other aspects such as safety or durability will not be covered in this research.
The main aspect about rush-hour lanes and pluslanes that has an influence on throughput is the clearness of the concept. Confusing aspects of rush-hour lanes and pluslanes can be the signaling system, the layout of the road and the speed limits. These will all be covered in this literature review. In the future, it is possible that managed lanes will be implemented as a so called 'schakelstrook' (switching lane). This concept will also be discussed.
The last factor that does not really influence performance in itself, but does have a big influence on policy making is the costs of the rush-hour lanes and pluslanes. To make a concise comparison between rush-hour lanes and pluslanes in the end, cost differences are included in this literature review.

2 Macroscopic and microscopic flow characteristics

An important part of this thesis is the link between the macroscopic and microscopic traffic characteristics, because the microscopic part of the driving simulator is meant to show the driving behavior that underlies the macroscopic characteristics derived in the ex-post evaluation. In the ex-post evaluation, detector loop data is used, whereas the driving simulator study provides information about the characteristics of individual vehicles. This first part of the literature study is focused on underpinning the methods that will be used in the two phases of the research.

For the ex-post evaluation it is important to underpin that the methods really prove the performance of the different rush-hour lane and pluslane lay-outs.

Regarding the driving simulator study, the microscopic traffic characteristics will be linked to the macroscopic traffic characteristics used for the ex-post evaluation to show behavioral aspects that are the cause of differences in performance.

Macroscopic indicators will form the main structure of this chapter. For each macroscopic traffic characteristic, underlying microscopic factors will be mentioned and explained. These relations can be used to explain the results from the driving simulator study and combine them with the results of the ex-post evaluation.

2.1 Speeds

Macroscopic and microscopic aspects

Average speeds of before and after situations are calculated in (Kusters, 1996), as well as the standard deviation of speeds, the minimum speed and the maximum speed. The deviation in speeds is an indicator for homogeneity of traffic. If speeds vary a lot, the traffic will be more heterogenic and the demand for overtaking becomes greater (Wardrop, 1952). This shows the connection between speeds and lane changing behavior.

It is found in (Hoogendoorn, 2012b) that (as expected) speeds on the left most lane are highest and speeds decrease as intensity increases. Because opening the extra rush-hour lane or pluslane increases capacity, the decrease in speeds in the same intensity regions is reduced. It is therefore more interesting to evaluate separate speed distributions per lane.

In the study of (Van Kooten, 2000), cumulative speed distributions are plotted for the situation with a pluslane open for traffic, compared to the situation where the pluslane is closed for traffic. Different lay-outs with the same speed limit can be compared with each other by using these speed distributions. It is expected that road users adept their speeds to new driving environments (in this case the opening and closing of the rush-hour lane / pluslane). This adaptation and the differences between different lay-outs can be used as an indication for performance of the road section.

Regarding the different speed limits at different rush-hour lane and pluslane sections, it is possible to compare the speed limit to the distribution of vehicle speeds, as described in (Parker, 1997). It shows the percentile speeds at which the speed limit is posted. In (Abraham, 2001), 85th percentile speeds (in free-flow conditions) are described as the speeds at which drivers feel comfortable travelling under the physical, environmental and traffic control conditions existing on an uncongested section of multilane highways.

From several studies it is shown that microscopic free speeds are found to be normally distributed (e.g. (McLean, 1978)). This fact can be used to compare different speed distributions with each other.

2.2 Lane flow distributions

Macroscopic aspects

In (Kusters, 1996) the lane flow distributions are plotted per day. Over the period from January 5th 1996 till May 3th 1996 this gives a plot of the average lane flow distributions over a certain period (between 07.00 and 10.00) for each day.

In the evaluation of (Van Kooten, 2000), lane flow distributions are plotted as the average percentage of flow that uses a certain lane at certain intensities. According to (Knoop, 2010) this has the disadvantage that for each intensity-measure, two traffic states are possible: congested and uncongested. Also, expressing it as a function of speed has a disadvantage: at the free flow region, speeds are nearly constant, whereas lane distribution will change considerably. The best way to express lane flow distributions is as a function of density. This also has a drawback: it is

very hard to measure density directly and impossible by only using detector loops. To calculate density, flow is divided by space mean speed; however, only time mean speed is measured. Using the formula
$u_S = u_L - \frac{\sigma_L}{u_L}$ (Knoop, 2010), space mean speed can be estimated from the time mean speed by using the variance in speeds (σ_L). This is a very straight-forward way of estimating space mean speeds from time speeds. In the thesis of (Lint, 2004), more detailed conversions from time mean speeds to space mean speeds can be found.

A combination of both methods for showing lane flow distributions (from (Kusters, 1996) and (Van Kooten, 2000)) can be used. The first method is better suited to locate 'outliers', i.e. lane flow distributions at a certain day that are significantly different from the average over all days. Filtering these out can reduce the standard deviation of the average lane flow distributions and therefore increase their accuracy. The method of (Van Kooten, 2000) gives most information about the performance of the different lanes.

(Wu, 2006) Derived equations for lane flow distributions on highways with 2, 3, 4 and 5 lanes. For this he used a negative shifted exponential function for the gap-distribution.

The generalized regression model to be fitted to data is given by the following equations:

$$\begin{cases} p_i = a \cdot \left(1 - b \cdot e^{-c \cdot {q_{sum}}^{d}}\right) \cdot {q_{sum}}^{-e} & \text{for i} \neq 1 \\ p_1 = 1 - \sum_{i=2}^{n} p_i & \text{for i} = 1 \end{cases}$$

This regression function is recommended for fitting real lane flow-distributions under arbitrary traffic conditions.

For a 3-lane highway, the fit on data is shown in Figure 2.1.

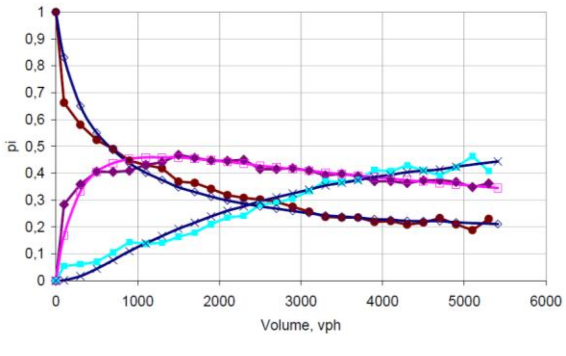


Figure 2.1: Example of lane flow distributions (Wu, 2006)

Microscopic aspects

Lane flow distributions are strongly related to the microscopic indicator of lane changes. Lane changes are widely researched and can be tracked in the driving simulator. Differences in lane change behavior for different lay-outs can therefore be researched and can give an explanation to differences in lane flow distributions.

Two main factors influence lane change behavior: the desire to change lanes and the possibility to change lanes (Knoop, 2010). As rush-hour lanes and pluslanes are often designed with smaller widths, this can influence the desire to change to that lane. Also, the continuous markings of rush-hour lanes can influence this behavioral aspect.

In (Kesting, 2007) two ways of presenting lane change behavior are used. At first, the number of lane changes are shown per location. The second one shows the lane changing rate (in [1/(h/km)]) per density. The second method shows a density with maximum lane-changing rates between 10 veh/km/lane and 15 veh/km/lane. These two methods both show the relation between intensities (densities) and lane changing. As intensities are directly connected to headways (see also chapter 2.3 about maximal intensities and capacity) this also gives an extra connection between lane changing and headways.

In the research of (Rest, 2010), lane flow distributions are used as a performance indicator. They are represented as the average occupation of a lane at certain intensity-intervals ranging from 2000 veh/h till 7000 veh/h. It is concluded that rush-hour lanes and pluslanes do not differ much from regular right and left lanes at high intensities.

In the article of (Wu, 2006), the probability that a vehicle changes from one lane to another is the probability that there is a large enough gap on the desired lane. The demand of overtaking can be expressed by a predefined gap between the mentioned car and the vehicle in front of it. If the current gap approached this predefined gap, the vehicle must change a lane in order to maintain its desired speed. This leads directly to the model that estimates the macroscopic lane flow distributions. This method again confirms the strong connection between lane changing behavior and intensities / headways.

(Knoop, 2010) describes the process of lane changing at a merging zone using the scheme in Figure 2.2. This scheme is changed slightly, as speed limit and road lay-out both influence the desired speed. The relation between free flow speeds and, for example, lane width is added as a compensation factor in the Highway Capacity Manual (TRB, 2000). The influence of speed limits on speeds is researched, among others, by (Parker, 1997). Also, the merging process is neglected in this research, creating the new scheme in Figure 2.2 on the right.

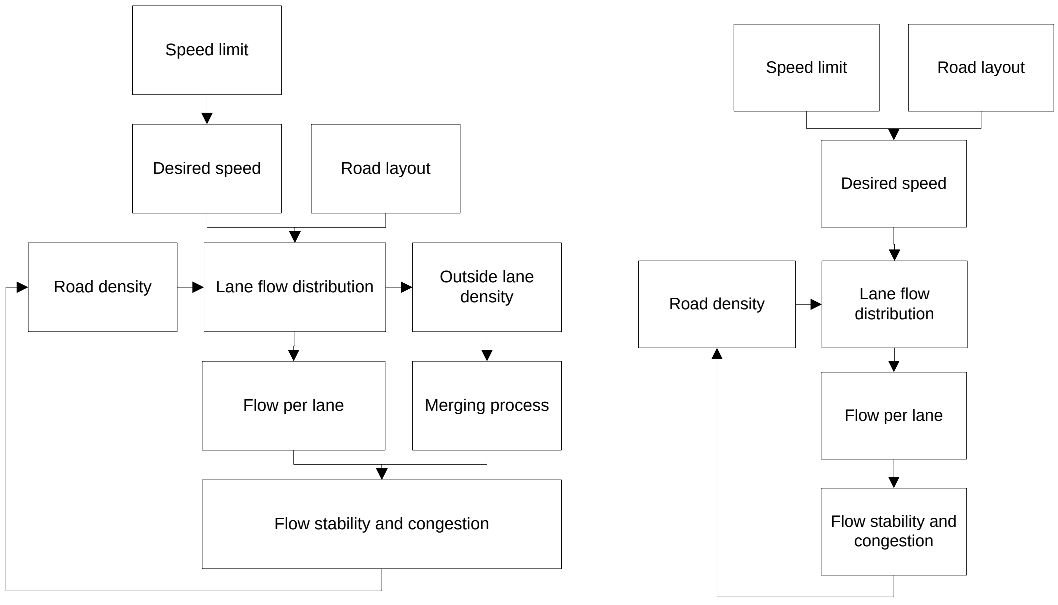


Figure 2.2: On the left, the lane changing process at a merging zone, according to (Knoop, 2010). On the right, the lane changing process when the merging part is neglected.

2.3 Intensities

Macroscopic aspects

One of the most important indicators of performance is the capacity of a lane. The definition of capacity is taken from (Heikoop, 2011):

Capacity is the maximum number of vehicles per unit of time (usually veh/h) that can reasonably pass a given cross-section or uniform segment of a lane or carriageway during a certain time period under prevailing road conditions, traffic conditions and control conditions.

A few important aspects of capacity can be deduced from this definition:

- Capacity is dependent on the percentage of trucks ('*… maximum number of vehicles per unit of time…')*

  In this research it is not possible to derive the truck percentage from data. It is, however, possible to indicate the influence of different truck percentages on the capacity estimation.
- Capacity is stochastic ('*…that can reasonably pass…')*
- Capacity depends on the chosen time period ('*…during a certain time period…')*

  Measuring during short time periods (for example 1 min, as is the standard aggregation level of detector loop data) capacity measurements will be higher than for longer time periods. In the CIA, an aggregation of 5 min is used. As values from the CIA will be used for validation of the capacity estimate, an aggregation of 5 min will also be used in this research.
- Capacity depends on several conditions that need to be standardized ('*…under prevailing … conditions')*

In (Hoogendoorn, 2005) it is said that using the fundamental diagram for free-flow capacity estimation can be done in two ways:

- A model (q(k)) can be fitted to the flow-density data. This has the downside that the dq/dk = 0 does not hold for the free-flow part of q(k) and is therefore not suitable
- Assume a value for capacity density k_c. This is suitable for comparison and not for determining an absolute value, as the calculated capacity depends strongly on the assumed k_c.

If capacity estimation is to be made with the fundamental diagram, it needs to be checked for reliability. No bottleneck occurs at sections with rush-hour lanes and pluslanes. The only macroscopic method that does not need bottleneck data is the fundamental diagram method (Minderhoud, 1996). Curve-fitting is then still possible, but a lot of data is needed to provide reliable results. The result must therefore be checked with known information about capacity at rush-hour lanes and pluslanes.

As there is not much information about capacities of rush-hour lanes, all available information needs to be combined to give a reliable estimate. As (Wu, 2006) states, it is possible to estimate capacity of a lane by assuming the most occupied lane being at capacity and dividing the capacity values according to the lane flow distribution at capacity flow rates. Also, the capacity estimations for a pluslane by (Bekkum, 2000) and (Van Kooten, 2000) can be used for validation as well as the lower bound capacity estimation of (Kusters, 1996)

If reliable capacity estimation is not possible, highway sections can also be compared with each-other by capacity indications. For example, (Chung, 2006) uses the 99^{th} percentile flow rate of different alternatives to represent the capacity. Other methods, such as the median of maximum pre-breakdown flow rates or 15^{th} percentile are mentioned in (Dervisoglu, 2008). Also, the method mentioned before by (Wu, 2006) can be used to compare rush-hour lane and pluslane sections with each-other.

Microscopic aspects

There are numerous microscopic factors that influence capacity. As mentioned in (Minderhoud, 1996) one of the most important microscopic factors is time headway, as the definition for capacity is:

'*The capacity of a single lane of a road at a specific cross-section is the inverse of the mean time headway of constrained vehicles since it is assumed that, during capacity conditions of a road, all drivers are constrained drivers*'

For this research, the driving simulator study can be used to determine the average headways on the rush-hour lane of constrained vehicles. The research performed by (Rest, 2010) shows the number of vehicles with a headway <1s for different scenarios. These small headways increase with increasing intensity and the number of vehicles with small headways is largest on the left lane (independent of pluslanes or rush-hour lanes present on the cross section). In the research, no connection between the lane width and headways could be found.

In (Brackstone, 1999), a summary is provided for the history of car-following models. Three different types of car-following models can be distinguished:

- Stimulus-response models
- Safety distance models
- Psycho-spacing models

In most of the models, the acceleration *a* at time *t* is dependent on the speed of the vehicle *v*, reaction time *τ*, relative speed Δ*v* and distance to lead vehicle Δ*x*.

$a_i(t) = f_c(v, \tau, \Delta v, \Delta x)$ (Hoogendoorn, 2012a)

In the psycho-spacing model of (Leutzbach, 1986), the term 'penduling' is introduced, with regard to the fact that spacing varies around a constant value, even if the lead vehicle has a constant speed.

Headways also form the connection between the other macroscopic indicators 'speed' and 'lane flow distributions'. All factors that influence capacity (both macro, as well as micro) are shown in the scheme of Figure 2.3 as composed by (Hoogendoorn, 2012b). This was a research performed to analyze the influence of ADAS (i.e. Advanced Driver Assistance Systems). The scheme, however, is also informative when the ADAS-influence is neglected (see Figure 2.3). As can be seen, both car-following behavior and lane changing behavior are the main factors that influence the capacity. Also, the other indicators mentioned in the preceding chapters (speeds and lane flow distributions) are indicated in the scheme.

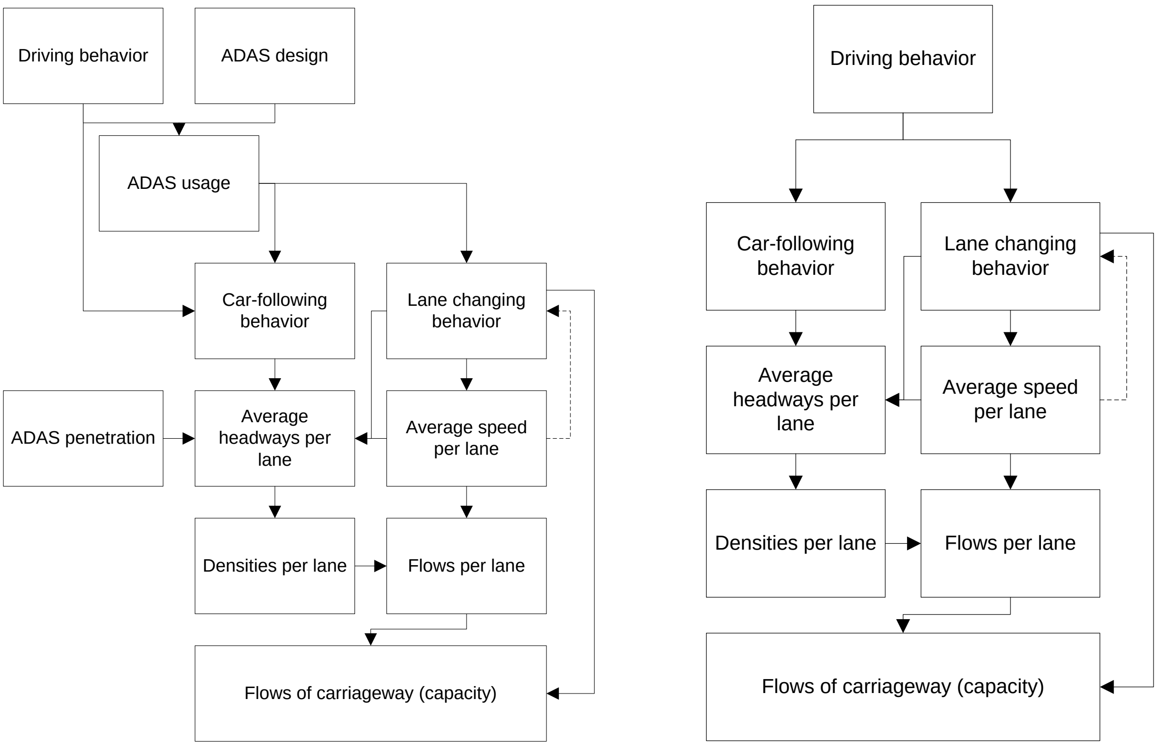


Figure 2.3: On the left: factors influencing capacity including ADAS, according to (Hoogendoorn, 2012). On the right: the factors influencing capacity when ADAS is neglected

2.4 Synthesis

Several indicators can be used to describe the performance of a highway section. The main macroscopic indicators for throughput are speeds, intensities and densities and are related to each-other with the fundamental diagram. Speeds and intensities are measured directly from the detector loop data and are used in this chapter as the two main indicators to which underlying microscopic characteristics will be linked. A third macroscopic performance indicator will be treated separately in this research, namely lane flow distributions.
The schemes of (Knoop, 2010) and (Hoogendoorn, 2012) can be combined and complemented with the new information to the scheme in Figure 2.4 on the next page. It can be seen from this scheme that the indicators 'intensities', 'speeds' and 'lane flow distributions' fit the requirements for this research. Combined, they give insight in the performance of carriageways and lanes. Also there is a crisp link between microscopic and macroscopic aspects of the indicators. This is important, because this link will be used to form the synthesis between the ex-post evaluation (section B) and the driving simulator study (section C) in this research.
As the indicators are tightly connected, a choice needs to be made to cover them with clear relations. Lane flow distributions will in this research be shown as the relation between total intensity level and the average distribution between the lanes. One rush-hour lane performs better than the other when the occupation rate of that lane exceeds the occupation rate of the other rush-hour lane and the same applies for pluslanes. Speeds will be clarified with the relation between intensity per lane and average speeds driven at that intensity level. Performance increases when free-flow speeds driven at the section increase.

In case of rush-hour lanes and pluslanes, understanding the concept can have an influence on performance. The clearness of the signaling system, the layouts and the speed limits will be covered in the next chapter. Furthermore, the clearness of a new form of managed lane called 'switching lane' is explained.

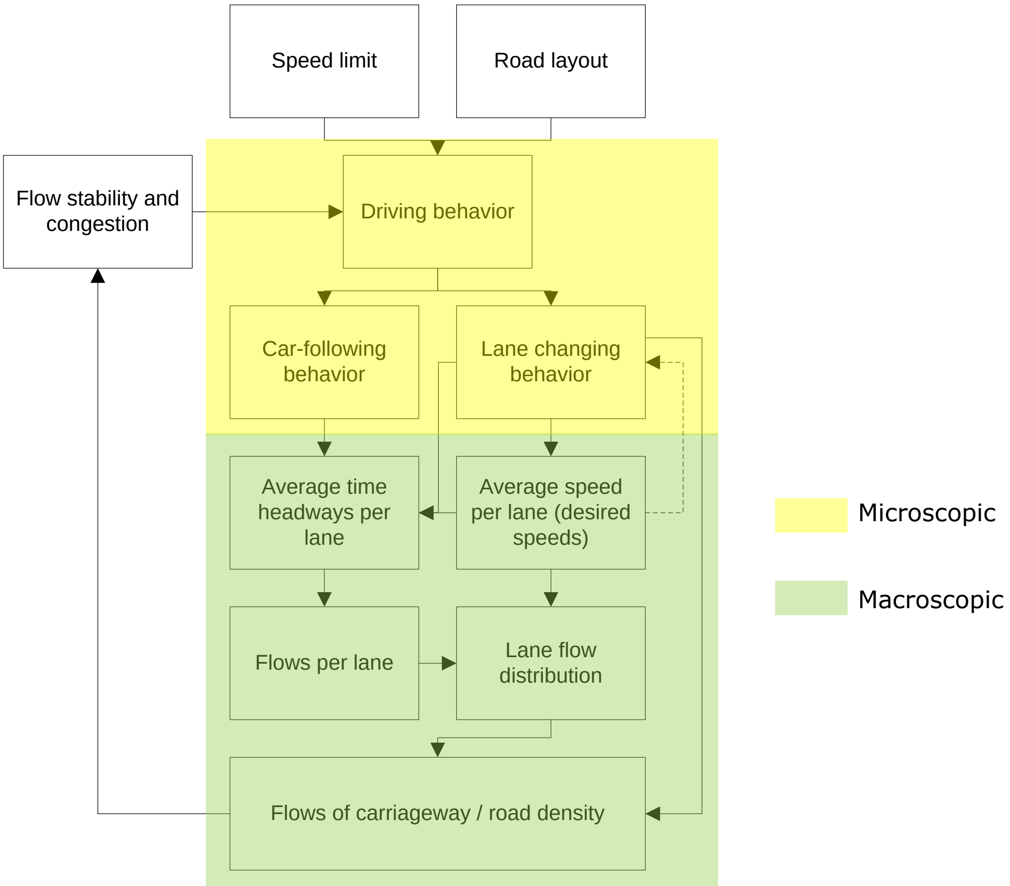


Figure 2.4: Macroscopic and microscopic performance indicators

3 Clearness of rush-hour lanes

Understanding the concept of a rush-hour lane plays a big role in the performance and has been researched in the past. Drivers should be able to understand when the rush-hour lane is open for driving and when it's closed. Also, it is important that drivers understand that the rush-hour lane is still a regular hard shoulder when the red cross is shown above it. In this section, several aspects of understandability are covered. At first, the understandability of the signaling system is explained. After that, the differences between several lay-outs are discussed and the compliance to speed limits is studied. As a last part of this chapter, the new concept 'switching lane' is discussed.

3.1 Signaling system

In (Zijdenbos, 1997), the understandability of the signaling system of rush-hour lanes is researched. The older rush-hour lanes only had the red cross and green arrow on the matrix signs, indicating respectively a closed and an open rush-hour lane. It is also mentioned that the first rush-hour lane at the A28 was constructed with broken 9-3-markings instead of continuous markings because of legal issues and increasing clarity. Another legal problem was the fact that a red cross meant 'this lane may not be driven'. That's why research needed to be performed on extra signaling in the form of a special rush-hour lane sign. In the research, several inquiries were performed. The conclusions of the research is that the red cross / green arrow is very clear in notifying drivers if the shoulder lane is accessible or not. It especially performs better when the sign is presented for a short time only. It also is preferred compared to a sign that shows the allowed maximum speed above the lane.
However, it is not very clear that the rush-hour lane is also a refuge area for car failures when closed. The extra rush-hour lane sign helped in making this clear (note that in this research, the old sign was tested, see Figure 3.1 (Kraaijeveld, 2011)). The broken markings (9-3 markings) are reducing the understandability of this fact. It should be noted here that this research is performed in the period that rush-hour lanes became operational for the first time in the Netherlands and thus participants needed to get used to the concept altogether.
In (XTNT, 2011), participants mentioned here that the extra signs are not necessary, because the matrix signs give enough information.

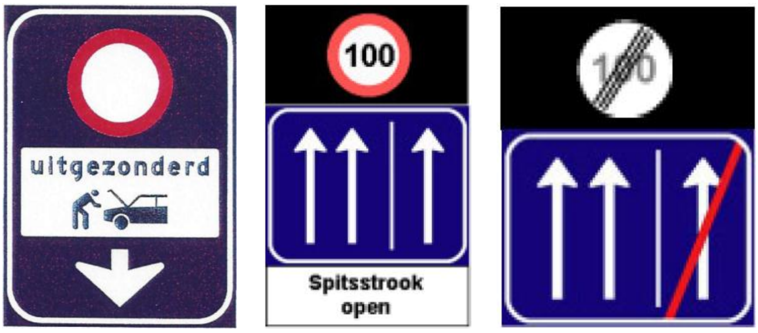


Figure 3.1: From left to right: old sign, new sign 'open', new sign 'closed'

3.2 Lay-outs

Another study to the understandability is performed by (Martens, 2002). Several lay-outs of rush-hour lanes are tested in this research. Participants made several mistakes. An important conclusion is that most mistakes are made when no red crosses or green arrows where shown for a longer period of time (i.e. in-between signaling portals). It should be noted that only a small number of participants (24) performed the tests and that they were all informed to keep right during the test. All participants experienced 38 conditions. They all first drove on the zero-alternative. The other lay-outs are randomized to counterbalance learning effects.
The researched lay-outs are shown in Figure 3.2.
All lay-outs are tested on 6 scenarios:

1. Use onramp to merge into traffic; rush-hour lane open
2. Use onramp to merge into traffic; rush-hour lane closed
3. Stay on the main carriageway; rush-hour lane open
4. Stay on the main carriageway; rush-hour lane closed
5. Use off-ramp to leave carriageway; rush-hour lane open
6. Use off-ramp to leave carriageway; rush-hour lane closed

For this research, scenarios 3 and 4 are especially interesting. In short, the conclusions about the understandability of the different lay-outs are as follows.

Lay-out 1a: 'Rush-hour lane along off-ramp' performs significantly ($p < 0,02$) worse than the zero-alternative when the rush-hour lane is opened. Closed rush-hour lanes don't show a significant difference.

Lay-out 1b: 'Rush-hour lane along on-ramp' shows a trend of performing better ($p < 0,06$) than the zero-alternative when the rush-hour lane is opened. Closed rush-hour lanes don't show a significant difference.

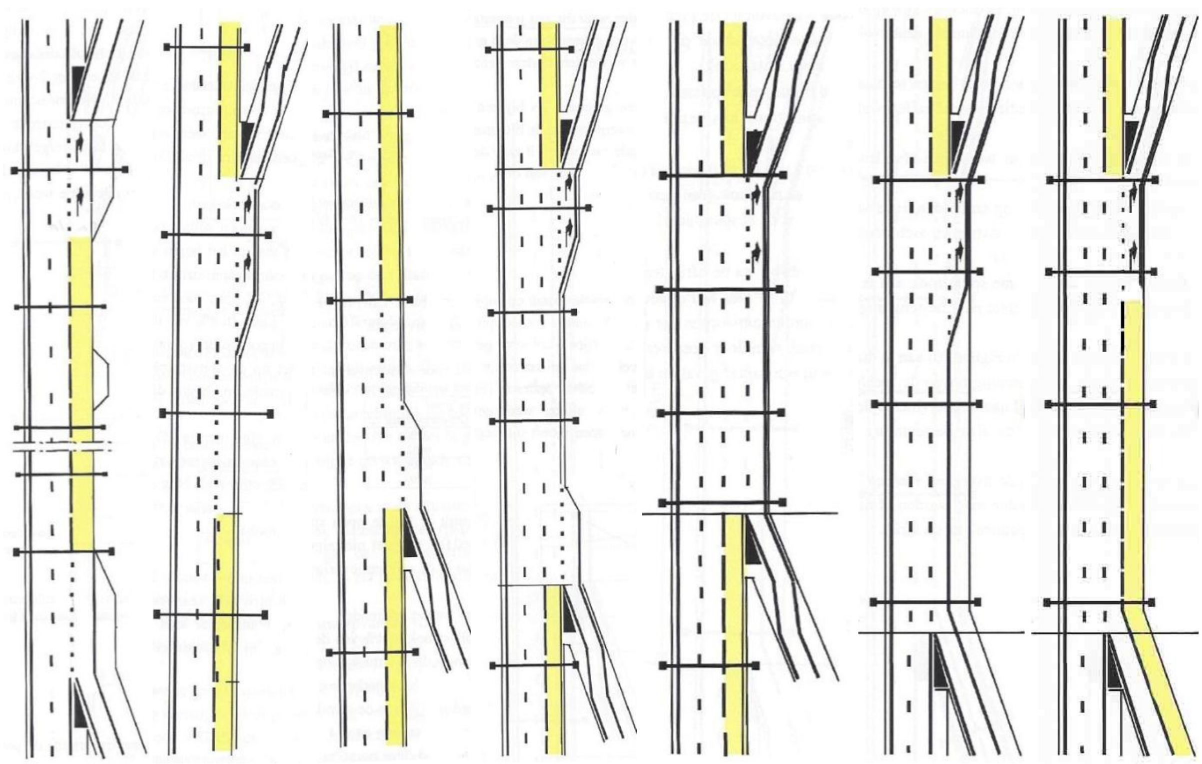
Lay-out 2: 'Rush-hour lane along on-ramp and off-ramp' performs significantly ($p < 0,008$) better than the zero-alternative when the rush-hour lane is opened. Closed rush-hour lanes don't show a significant difference.

Lay-out 3: 'Rush-hour lane along weaving section' shows a trend ($p < 0,06$) of performing better than the zero-alternative when the rush-hour lane is closed. Closed rush-hour lanes perform significantly ($p < 0,0001$) worse than the zero-alternative. This was mainly due to wrong signaling above the lanes.

Lay-out 4: 'Rush-hour lane after merging section and off-ramp' no significant changes or trends were found in the comparison with the zero-alternative. Closed rush-hour lanes don't show a significant difference.

Lay-out 5: ‘Rush-hour lane along merging area / offramp’ performs significantly (p < 0,02) worse than the zero-alternative when the rush-hour lane is opened. Closed rush-hour lanes don’t show a significant difference.

It can be seen from these results that an open rush-hour lane leads to more confusion about the correct lane to drive than a closed rush-hour lane. This matches with the research of (Zijdenbos, 1997) that the red cross is a clear way of notifying drivers that the lane cannot be driven.
Furthermore, lay-outs 1a and 5 perform significantly worse than the zero-alternative. At lay-out 1a, 33% only made use of the rush-hour lane after the offramp. At lay-out 5, 58% did not use the rush-hour lane at the section with 4 lanes. This was understandable, as the destination of the 4th lane was indicated vaguely at the intersection.



0 1a 1b 2 3 4 5

Figure 3.2: Rush-hour lane lay-outs from (Martens, 2002). On the left, the zero-variant is shown

3.3 Speed limits

The compliance to speed limits can be found in several studies. In the study of (Van Kooten, 2000), the speed limit of 70 km/h on the pluslane of the A27 is not respected at all. This is also confirmed by inquiries, as 70% of the respondents think the speed limit is too low. The research by (XTNT, 2011) also confirms the dislike towards speed limits. The speed limit of 80 km/h at the pluslane of the A27 is still considered far too low. During the research of (Kusters, 1996), a speed limit of 90 km/h at the rush-hour lane and a limit of 100 km/h downstream of the rush-hour lane section were set. The lower speed limit at the rush-hour lane is less respected than the downstream speed limit, however, speeds are lower on both sections than a regular 120 km/h section. The speed limits these days are always 100 km/h or 120 km/h for rush-hour lanes and pluslanes. The only exception to this is the pluslane at the A28 between Ommen and Zwolle. Here, a speed limit of 80 km/h is operational when the pluslane is opened and a limit of 100 km/h is set when the pluslane is closed (Helleman, 2011).

3.4 Switching lanes

Today, Rijkswaterstaat is performing research to the so called 'schakelstrook' (hereinafter called switching lane). The research is recent, but the most interesting piece about is from (Coopmans, 2007). The research is about the first base-design of the switching lane. The idea is that the road section with a switching lane has only standard 3-9 markings applied on all lanes. The function of the switching lane can be determined for different traffic conditions. The standard function of all lanes is 'driving'. When the switching lane is turned off, the function 'emergency stop only' should be indicated by a symbol in the signaling system. To increase the credibility of the closure it is highly important in this sense that the driver is informed about the reason of the lane closure. In (Barten, 2008) it is concluded from a driving simulator study that the situation is increasing the risks because of its complexity. Especially the combination of regular markings with the sign 'lane closed' or 'emergency stopping only' is hard to understand. Open switching lanes on the right are probably well understandable as the normal function of the lane is 'driving'.

3.5 Synthesis

Performance of rush-hour lanes can be influenced by the clearness of the concept. Several unique factors of a managed lane make it different from a regular right lane or left lane and can therefore be confusing. In this chapter, the clearness is analyzed of the signaling system, of the layouts, of the different speed limits and of a new form of managed lane: the switching lane.
Studies prove that the combination of red crosses for closed – and green arrows for opened lanes is very clear for road users. In the beginning of the rush-hour lane concept, there was a need for extra information concerning the use of the rush-hour lane as an emergency lane. Therefore, an extra sign was introduced. In a more recent study, participants mentioned that the sign is not needed and the combination red cross / green arrow provides enough information.
Concerning different lay-outs of rush-hour lanes, it can be seen that when rush-hour lanes are opened for traffic, choosing the right driving lane proves to be difficult. Some lay-outs perform worse than others, but this is mainly due to counter-intuitive signaling at the study.
Speed limits of 70 km/h are considered far too low. Also, a speed limit of 90 km/h is less respected than a speed limit of 100 km/h at a regular highway section. People tend to dislike speed limits at managed lanes altogether. These days, almost all rush-hour lane and pluslane sections have a speed limit of 100 km/h. There are 2 exceptions: The rush-hour lane at the A50 between junction Ewijk and junction Valburg has a permanent speed limit of 120 km/h and the pluslane at the A28 between Ommen and Zwolle has a speed limit of 80 km/h when the pluslane is opened.
Rijkswaterstaat is performing research on a new lay-out of highways, called 'schakelstroken' ('switching lanes'). In this lay-out, all lanes will have 3-9 markings present. The function of the switching lane can be determined for different traffic conditions. In case of the switching lanes, closed rush-hour lanes will become less understandable, because of the complexity of the combination 'lane closed' with broken markings. Open rush-hour lanes will become more understandable as the normal function of the rightmost lane is 'driving'.

The differences in costs between rush-hour lanes and pluslanes are covered in the next chapter. To give advice on the preferred measure, it is important to gain insight in the costs of both measures. One measure can perform better than the other, but when it also costs significantly more it is possible that policy makers still prefer the less-performing, cheaper measure.

4 Costs

In this chapter, the costs of rush-hour lanes and pluslanes will be compared. If the costs of the best performing managed lane are substantially higher, the other less performing option can still be most preferable. Not much research is performed on this subject and therefore it will not be elaborated in much detail. However, when giving advice about the most preferable option, it is important to take note of the underlying costs of the measures.

4.1 Rush-hour lanes vs. pluslanes

A detailed cost-description of a pluslane is given by (Bekkum, 2000) in an evaluation report of the pluslane at the A4 between Nieuw-Vennep and Hoofddorp. The pluslane is 2550 m long.
The costs are defined in detail for the 2 construction years 1999 and 2000. Highest costs are made by re-profiling the road section, the cameras that need to be placed at the pluslane and the portals, signaling system and road signs. Total costs are *f* 9.472.672,- per 2550 m. This is equal to a total cost of approximately *f* 3.700.000,- per kilometer. From now on the guilder costs will be converted to euro's by the conversion 1 euro = 2,20371 guilders. The costs per kilometer are then € 1.680.000,-.
The calculation of costs in (Van Kooten, 2000) is comparable. The pluslane is 10,1 km long and the total costs per kilometer are € 290.000,-. This amount is far lower than the amount as it was calculated by (Bekkum, 2000).
In (Kusters, 1996) costs are divided into installation-costs and exploitation-costs and therefore it is hard to compare it with the analysis of (Bekkum, 2000). The total costs of the rush-hour lane are € 2.040.000,- and the length is 4.000 m, so the costs per km are € 510.000,-. When the exploitation-costs aren't taken into account, the costs per km are € 280.000,-.
In (Cluitmans, 2002) costs are subdivided into product costs and direct construction costs (according to one of the definitions of Rijkswaterstaat) and are summarized for several rush-hour lanes and pluslanes. Production-costs are the direct costs that are needed to physically realize the project. It includes: costs for the contractor, and costs for the definitive product and the construction of it. According to the definition of Rijkswaterstaat, all other costs are direct construction costs. These therefore include all preparation and evaluation costs.
For rush-hour lanes and pluslanes, the subdivision of costs is shown in

Table 4-1. As can be seen, a lot of variation in costs per kilometer is found in different projects. Also, a lot of variation can be found in the subdivision between PC and DCC. The differences between the rush-hour lanes are mainly caused by including different aspects into the costs. The costs of the pluslanes included different aspects. Sound-proofing was, for example, not included at the costs of all pluslanes. Costs are assumed to stay constant per kilometer for both rush-hour lanes and pluslanes. The determined means and medians can now be used to compare the two measures with each-other. Rush-hour lanes cost, on average, € 770.000,- per kilometer and pluslanes cost, on average, € 1.675.000,- per kilometer. The variation is large, because the minimum cost of a rush-hour lane is € 250.000,- and the maximum cost is € 1.600.000,- per kilometer. Pluslanes have a minimum cost of € 1.000.000,- and a maximum cost of € 2.500.000,- per kilometer.

Table 4-1: Costs per kilometer for rush-hour lanes (at the top) and pluslanes (at the bottom)

Costs per kilometer in k€ (1 direction) - **Rush-hour lanes**	PC	DCC	Total
Average	669	101	770
Median	637	102	740
Lowest boundary	215	23	247
Highest boundary (including signaling system)	1468	163	1631

Costs per kilometer in k€ (1 direction) - **Pluslanes**	PC	DCC	Total
Average	1338	337	1675
Median	1135	291	1673
Lowest boundary	227	15	915
Highest boundary (including signaling system)	2555	724	2569

4.2 Synthesis

This paragraph gives insight in the differences in costs of rush-hour lanes compared to pluslanes. When giving advice on the preferred managed lane at the end of this research, it is important to indicate the costs as an important factor for policy makers.

The definition of costs is different in the evaluation studies used in this analysis. This increases the variation in costs per kilometer for both measures and makes a comparison between the cost of rush-hour lanes and pluslanes hard. Costs are assumed to stay constant per kilometer for both rush-hour lanes and pluslanes in this analysis. It can be seen that rush-hour lanes cost, on average, € 770.000,- per kilometer and pluslanes cost, on average, € 1.675.000,- per kilometer. The variation is very big, because the minimum cost of a rush-hour lane is € 250.000,- and the maximum cost is € 1.600.000,- per kilometer. Pluslanes have a minimum cost of € 1.000.000,- and a maximum cost of € 2.500.000,- per kilometer. It can be seen that, despite the large variations in costs, pluslanes are more expensive than rush-hour lanes. These higher costs for pluslanes need to be taken into account when an advice is given about the managed lane that performs best in this research.

All aspects of the literature review are now covered. In the next chapter, the sub-question for this literature review is answered. Also, the link between this literature review and the next sections of this research will be explained in the synthesis.

5 Conclusion

5.1 Answering the sub-questions

To recap, the sub-question for the literature review is:

A0 - How is performance defined in this research?

Three main performance indicators where elaborated: speeds, intensities and lane flow distributions. These where proven to fit the requirement of linking the macroscopic data from the ex-post evaluation to the microscopic data from the driving simulator study. Lane flow distributions will in this research be shown as the relation between total intensity level and the average distribution between the lanes. One rush-hour lane performs better than the other when the occupation rate of that lane exceeds the occupation rate of the other rush-hour lane and the same applies for pluslanes.

Speeds will be clarified with the relation between intensity per lane and speeds driven at that intensity. Performance increases when free-flow speeds driven at the section increase.

Furthermore, the main factors influencing the clearness of the rush-hour lane concept were reviewed. The rush-hour lane sign is not needed to improve the understandability of the rush-hour lane, the combination of green arrow and red cross suffices. The signaling system is therefore expected not to have an influence on the performance.

Regarding layouts, opened rush-hour lanes are less clear than closed rush-hour lanes. As only open rush-hour lanes and pluslanes are used in this research, this can have an influence on the performance of the lanes.

Speed limits are disliked in general at sections with managed lanes. It is expected that compliance to speed limits will be low.

Pluslanes cost more than rush-hour lanes. This nuances the recommendations about the best performing managed lane in the conclusion of the research.

5.2 Synthesis between sections

In this literature review, performance is defined for this research. Lane flow distributions and intensity-speed relations will be used as the macroscopic performance indicators for the ex-post evaluation (section B). These are linked to car-following behavior and lane changing behavior as microscopic indicators that will be used in the driving simulator study (section C) as can be seen in Figure 2.4.

The signaling system is expected not to affect the performance of rush-hour lane and pluslanes sections. The effect of reducing the signaling on the occupation of rush-hour lanes is analyzed in the driving simulator study (section C)

The fact that layouts of open rush-hour lanes are less clear than closed rush-hour lanes, can have an influence on the performance. The driving simulator study is focused on analyzing the influence of broken markings on the occupation of rush-hour lanes. Adding broken markings instead of continuous markings to a rush-hour lane section may add to the understandability of the concept. As broken markings are also used at the new switching lane concept, conclusions from the driving simulator study can also be used for further research to that concept in the future.

Furthermore, it is expected from this literature review that the compliance to the speed limits will be low at the rush-hour lane and pluslane sections.

The last part of this section gives insight in the cost differences of rush-hour lanes and pluslanes. Pluslanes turn out to be more expensive than rush-hour lanes. This conclusion will be used to give a more concise advice to policy makers when they are choosing a form of managed lane in the future.

The ex-post evaluation in the next section will give insight in the performance of rush-hour lanes and pluslanes. The first part of the section describes the experimental setup of the research phase.

The second part focuses on the performance of rush-hour lanes and pluslanes. The difference in performance a rush-hour lane compared to a regular right lane and a pluslane compared to a regular left lane will be analyzed. After that, the performance of different locations at rush-hour lane and pluslane sections are researched.

The third part focuses on the design factors causing the differences in performance. Three design factors are included: the lane width, the speed limit and the total number of lanes.

The best performing rush-hour lane is compared to the best performing pluslane in the last part of the ex-post evaluation.

Section B

Ex-post evaluation

6 Experimental setup

Using the results from the literature study, the performance of rush-hour lanes and pluslanes can be researched. In this phase of the project, four steps have been taken:

- Preliminary research
- Data collection
- Data filtering
- Data analysis - results

These steps will be covered separately in the following paragraphs.

6.1 Preliminary research

As a first step for the ex-post evaluation, the existing rush-hour lanes and pluslanes in the Netherlands need to be summarized. All important characteristics should be examined to gain insight in the rush-hour lanes and pluslanes that are suitable for this research. The properties that are important in this evaluation are:

- lane widths
- the begin and endpoint of the section (and therefore the length)
- location of detectors
- speed limits
- the number of and distance between on and off-ramps on the section

Data is collected from a study performed by XTNT, commissioned by Rijkswaterstaat. All information about rush-hour lanes and pluslanes is collected in a big Excel-sheet. The data is organized to be suited for this research and only the important characteristics as mentioned before are filtered out. The data is compared with data from (Helleman, 2011) for the locations and with data from 'wegaanpassingsbesluiten' for the lane widths.

6.1.1 Filtering the sections

Availability of data

To gain insight in the road sections that are useful for the next phases of this research, data needs to be available for a sufficient amount of time. Detector-loop data is available of the period from 01-01-2007 until 12-10-2011. Determining the available data per road section is therefore easily done by subtracting the opening data of the rush-hour lane or pluslane from the end date. A minimum of 200 days of data will be the limit at which road sections are filtered.

Lengths of sections

For the performance study it is important that stable sections are researched. This means that a certain length is needed to give a good indication for the usage of the rush-hour lanes and pluslanes.

For the driving simulator study the zero-alternative should have a certain maximum length that can be determined from the maximum time that people can keep their concentration while driving in the driving simulator. The maximum time is assumed to be 30 minutes. Lengths are available at the document of (Helleman, 2011)

Total number of lanes

The influence of the presence of other lanes on a road section will be investigated. Most road sections have 2 regular lanes with one managed lane added (2+1). The exceptions are:

- The pluslane at the A12 between Woerden and Gouda. The configuration of this section is 3+1
- The pluslane at the A4 between Nieuw-Vennep and Hoofddorp. The configuration of this section is 4+1
- The rush-hour lane at the A13 between Berkel & Rodenrijs and Delft-Zuid. The configuration of this section is 3+1

Lane widths

The average lane width measured for pluslanes is 2,80 m. The smallest width is 2,50 m for a connecting road section at a junction and 2,70 m for a regular section with a pluslane. The biggest width is 3,34 m for the pluslane at the A4 between Hoofddorp and Nieuw-Vennep, however, this measurement is not very reliable. It was measured from an old AutoCad drawing. Therefore the section of the A4 is neglected and 3,10 m is the maximum width for the rest of the pluslanes at the A1 between junction Beekbergen and junction Deventer-Oost. At rush-hour lanes, lane widths are 3,28 m, 3,35 m or 3,50 m.

Markings

In the case of rush-hour lanes, all markings are applied as continuous lines. This is due to the fact that the rush-hour lane acted only as a hard shoulder in the before-situation. In the driving simulator study the effect of applying other markings on the driving behavior will be tested.

Also, the rush-hour lanes have an extra marking on the right side of the hard shoulder with a width of 0,05 m. At regular hard shoulders, this marking is not present. It is added to indicate the start of the soft shoulder and to increase the guidance of traffic. The width is 0,05 to increase the safety by ensuring that the hard shoulder is not a regular driving lane in case of a closed rush-hour lane (Hennink, 2011).

In case of pluslanes, special markings will be applied. There is one pluslane (at the A4 between Hoofddorp and Nieuw-Vennep) that is constructed with regular 3-9 markings (3m closed, 9 m opened) applied. This pluslane therefore looks like a regular lane. All other pluslanes in the Netherlands have 9-3 pluslane-markings applied (Hennink, 2011) (9m closed, 3m opened). As data from the A4 section is unreliable, it will not be added to this research.

Lengths in-between junctions

To compare different rush-hour lane and pluslane-sections it is important to collect data from stable areas (i.e. with no added turbulence). The distances in-between junctions are measured within the program Jedi from Fileradar B.V. The kilometersigns of rush-hour lanes and pluslanes that are drawn in Jedi do not always match up with the summaries of XTNT and Rijkswaterstaat. The choice is made to judge the kilometersigns from the summaries as leading. The measurements at the beginning and ending of the managed lanes can differ slightly, however, the measurements of lengts in-between the junctions are very reliable.

Speed limits

The normal design speed for all road sections is 120 km/h. However, when rush-hour lanes and pluslanes are opened for traffic, the speed limit will, in most cases, become 100 km/h. The exceptions are:

Pluslanes

- A4 Between Hoofddorp and Nieuw-Vennep (both ways): permanent 120 km/h
- A28 Between Zwolle-Zuid and Ommen (both ways): 100 / 80 km/h
- A28 Between Leusden-Zuid and junction Hoevelaken (both ways): permanent 100 km/h
- A12 Between Zoetermeer and junction Gouwe (both ways): permanent 100 km/h

Rush-hour lanes (all **permanent 100 km/h**, unless it is expressly stated differently)

- A1 Between Muiden-Oost and junction Muiderberg (south carriageway)
- A1 Between Bussum and junction Eemnes (both ways)
- A4 Between junction de Nieuwe Meer and junction Badhoevedorp (both ways)
- A6 Between junction Muiderberg and Almere Stad West (south carriageway)
- A9 Between junction Diemen and junction Holendrecht (both ways)
- A9 Between junction Badhoeverdorp and junction Raasdorp (south carriageway)
- A10 Between junction de Nieuwe Meer and junction Amstel (both ways)
- A50 Between junction Ewijk and junction Valburg (both ways): **permanent 120 km/h**
- A27 Between junction Everdingen and junction Lunetten (east carriageway)
- A13 Between Berkel en Rodenrijs and Delft-Zuid (east carriageway)

6.1.2 Choosing useful sections

The important characteristics of all rush-hour lanes and pluslanes have now been summarized in a big Excel-sheet (see appendix 16). For this research, it is not possible to evaluate all of them. As the factors to be researched are **lane width, speed limit** and **total number of lanes**, it is important to have enough variety in these factors when choosing the final rush-hour lane and pluslane sections for this research. The factors can take several values:

Table 6-1 – Factor values

Lanes	Speed limit	Lane width
2+1	100 / 80	narrow (< 3,00 m)
3+1	100 / 100	average (3,00 – 3,25 m)
	120 / 100	wide (> 3,25 m)
	120 / 120	

Table 6.1 contains the rush-hour lanes that will be used in this research. Table 6.2 contains the pluslanes that will be used in this research. All factor values appear at least once for both forms of managed lanes, except for the speed limits, as can be seen in paragraph 6.1.1.

Table 6-2 – Rush-hour lanes to be used

Location	Lanes	Lane widths (from left to right)	Speed limit (closed / open)	Factors
A1 – Hoevelaken - Barneveld	2+1	3,35|3,50|**3,50**	120 / 100	Speed: 120/100
A2 – Kerensheide - Vonderen	2+1	3,25|3,40|**3,28**	120 / 100	Width: narrow Speed: 120/100
A2 – Vonderen - Urmond	2+1	3,25|3,40|**3,35**	120 / 100	Width: average Speed: 120/100
A13 – Berkel & Rodenrijs - Delft- Zuid	3+1	3,25|3,40|3,40|**3,35**	100 / 100	Width: average Speed: 100/100 Lanes: 4
A50 – Ewijk - Valburg	2+1	3,50|3,50|**3,50**	120 / 120	Zero alternative

Table 6-3 – Pluslanes to be used

Location	Lanes	Lane widths (from left to right)	Speed limit (closed / open)	Factors
A1 – Beekbergen – Deventer-Oost	2+1	**3,10**|3,50|3,45	120 / 100	Zero alternative
A12 – Ede - Veenendaal	2+1	**3,00**|3,50|3,35	120 / 100	Width: Average
A12 – Woerden - Gouda	3+1	**2,75**|3,50|3,50|3,50	120 / 100	Width: narrow Lanes: 4
A12 – Zoetermeer - Gouwe	2+1	**2,75**|3,50|3,25	100 / 100	Width: narrow Speed: 100/100
A27 – Gorinchem - Noordeloos	2+1	**2,70**|3,00|3,25	100 / 80	Width: narrow Speed: 100/80

6.2 Data collection and filtering

6.2.1 Data collection

The next step will be the collection of data for the selected road sections. Data needs to be collected on the subsections resulting from the location research. For this purpose, the program *Jedi* by Fileradar B.V. is used (now called *Dante)*. This program makes use of the MoniCa detector loop-data from Rijkswaterstaat. MATLAB is used in combination with *Jedi* to assess the data efficiently. Only data of regular workdays is used. All weekends and holidays are filtered out.
Jedi contains the whole network of highways in the Netherlands. Using the MATLAB-script 'Data-Collection' that can be seen in appendix 17, data of the selected roadway section will be structured from *Jedi* into a MATLAB database. A few input variables need to be taken into account for the script:

- The start date from which data should be collected needs to be set in *Jedi*
- The road section needs to be selected (i.e. both links as well as detectors)
- The time period needs to be implemented in the MATLAB script (for example 120 days)
- The carriageway position needs to be implemented in the MATLAB script (right or left). It can be found by looking at the properties of a selected link.
- The name of the data file needs to be written in the MATLAB script.

The script will now start writing data to a structure in MATLAB that has the following layers:

- Roadway number (A50, for example, is located in cell 50)
- Day (from 1 to selected number of days)
- Detector id (As can be found in the properties of detectors in *Jedi*)
- Detector number (1 is left-most lane)
- Flow and speed vector of that day, containing flows per minute and average speeds per minute

Detector data of all highways in the Netherlands is available for the period 01-01-2007 till 12-10-2011. The data is collected by Rijkswaterstaat and is in the form of 1 minute aggregated loop data. It's copied to the hard-disk to speed up the handling. The program *Jedi* can be used for several data analyses. However, for this research, *Jedi* is only used to transfer the data to MATLAB-matrices. All data analyses are performed in MATLAB. The new program *Dante* has fewer options for the connection with MATLAB that is the reason that the older program *Jedi* is used in this research.
Data will be collected for a period of 120 days (01-01-2011 till 01-05-2011). The first idea was to add data of a full year, but the memory of the laptop was insufficient to handle the size of the data files. Data will only be reviewed of the assumed rush-hours between 06.00 and 10.00 and between 15.30 and 19.30. Furthermore, data from holidays and weekend-days is filtered out.

6.2.2 Data filtering

Raw data is collected from the detectors. This data first needs to be filtered to become suitable for research. The filtering process is done in a few steps:

1. Filtering wrong detectors measurements
2. Filtering data that is not in free-flow state
3. Filtering negative flow data
4. Aggregate data

All 4 filters will now be explained in more detail.

Filtering wrong detector measurements

The first filter deals with wrong detector data. Detectors write speeds above 250 km/h if something went wrong in measuring. This can have several causes, eg. no traffic was measured during the minute, the rush-hour lane was closed or the measurement was in some way unreliable.

At first it seemed that consistent combinations of speed and flow where used to indicate the difference between a measurement 'no traffic' and a measurement 'rush-hour lane closed'. This would be useful for this research, as also the data from a closed rush-hour lane could then be used. However, after some analyses, the combinations turned out to be inconsistent for different measurements. No clear logic was found and therefore all speeds above 250 km/h where filtered out of the data and no data from closed lanes will be used.

Filtering data that is not in free-flow state

Congested states of the rush-hour lanes are unreliable, as no bottlenecks are present at the rush-hour lane sections (only spill-back congestion occurs). Therefore, only free-flow data will be used in this research. All traffic traveling at speeds above 80 km/h is in considered free-flow state (in other words, the capacity speed is 80 km/h, (Hoogendoorn, 2005)). The filter therefore removes all measurements with speeds below 80 km/h.

Filtering negative flow data

Another way for detectors to indicate wrong data is a flow measurement of -1 veh/h. All these measurements are filtered out by removing all negative flows from the data.

Aggregating the data

The used data is in the form of 1-minute aggregation. As this data is very detailed, it contains a lot of disturbances. An aggregation level of 5 minutes is more suitable for research purposes. Data is therefore aggregated in the following way:

- Flows are added for every 5 minutes of data. Wrong data is searched. If one or more wrong data points are present in the 5 minutes, they are ignored and filtered out.
- Mean speeds are calculated for the same 5 minutes as filtered in the aggregation of flows.

Another important aspect of this last filter is the fact that on carriageway level, **all flows and speeds are filtered out if one or more flows or speeds are considered wrong.** This means that if a measurement at one lane is wrong, all measurements of the whole carriageway are considered wrong. This is especially important when analyzing lane flow distributions, but the same filter is used for deriving speed-intensity relations.

6.3 Synthesis

The experimental setup in the preceding chapter describes the methodologies used in this part of the research. The preliminary research is aimed at selecting the right rush-hour lane and pluslane section for this research. The sections are filtered to be suitable for the analysis of the 3 design factors: the lane width, the speed limit and the total number of lanes. All possible factor values as mentioned in Table 6-1 should appear at least once in the sections. Tables 6-2 and 6-3 summarize the sections that are used within this research; a total of 5 rush-hour lane section and 5 pluslane sections.

The next step in the research was the collection and filtering of the data. Data is collected using a connection between the program Jedi by Fileradar B.V. and MATLAB. The filter process has 4 steps:

1. Filtering wrong detectors measurements
2. Filtering data that is not in free-flow state
3. Filtering negative flow data
4. Aggregate data to 5 minute averages

The next chapter of this section shows the results from the ex-post evaluation. The results are sub-divided into 3 paragraphs.

Paragraph 7.1 compares the performance of rush-hour lanes and pluslanes. At first, rush-hour lanes are compared with a regular right lane and pluslanes are compared with a regular left lane.

Subsequently, performance of different locations at the rush-hour lane and pluslane sections from Tables 6-2 and 6-3 is analyzed.

The next paragraph focuses on the design factors that cause differences in performance of rush-hour lanes and pluslanes.

The last paragraph compared the best performing rush-hour lane with the best performing pluslane to give an advice on the preferred managed lane.

7 Results

The ex-post evaluation is used to give an answer to 5 research questions in particular. To recap, they are stated again below:

- *What is the **performance** of a rush-hour lane compared to a regular right lane?*
- *What is the **performance** of a pluslane compared to a regular left lane?*
- *What is the **performance** of different locations at rush-hour lane and pluslane sections?*
- *What is the **performance** of a rush-hour lane compared to a pluslane?*
- *What are the underlying **design factors** causing the differences in performance?*

The parts of the research questions that identify the need of the ex-post evaluation are highlighted: '**comparison in performance**' and '**design factors**'. These two terms are used to organize the results of the study. The word performance is used in this sense to reduce the total number of research questions. Lane flow distributions and intensity-speed relations are both used to indicate the performance of the different rush-hour lane and pluslane sections. In the literature review, the necessity of these 2 performance indicators is underpinned (see section A). Both of them will now be elaborated and also the relation with performance will be indicated.

Performance - Lane flow distributions

Lane flow distributions give information on the occupation of the different lanes at different intensities or densities. In this research, total flows are used instead of densities, because only free-flow data is used (above 80 km/h, see paragraph 0). The plots are displayed as the mean flow fraction and the 25th and 75th percentile of the flow fraction per lane from a turbulence-free detector on the section. This method is altered slightly from the method used in (Rest, 2010) as standard deviations where used in that document instead of percentile values.

Performance of one lane is considered higher than another when the mean flow fraction of that lane is higher than the mean flow fraction of another lane. The mean flow fractions of the other two lanes are not considered in this comparison, i.e. a rush-hour lane is compared with a right lane or another rush-hour lane and a pluslanes is compared with a left lane or another pluslane.

Performance - Intensity-speed relations

Speeds gained from the detectors are the arithmetic mean of the speeds aggregated to 5 minutes. For more information about the filtering of the data, see paragraph 6.3. Data is plotted as the mean speed and 25th and 75th percentile speeds at flow intervals from a turbulence-free detector at the section. 50 flow intervals are created between 0 veh/h/lane and 3000 veh/h/lane. All lanes are plotted in 1 figure. This method is altered slightly from the method used in (Rest, 2010) as standard deviations where used in that document instead of percentile values.

Performance of one rush-hour lane is considered higher than another when the free-flow speeds driven on the section of the first one are higher than the speeds driven on the section of the other one. Speeds of all lanes are considered in this comparison.

For clarity, all data from right lanes is colored blue, data from middle lanes is colored green and data from left lanes is colored red throughout the research.

7.1 Comparison in performance

In this section, a performance comparison is made for 4 different aspects of rush-hour lanes and pluslanes:

- rush-hour lane vs. regular right lane
- pluslane vs. regular left lane
- different locations of rush-hour lane and pluslane sections
- rush-hour lanes vs. pluslanes

7.1.1 Rush-hour lane vs. regular right lane

To analyze the differences in performance between a rush-hour lane and a regular right lane, first a highway section with 3 regular lanes should be selected. In this research, the A16 between junction ''s-Gravendeel' and junction 'Klaverpolder' (from south to north) near Dordrecht will be used (see Figure 7.1). This is a section with no turbulence in the form of on-ramps and off-ramps present.

The rush-hour lane section at the A50 between junction Ewijk and junction Valburg is used for this comparison, as it is expected to be the best performing rush-hour lane section. The speed limit is set permanently at 120 km/h, the lane width of the rush-hour lane is the same as the middle-and left lane (3,50 m) and there are a total of 3 lanes present (the configuration is 2+1).

For both sections, detectors are used that are in a turbulence-free part. This means that no on-ramps and off-ramps are present within 1 km of the detector. The main performance indicators will be used for this research, i.e. speeds and lane flow distributions.

The main **hypotheses** for this part of the research are:

Hypothesis 1: Speeds of traffic driving at a rush-hour lane section are structurally lower than speeds driven on a section with 3 regular lanes

Hypothesis 2: Traffic makes significantly less use of the rush-hour lane compared to a regular right lane

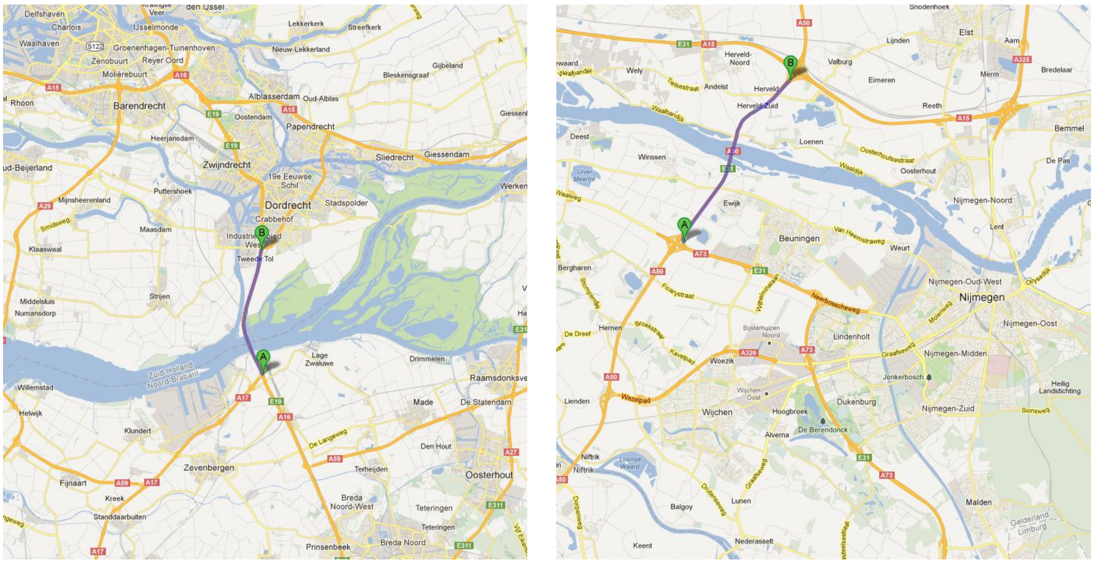


Figure 7.1: The used sections: on the left, the section at the A16 with 3 regular lanes, on the right, the section at the A50 with a rush-hour lane (source: maps.google.com)

Speeds

Intensity-speed relations for both sections are added to appendix 19. Mean speeds on the rush-hour lane range between 85 and 90 km/h, whereas speeds on the regular right lane range between 90 and 100 km/h. The speeds driven on the regular right lane are between 10% and 14% higher compared to the rush-hour lane as can be seen from the plot in Figure 7.2. The presence of a rush-hour lane also has a big influence on the speeds driven at the middle lane and the left lane. Speeds at both the middle lane and the left lane are substantially lower at the rush-hour lane section. On the regular middle lane, speeds range between 100 and 120 km/h, at the rush-hour lane section they vary between 95 and 110 km/h. Speeds are up to 14% lower. Also, the speeds seem to be less influenced by the intensity level.

On the regular left lane, speeds range between 110 and 130 km/h, at the rush-hour lane section they vary between 110 and 120 km/h. Speeds differ between 8 and 10%.

As the A50 turns out to be the worst performing rush-hour lane section (see paragraph 7.2), the section of the A2 between junction Kerensheide and Vonderen is also analyzed for speed differences. Note that the speed limit at this section is 100 km/h when the rush-hour lane is opened; therefore it is compared to the section at the A4 between junction Leidschendam and junction Zoeterwoude-Dorp with 3 regular lanes. Plots of the differences are shown in Figure 7.3. As can be seen, speeds on the middle lane and the left lane are approximately 5% lower than the speeds at the A4 section. Speeds driven at the rush-hour lane are highly comparable with speeds driven at the regular right lane.

In appendix 23, truck percentages are shown for all rush-hour lane and pluslane sections used in this research. For the A2 between Kerensheide and Vonderen, a truck percentage of 20% is assumed (Rijkswaterstaat, 2010a). For the A50 between Ewijk and Valburg, a truck percentage of 30% is assumed (Rijkswaterstaat, 2010b). The differences in speed can therefore for a large part be explained by the amount of trucks driving on the rush-hour lane. A more detailed comparison between the two rush-hour lane sections will be made in paragraph 7.2.

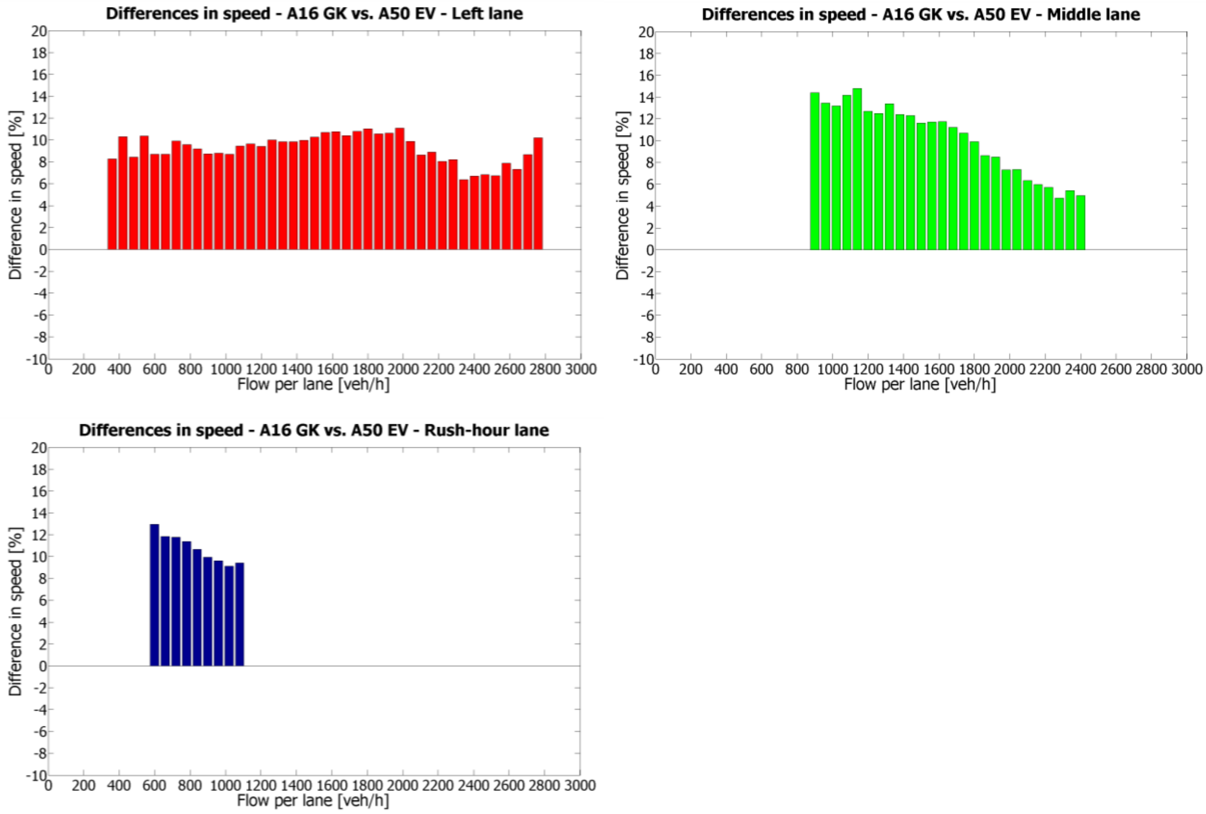


Figure 7.2: Differences in speed between the A16 with 3 regular lanes and the A50 with a rush-hour lane.

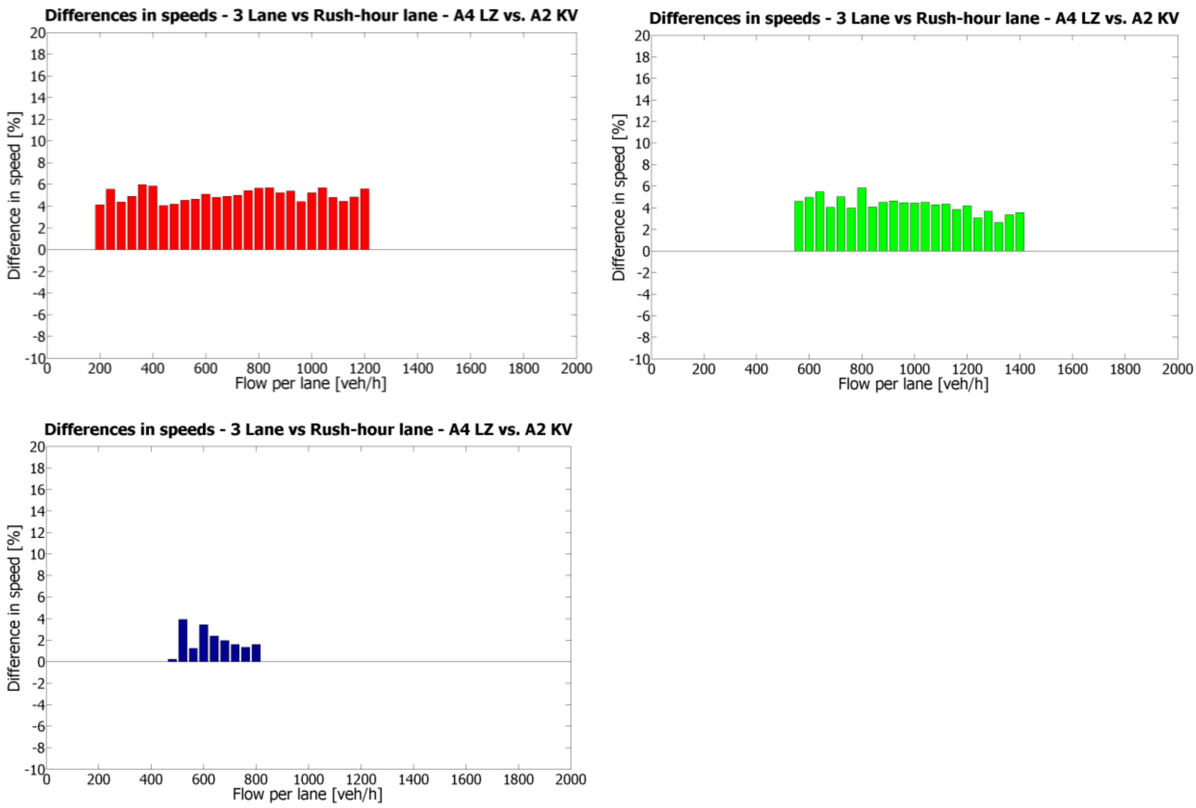
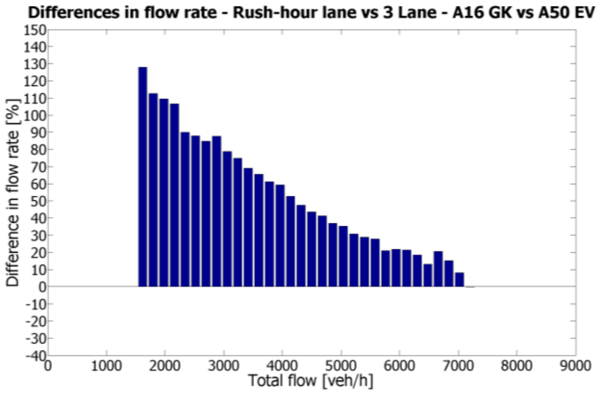


Figure 7.3: Differences in speed between the A4 with 3 regular lanes and the A2 with a rush-hour lane.

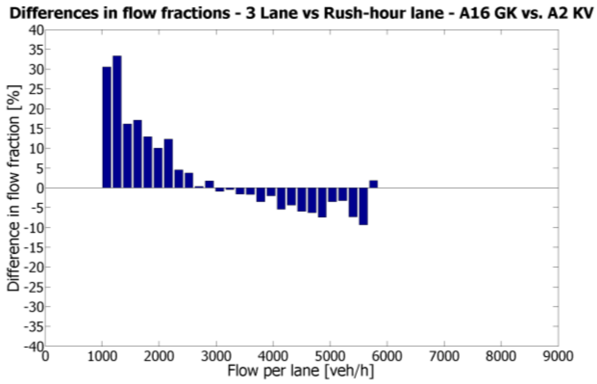
Lane flow distributions

Lane flow distributions of both sections are added to appendix 22. It can be seen from Figure 7.4 that the occupation of the regular right lane is substantially higher (between 15% and 120%) than the occupation of the rush-hour lane at the A50 section. At the rush-hour lane, the occupation level stays constant over the whole range of intensities at a level of approximately 17%. The regular right lane is occupied most at low intensities (as expected) at about 45%. As intensities increase, the occupation of the right lane decreases gradually to a lowest occupation percentage of 21%.
As later in the research it was found that the A50 was, unexpectedly, the worst performing rush-hour lane section regarding occupation, a comparison is also made between the best performing rush-hour lane section at the A2 between junction Kerensheide and junction Vonderen and the section at the A16 (see also paragraph 7.2). The differences in flow fraction of the A16, compared to the A2 are shown in Figure 7.5. This rush-hour lane performs much better than the A50 section, regarding occupation rates. It can be seen that the rush-hour lane is far less occupied at low intensities, but at higher intensities, the flow fraction is about 10% higher, compared to the right lane of the A16. This is, however, mainly caused by the lower speed limit on the rush-hour lane. As a final comparison, the differences in flow rate are also shown between the rush-hour lane at the A2 and the section with 3 regular lanes at the A4 between junction Leidschendam and junction Zoeterwoude-Dorp with a 100 km/h speed limit (see Figure 7.3). Flow rates are between 15% and 30% higher at the A4 section.
A regular right lane is the most occupied lane at low intensities with flow rates up to 50%, whereas the A2 is only occupied up to 40%. At the rush-hour lane section the middle lane has a higher occupation rate for all intensity levels. The lower flow rate at low intensities indicates a natural dislike to driving on the rush-hour lane. In the situation where the rush-hour lane is opened, the middle lane is still the preferred lane, even at the lowest intensity rates measured.
In paragraph 7.2, more detailed research is performed on the design factors causing these differences in occupation. Also, the section of the A50 is programmed into a driving simulator to study the behavioral aspects that cause the lower occupation of this rush-hour lane. For this part of the research, see section C.



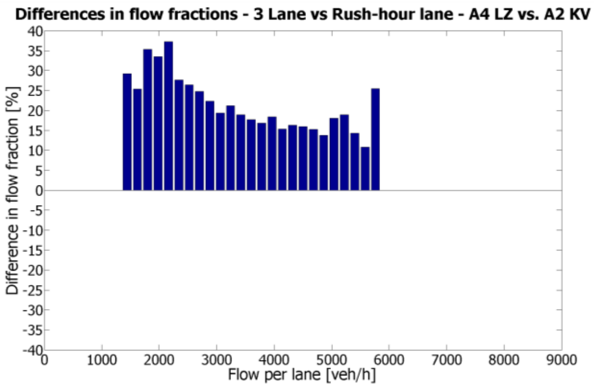
Note the differences in scale!

Figure 7.4: Relative differences in flow fraction of the right lane. The A16 with regular 3 lanes compared to the A50 with a rush-hour lane.



Note the differences in scale!

Figure 7.5: The differences in flow fraction between the A16 with 3 regular lanes and the A2 with a rush-hour lane.



Note the differences in scale!

Figure 7.6: The differences in flow fraction between the A4 with 3 regular lanes and the A2 with a rush-hour lane.

7.1.2 Pluslane vs. regular left lane

To analyze the differences in performance between a pluslane and a regular left lane, the A4 between junction 'Leidschendam' and junction 'Zoeterwoude-Dorp' (from south to north) will be used. The speed limit on this highway section is 100 km/h.

The pluslane section on the A1 between junction Beekbergen and junction Deventer-Oost is used for this comparison, as it is expected to be the best performing pluslane section (see Figure 7.7). The speed limit is set at 120 km/h if the pluslane is closed and 100 km/h if the pluslane is opened. The lane width of the pluslane is 3.10 m, which is the widest of all pluslanes in the Netherlands. There are a total of 3 lanes present (the configuration is 2+1). The middle lane has a width of 3,50 m and the right lane a width of 3,45 m.

For both sections, detectors are used that are in a turbulence-free part. This means that no on-ramps and off-ramps are present within 1 km of the detector. The main performance indicators will again be used for this research, i.e. speeds and lane flow distributions.

The main **hypotheses** for this part of the research are:

Hypothesis 3: Speeds of traffic driving at a pluslane section are structurally lower than speeds driven on a section with 3 regular lanes

Hypothesis 4: Traffic makes significantly less use of the pluslane compared to a regular left lane

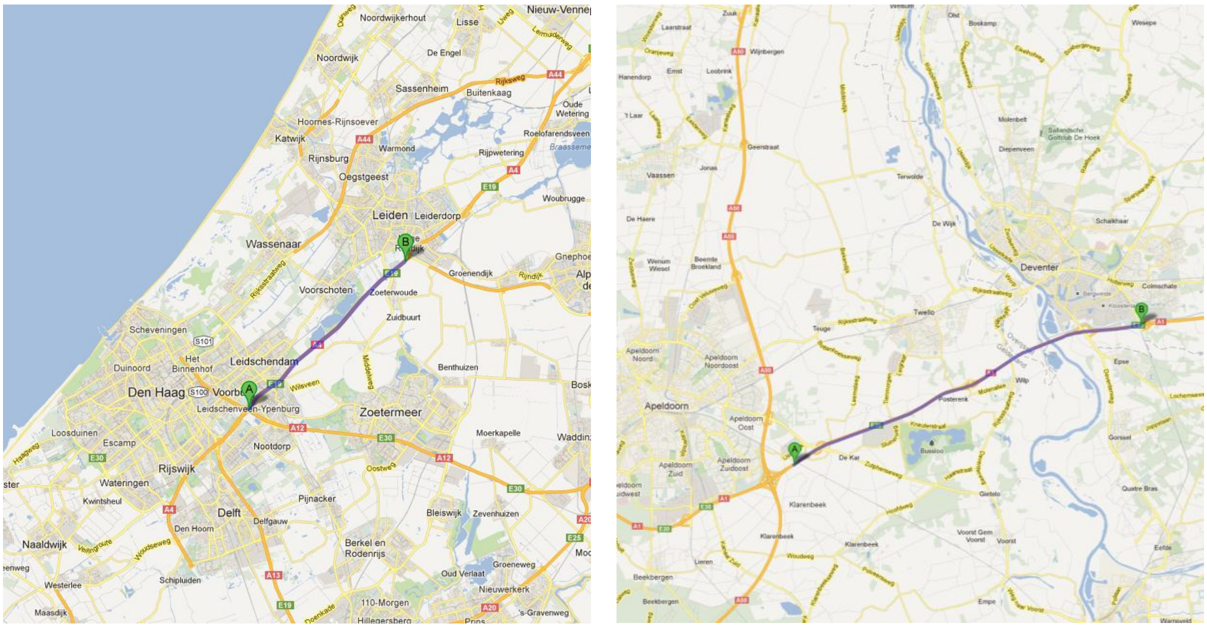


Figure 7.7: The used sections: on the left, the section at the A4 with 3 regular lanes, on the right, the section at the A1 with a pluslane (source: maps.google.com)

Speeds

Intensity-speed relations for both sections are added to appendix 19. Speeds as driven on the pluslane are lower than speeds at the regular left lane. The differences lie between 1% and 5%, as can be seen from Figure 7.8. At the middle lane and the right lane, the same pattern can be observed. At higher intensities, the speed differences of the pluslane compared to the left lane can be neglected. It is interesting to see that at both sections the speed limit of 100 km/h is not well-respected. Especially at low intensities, speeds on the left lane are on average between 110 km/h and 120 km/h.

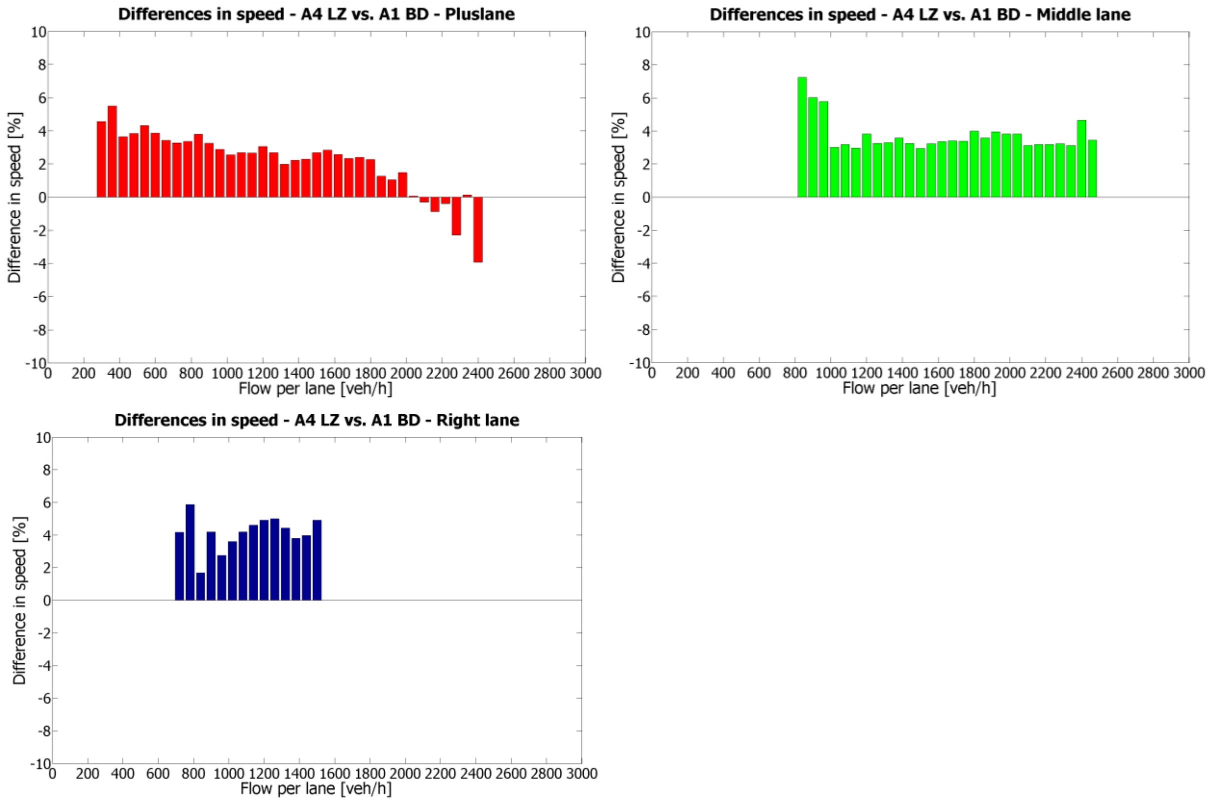


Figure 7.8: Relative speed differences when comparing the A4 section with 3 regular lanes with the A1 section with a pluslane

Lane flow distributions

Lane flow distributions for both sections are added to appendix 22. Relative differences are calculated in percentage of change. As can be seen from Figure 7.9, the flow fractions are lower at the pluslane when regarding low intensities. At low intensities, the left lane at the A4 is occupied more, whereas at high intensities the pluslane of the A1 is occupied slightly more. Regarding the lower flow rate at low intensities, the difference between a rush-hour lane and a pluslane is, in this sense, that the rush-hour lane should be the preferred lane at low intensities, whereas the pluslane is not. At low intensities, left lanes and pluslanes are used as overtaking lanes. The lower speeds, as mentioned in the last paragraph are the main cause of the lower occupation values. A natural dislike for driving on the pluslane could also add to the lower occupation levels. It would, however, be expected that the pluslane would then also show lower flow rates at high occupations in free-flow state. Since this is not the case, the difference in occupation is expected to be caused by the lower speeds.

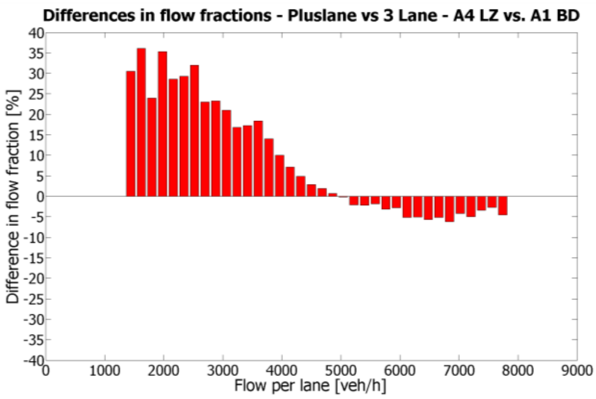


Figure 7.9: Differences in flow fraction between the left lane of A4 and the pluslane at A1

7.1.3 Different locations of rush-hour lane- and pluslane sections

The following locations of rush-hour lane and pluslane sections will be analyzed:

- The **start** of different rush-hour lane and pluslane sections
- A **turbulence-free** location at different rush-hour lane and pluslane sections
- The **end** of different rush-hour lane and pluslane sections

All sections summarized in Table 6-2 and Table 6-3 will be used for this part of the research. For all sections, suitable detectors have been identified. The global locations of these detectors are added to appendix 18.

The main **hypotheses** for this part of the research are:

Hypothesis 5: Traffic makes significantly less use of the rush-hour lane and/or pluslane at the start of the section compared to a turbulence-free section.
Hypothesis 6: Traffic makes significantly less use of the rush-hour lane and/or pluslane at the end of the section compared to a turbulence-free section.

Lane flow distributions will be analyzed of different locations at rush-hour lane and pluslane sections. Note here that data was scarce at the start and end-detectors. Some detectors did not produce data at all and some detectors are located some distance from the start or end of the section. Also, information about the lay-out at the start and end of the section is not always available.

The lane flow distributions of all detectors are shown in appendix 21 each start and end-detector, the relative differences in flow rate compared to the no-turbulence detector are determined. All sections are analyzed separately.

Rush-hour lanes

A1 - Hoevelaken-Barneveld

At the section on the A1 between junction Hoevelaken and junction Barneveld data is only collected from a detector at the start. It is interesting to see that the rush-hour lane is up to 60% less occupied at the start of the section. A plot of the relative differences in flow rate is shown in figure 7.10 on the left. A picture of the layout at the start of the section is shown in figure 7.10 on the right. As can be seen, the rush-hour lane starts at an on-ramp. The edge-line of the shoulder lane starts at the on-ramp. The differences can be explained by the fact that traffic merges first onto the A1, then notices the signs of the open rush-hour lane and reorganizes after that.

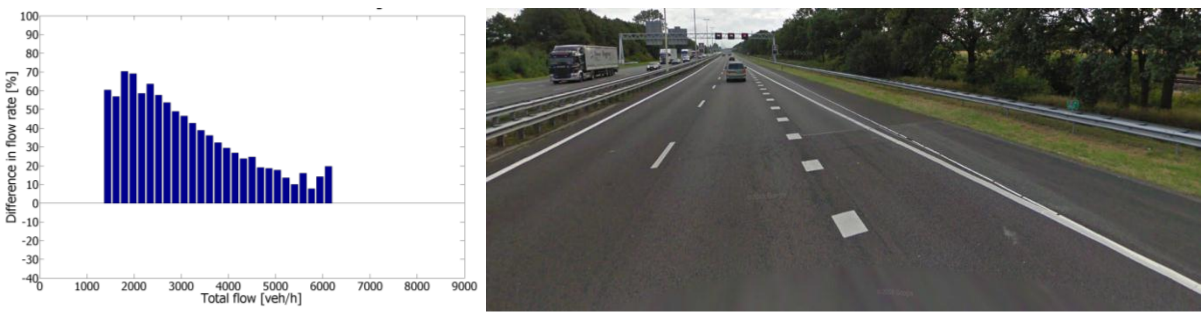


Figure 7.10: On the left: differences in flow rate between a no-turbulence detector and a start detector at the A1. On the right a picture of the lay-out at the start of the section (source: Google)

A2 - Kerensheide-Vonderen

At the section on the A2 between junction Kerensheide and junction Vonderen, data is only collected from a detector at the end. Differences are small and there is no information available of the lay-out at the end of this section (see Figure 7.11). The section will not be analyzed in further detail.

A2 - Vonderen-Kerensheide

At the section on the A2 between junction Vonderen and junction Kerensheide data is only collected from a detector at the end (see Figure 7.11). As no information is found about the lay-out at the end of the section, it will not be analyzed in further detail.

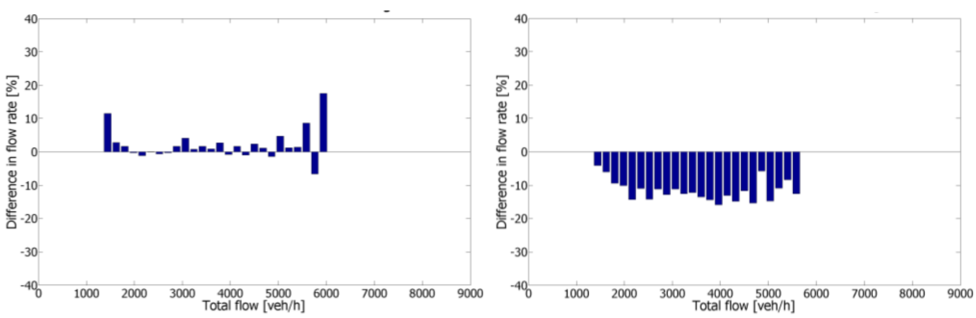


Figure 7.11: Differences in flow fraction between a no-turbulence detector and an end detector at the A2.On the left: the A2 from south to north between junction Kerensheide and junction Vonderen. On the right: the A2 from north to south.

A50 - Ewijk-Valburg

At the section on the A50 between junction Ewijk and junction Valburg, data is collected from start- and end detectors (see Figure 7.12). Results show that both at the start as well as at the end, the rush-hour lane is occupied more than at the no-turbulence detector. It is interesting to see that the layout is probably the cause of this.

The rush-hour lane section starts at junction Ewijk, at the A73 highway. When the rush-hour lane is opened, the off-ramp at the A73 has 2 lanes, the right-most lane being the rush-hour lane. The rush-hour lane continues without disturbances at the A50 (see Figure 7.13). It is expected that traffic makes use of the rush-hour lane more at the start because it continues driving at the rush-hour lane from the off-ramp at the A73. The higher occupation rates at the end can be explained by traffic get in the rightmost lane prior to leaving the A50 to the A15 at junction Valburg.

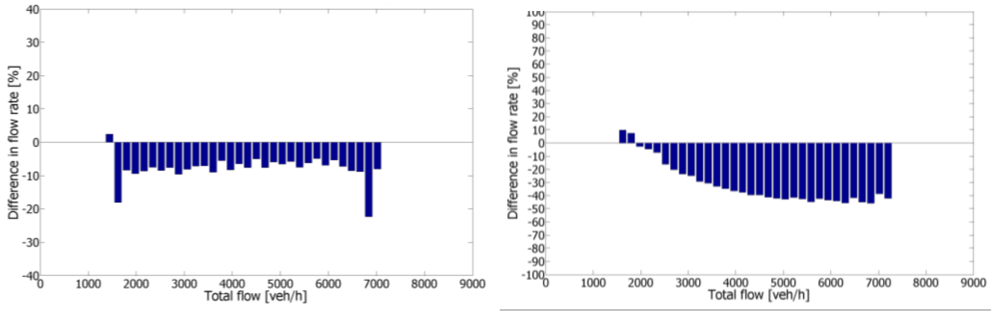


Figure 7.12: Differences in flow fraction. On the left: a no-turbulence detector compared to a start detector at the A50 section, on the right compared to an end detector. Note the differences in scale.

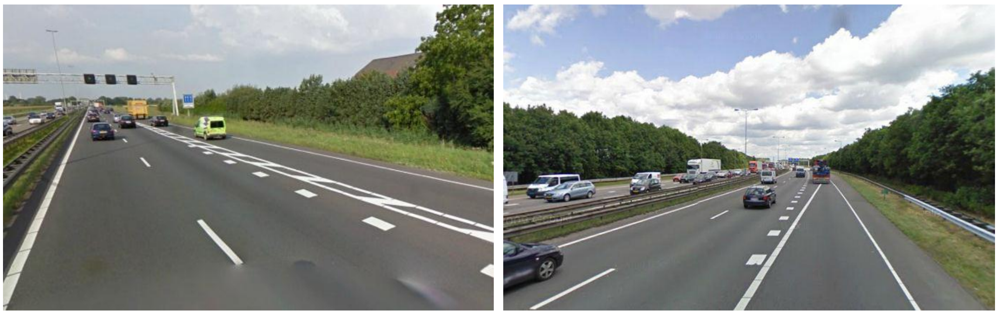


Figure 7.13: Layouts of the A50 section. On the left the start of the section, on the right the end of the section

Pluslanes

A1 - Beekbergen-Deventer-Oost

At the section on the A1 between junction Beekbergen and junction Deventer-Oost, data is collected from start and end detectors. Both detectors show a higher occupation of the pluslane when compared to a no-turbulence detector (see Figure 7.14). When looking at the lay-outs as shown in Figure 7.15, the higher occupation of both detectors can be explained by the merging traffic. The pluslane starts and ends at a section where an on-ramp is located. This causes traffic to make room for merging traffic, as is concluded in the research of (Knoop, 2010). The end-detector is located approximately 1 km upstream of the absolute location of the end of the pluslane.

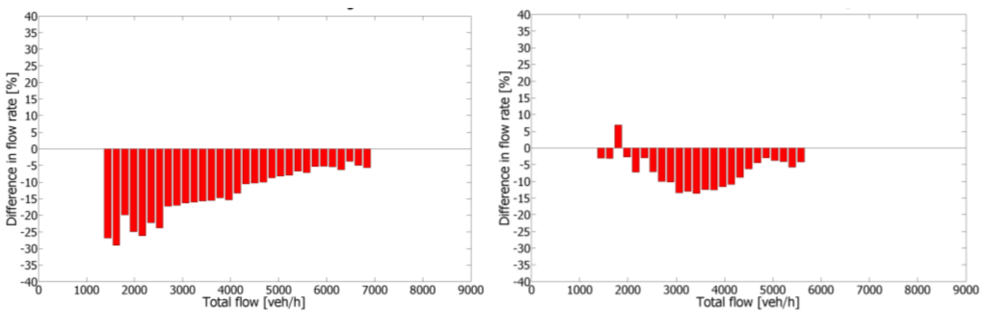


Figure 7.14: Differences in flow fraction at the A1. On the left a no-turbulence detector compared to a start-detector, on the right compared to an end-detector.

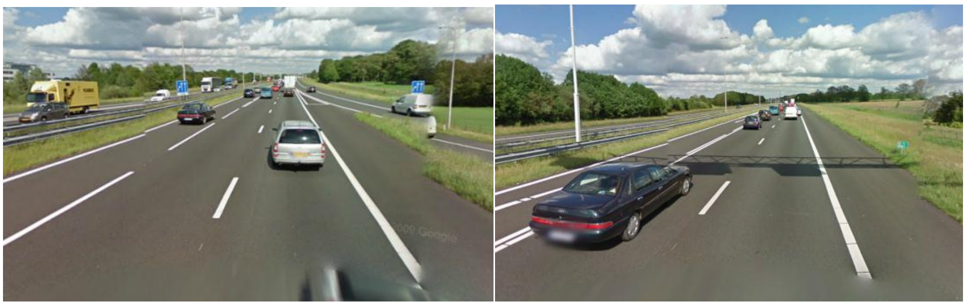


Figure 7.15: Layouts at the A1. On the left the start, on the right the end of the section

A12 - Ede-Veenendaal

At the section on the A12 between junction Ede and junction Veenendaal, data is collected from a detector at the start of the section only. The higher occupation at this start detector can be explained by the fact that an on-ramp is located downstream of the detector. This causes traffic to make room for merging traffic, as is concluded in the research of (Knoop, 2010). Note that the detector is located approximately 1 km downstream of the location as shown in Figure 7.16.

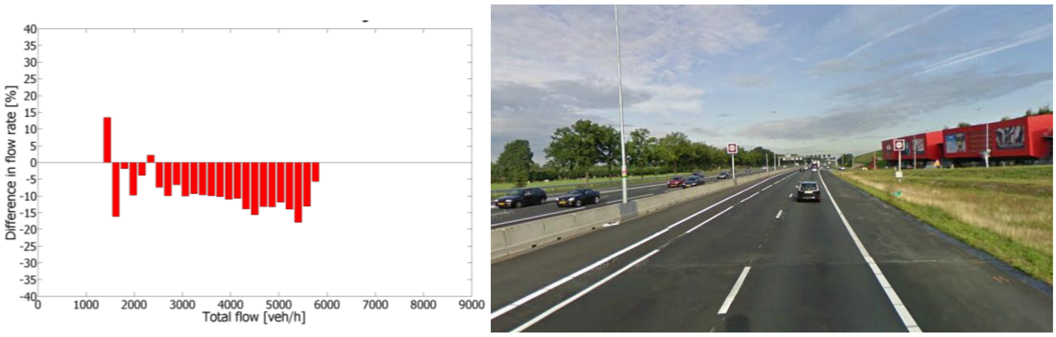


Figure 7.16: On the left: differences in flow fraction between the start detector and a no-turbulence detector. On the right: the lay-out at the start of the pluslane section

A12 - Gouwe-Zoetermeer

At the section on the A12 between junction Gouwe and junction Zoetermeer, data is collected from a detector at the start of section only (see Figure 7.17). The detector is located approximately 1 km downstream of the absolute start of the pluslane, at the location just upstream of the second portal. The data should be compared with a detector closer to the start of the pluslane to give a definitive explanation of the higher flow rates at this detector. No on or off-ramps are located near the location of the detector.

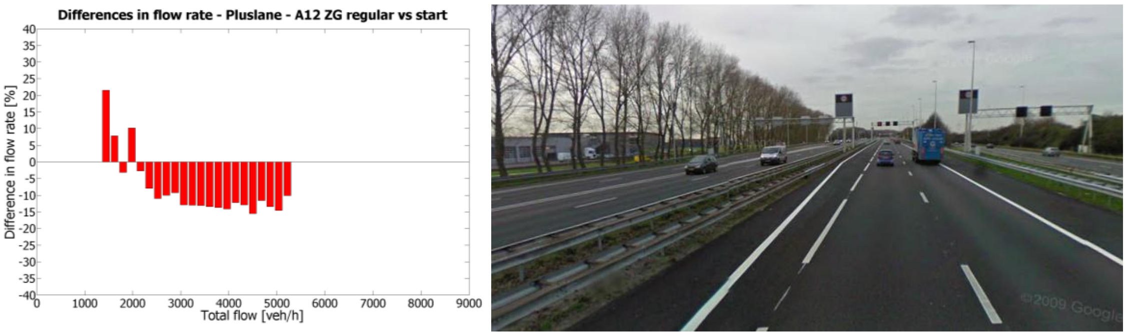


Figure 7.17: On the left: differences in flow fraction between the start detector and a no-turbulence detector. On the right: the lay-out at the start of the pluslane section

A27 - Gorinchem-Noordeloos

At the section on the A27 between junction Gorinchem and junction Noordeloos, data is collected from start and end detectors. Both detectors show significantly higher flow rates when compared to the turbulence-free detector (see Figure 7.18). The detector at the start is located approximately 200 m upstream of an on-ramp. The high difference in occupation cannot be fully explained by this fact. More detailed research should be performed to gain insight in the cause of these differences.

The detector at the end is located approximately 1 km upstream of the absolute end of the pluslane. The first signs of merging ('ritsen vanaf hier') are shown to traffic. This may be the cause of the large difference in flow rate. Pictures of the layout at the start and the end are shown in Figure 7.19.

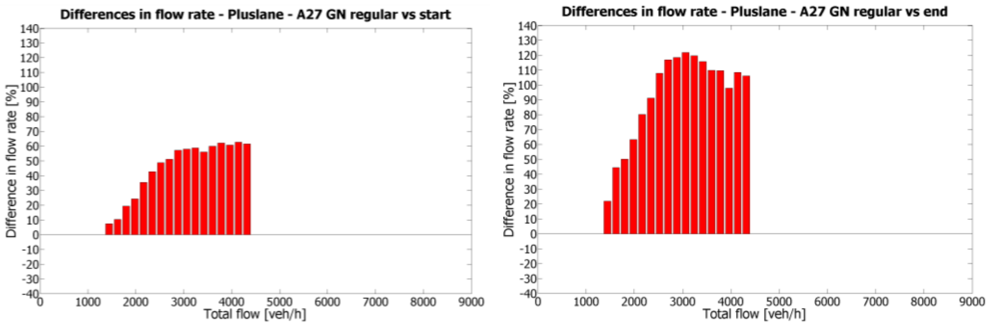


Figure 7.18: Differences in flow fraction at the A27. On the left a no-turbulence detector compared to a start-detector, on the right compared to an end-detector.

Figure 7.19: Layouts at the A27. On the left the start, on the right the end of the section

7.1.4 Synthesis

In this paragraph, the performance of rush-hour lanes and pluslanes was covered. The used performance indicators are lane flow distributions and intensity-speed relations. Regarding lane flow distributions, performance of one lane is considered higher than another when the mean flow fraction of that lane is higher than the mean flow fraction of another lane. The mean flow fractions of the other two lanes are not considered in this comparison, i.e. a rush-hour lane is compared with a right lane or another rush-hour lane and a pluslanes is compared with a left lane or another pluslane.

Regarding intensity-speed relations, performance of one section is considered higher than another when the free-flow speeds driven on the section of the first one are higher than the speeds driven on the section of the other one. Speeds of all lanes are considered in this comparison.

The first part of this paragraph is aimed at analyzing the differences in performance between a rush-hour lane and a right lane and between a pluslane and a left lane**.** The sections with 3 regular lanes that are used for this purpose are the A16 between junction s-Gravendeel and junction Klaverpolder with a speed limit of 120 km/h and the A4 between junction Leidschendam and junction Zoeterwoude-Dorp with a speed limit of 100 km/h. Two rush-hour lane sections are used for the comparison: the best-performing rush-hour lane section, located at the A2 between junction Kerensheide and junction Vonderen and the rush-hour lane at the A50 between junction Ewijk and junction Vonderen. Results show that the occupation rates of both rush-hour lanes are far lower than at the regular right lanes. The relative differences range between 15% and 120%.

When regarding speeds, the rush-hour lane section with a speed limit of 120 km/h at the A50 has lower speeds than the section with 3 regular lanes and a speed limit of 120 km/h at the A16. Differences lie between 10% and 14%. Speeds driven at the section at the A2 with a 100 km/h speed limit are also lower, but it shows smaller relative differences in speed with a maximum difference of 5%. Speeds driven on the rush-hour lane are highly affected by the percentage of trucks at the section.

The same is done for pluslanes, comparing the pluslane at the A1 between junction Beekbergen and junction Deventer-Oost with the left lane at the A4, as mentioned before. Flow fractions at the pluslane are up to 30% lower at low intensities. However, at higher intensities differences are much smaller. The left lane even has approximately 5% lower flow fractions compared to the pluslane.

When regarding speeds, the pluslane section with a speed limit of 100 km/h at the A1 has lower speeds than the section with 3 regular lanes and a speed limit of 100 km/h at the A4. The differences are, however, small with a maximum of 5%. At higher intensities, the speed differences between the left lane and the pluslane can be neglected.

Next, different locations on rush-hour lane and pluslane sections are analyzed for their occupation rates. For all sections mentioned in Table 6-2 and Table 6-3, data is collected - when possible- of detectors located at the start and the end of the section and compared with the data from a

detector at a turbulence-free section. Information about the lay-outs at the start and the end, as well as the detector data was scarce.
At rush-hour lane sections, it was interesting that the lay-out of the start and end seems to have a big influence on the occupation rates. When the rush-hour lane starts before an on-ramp or ends before an off-ramp, as is the case at the A50 section, it is occupied up to 50% more than a turbulence-free section. If the start of the rush-hour lane is situated after an on-ramp, as is the case on the A1 section, it is occupied up to 60% less than a turbulence free section.
Pluslane sections show mixed results. At sections where an on-ramp is located downstream of the detector, traffic makes room for the merging traffic and thus moves further to the left. This causes an increase in occupation rates of the pluslane at those locations. More detailed research should be performed to gain insight in the influence of different lay-outs at the start and the end of rush-hour lane- and pluslane sections.

The next chapter is focused on analyzing the design factors that have an influence on the performance of rush-hour lanes and pluslanes. Three design factors are analyzed in this section: the lane width, the speed limit and the total number of lanes. The same performance indicators of this paragraph are used for this analysis: lane flow distributions and intensity-speed relations.

7.2 Design factors

In this section, the design factors that influence performance of rush-hour lanes and pluslanes are analyzed. The design factors that are researched are:

- Lane widths
- Total number of lanes
- Speed limit

To analyze the influence of these factors, a selection of useful rush-hour lane and pluslane sections is made (see also paragraph 6.1.2). Rush-hour lanes will be analyzed first and the used sections are recapped in Table 7-1 on the next page.

The main **hypotheses** for this part of the research are:

Regarding rush-hour lanes:

Hypothesis 7: If the total number of lanes increases, the occupancy of rush-hour lanes decreases.

Hypothesis 8: If the total number of lanes increases, the speeds driven on rush-hour lanes do not change.

Hypothesis 9: If the lane width decreases, the occupancy of rush-hour lanes decreases.

Hypothesis 10: If the lane width decreases, the speeds driven on rush-hour lanes will become structurally lower.

Hypothesis 11: If a speed restriction is set on rush-hour lanes, the occupancy decreases.

Hypothesis 12: If a speed restriction is set on rush-hour lanes, speeds will decrease proportionally to this speed limit.

Regarding pluslanes:

Hypothesis 13: If the total number of lanes increases, the occupancy of pluslanes decreases.

Hypothesis 14: If the total number of lanes increases, the speeds driven on pluslanes do not change.

Hypothesis 15: If the lane width decreases, the occupancy of pluslanes decreases.

Hypothesis 16: If the lane width decreases, the speeds driven on pluslanes will become structurally lower.

Hypothesis 17: If a speed restriction is set on pluslanes, the occupancy decreases.

Hypothesis 18: If a speed restriction is set on pluslanes, speeds will decrease proportionally to this speed limit.

A lot of different rush-hour lane and pluslane sections are analyzed in this part of the research. To keep things organized, the graphs of intensity-speed relations and lane flow distributions of these sections are added to appendix 19 and appendix 20. Differences between the layouts will be analyzed in this section. Pairwise comparison is used for this purpose. The method basically means that each pair of alternative layouts will be compared with each other. The occupancy and speeds of rush-hour lanes are analyzed at first, pluslanes are analyzed after that.

7.2.1 Rush-hour lanes - occupancy

Table 7-1 shows the rush-hour lane sections that will be used in this part of the research.

Table 7-1: Rush-hour lanes to be used in this research, including the design factors

Location	Lanes	Lane widths (from left to right)	Speed limit (closed / open)	Factors
A50 – Ewijk - Valburg	2+1	3,50|3,50|**3,50**	120 / 120	Zero alternative
A13 – Berkel & Rodenrijs - Delft- Zuid	3+1	3,25|3,40|3,40|**3,35**	100 / 100	Width: average Speed: 100/100 Lanes: 4
A2 – Vonderen - Kerensheide	2+1	3,25|3,40|**3,35**	120 / 100	Width: average Speed: 120/100
A1 – Hoevelaken - Barneveld	2+1	3,35|3,50|**3,50**	120 / 100	Speed: 120/100
A2 – Kerensheide - Vonderen	2+1	3,25|3,40|**3,28**	120 / 100	Width: narrow Speed: 120/100

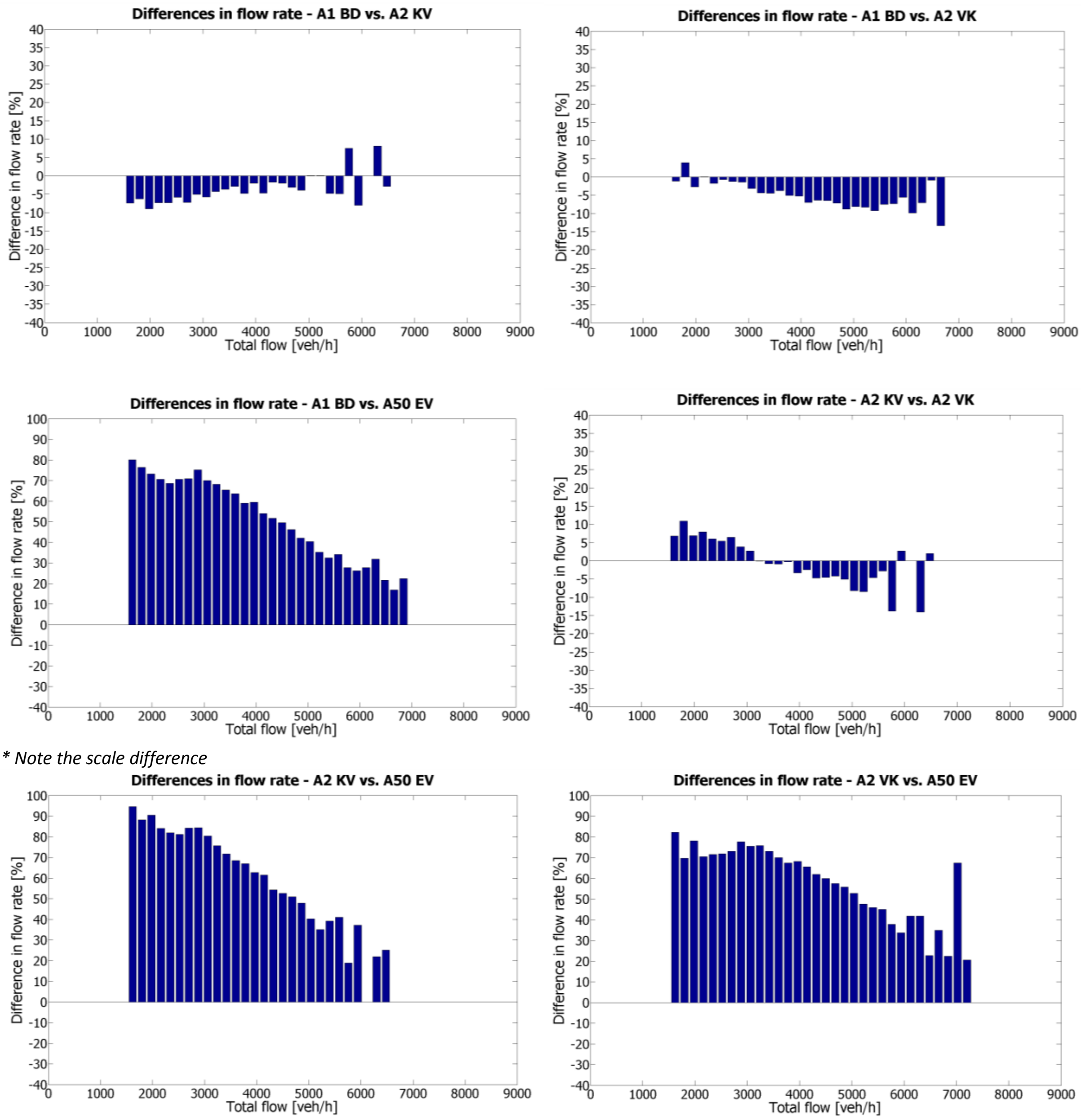
To determine the differences in occupancy, data of lane flow distributions are gathered for all sections as described in Table 7-1. In appendix 22, all lane flow distributions can be found. All plots of the relative differences between pairs of rush-hour lane sections are plotted in Figure 7.20. A total of 6 pairs are compared (note that the abbreviations represent the begin and end-junctions of the section):

- A1 HB vs. A2 KV
- A1 HB vs. A2 VK
- A1 HB vs. A50 EV
- A2 KV vs. A2 VK
- A2 KV vs. A50 EV
- A2 VK vs. A50 EV

Relative differences are plotted, i.e. an increase in occupation from 10% to 15% will be shown as the relative increase of 50% instead of the absolute increase of 5%. All intervals are plotted. The design factors - speed limit, lane width, 4 lanes - are analyzed separately.

The ranking of the 4 sections for flow fractions is as follows:

1 A2 between junction Kerensheide and junction Vonderen from south to north
2 A2 between junction Vonderen and junction Kerensheide from north to south
3 A1 between junction Hoevelaken and junction Barneveld
4 A50 between junction Ewijk and junction Valburg



** Note the scale difference*

** Note the scale difference*

** Note the scale difference*

Figure 7.20: Differences in flow rate of the rush-hour lane sections

Speed limit

It can be seen that the speed limit has a big effect on the occupation of the rush-hour lanes. The rush-hour lane section at the A50 was expected to perform best with its specifications. The speed limit of 120 km/h, however, has a negative effect on the occupation of the rush-hour lane. The other sections all have a limit of 120 km/h with closed and 100 km/h with open rush-hour lane.
The behavioral aspects that underlie this low occupation at the high speed limit are researched in the driving simulator study. For results of this study, you will be referred to paragraph 10.1.

Lane width

The rush-hour lane sections at the A2 both have smaller lane widths than regular. The section from south to north, between junction Kerensheide and junction Vonderen has a lane width of 3,28 m, the section from north to south has a lane width of 3,35 m. The other sections have a lane width of 3,50 m, which is equal to the width of a regular right lane. The A1 section performs slightly worse than both A2 sections at low intensities. As both rush-hour lane sections at the A2 perform best when regarding occupation rates, the lane width is in that sense not a determining factor. It is, however, interesting that the section with the smaller lane width has up to 10% lower occupation rates at higher intensities. As all other factors are equal for both rush-hour lane sections at the A2, this indicates that the lane width has an influence on the occupation of rush-hour lanes.

4 Lanes

The section with 4 lanes at the A13 between junction Berkel & Rodenrijs and junction Delft-Zuid is analyzed separately from the other sections. For a good comparison, the flow fraction is multiplied by the flow to get the intensity share per interval. To clarify this method, an example is given:

Suppose the flow fraction of a lane at a 3 lane section is equal to the flow fraction at a 4 lane section at 25%. The intensity level at the three lane section is 4500 veh/h, whereas the intensity level at the 4 lane section is 6000 veh/h. The relative difference between the intensity shares thus becomes: $\frac{0{,}25 \cdot 4500 - 0{,}25 \cdot 6000}{0{,}25 \cdot 4500} = -33\%$.

The results are shown in Figure 7.21. As can be seen, the rush-hour lane at the A13 shows the same pattern as the section at the A50, i.e. flow fractions stay approximately constant for all intensity levels. This indicates that at a section with 4 lanes, the preferred lane at low intensities is the middle-right lane, instead of the rush-hour lane. It should be noted here that the speed limit is also different than the other sections (permanent 100 km/h, so no transition), but it is expected that the differences are caused by the extra lane.

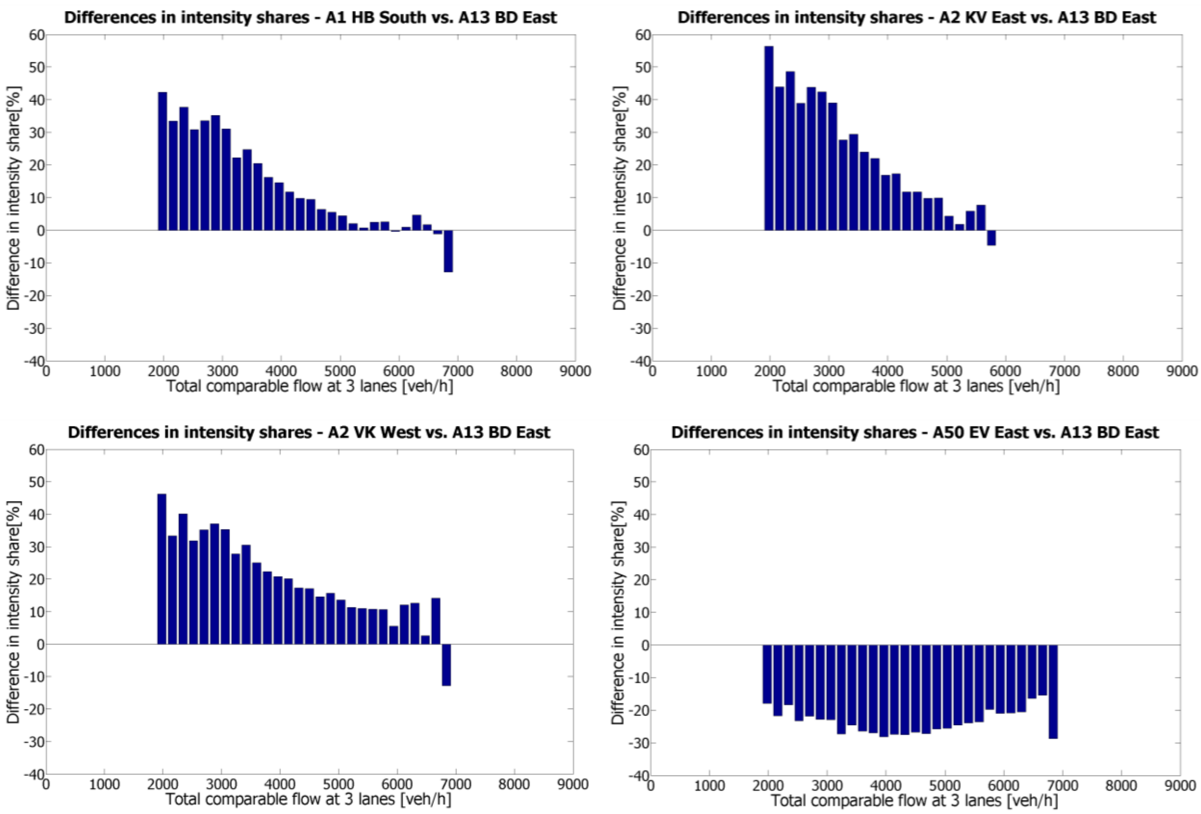


Figure 7.21: Differences in flow fractions for the 4 lane section compared to the 3 lane sections

7.2.2 Rush-hour lanes - speeds

Speeds driven on the section are compared for relative differences per intensity interval. All intensity-speed relations are added to appendix 19. The relative speed differences of rush-hour lanes are added to appendix 20. The same six pairs as in paragraph 7.2.1 are compared with each other. All 3 design factors - speed limit, lane width, 4 lanes - are treated separately. As the truck percentage is of a big influence on the average speeds, this is added as another comparing factor.

Truck percentages

As mentioned before in the analysis of paragraph 7.1.1, the truck percentage can have a large influence on speeds driven at the rush-hour lane. Truck percentages are analyzed in appendix 23 and summarized in Table 7-2. It can be seen that not only the truck percentage has an influence on the speeds driven. At the A50, the large truck percentage definitely has an effect on the speeds. At the A1, however, speeds are lower than at both sections of the A2, whereas the truck percentage is also lower.

Table 7-2: Truck percentages for the rush-hour lane sections

Rush-hour lane section	Truck % literature
A1 Hoevelaken - Barneveld	14% (MER,2006)
A2 Kerensheide - Vonderen	20% (MER,2010)
A2 Vonderen - Kerensheide	20% (MER,2010)
A13 Berkel & Rodenrijs - Delft-Zuid	0 - 10%
A50 Ewijk - Valburg	30% (TN,2005)

Speed limit

The speeds driven at the A50 with a permanent speed limit of 120 km/h on the rush-hour lane are lowest of all sections. A combination of the large truck percentage and the low overall occupation causes traffic to drive slower at the rush-hour lane (the ratio of trucks and regular passenger cars is worst of all sections). Speeds at the middle lane and left lane are comparable with the section at the A2 between junction Vonderen and junction Kerensheide. Speeds are a maximum of 4% lower at the A50 section.

The effect of this high speed limit on the behavior of traffic is analyzed in the driving simulator study in section C. All other sections have the same speed limit. The section at the A13 between junction Berkel & Rodenrijs and junction Delft-Zuid has a permanent speed limit of 100 km/h and will be analyzed separately at the '4 lanes' section.

Lane width

As speeds on the A1 section are lower than speeds at the A2 sections, lane width is in that comparison not a determining factor. When the difference between the A2 sections is analyzed, however, speeds driven at the rush-hour lane on the section with the smaller lane width are lower at higher intensities. As all other factors of these rush-hour lane sections are the same, it indicates that smaller lane widths have a negative influence on speeds.

4 Lanes

The section with 4 lanes at the A13 between junction Berkel & Rodenrijs and junction Delft-Zuid is analyzed separately from the other sections. As can be seen in Figure 7.22, speeds driven on the 4 lane section are comparable with speeds driven at the section on the A1 between junction Hoevelaken and junction Barneveld. Speeds on the A2 sections are up to 6% higher.

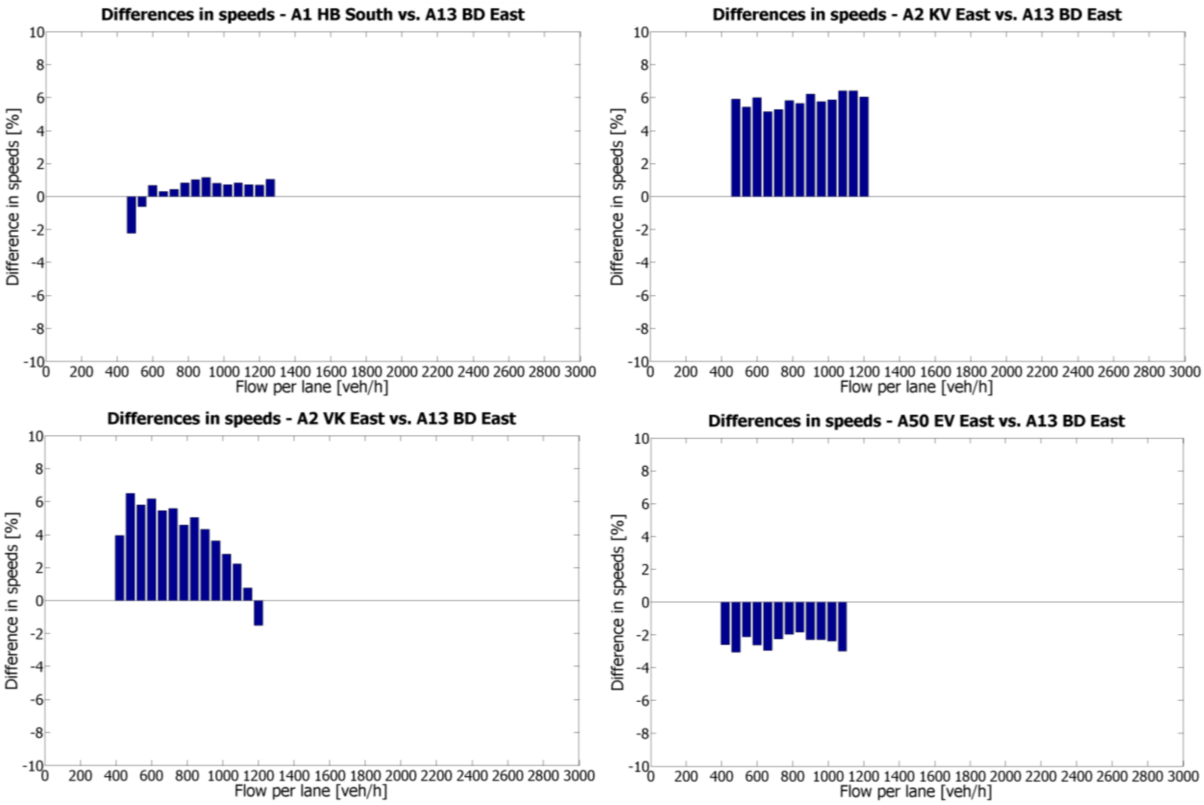


Figure 7.22: Speed differences of the 4 lane section compared to the 3 lane sections

7.2.3 Pluslanes - occupancy

In Table 7-3, the pluslane sections are shown that will be used for this research.

Table 7-3: Pluslanes to be used in this research, including the design factors

Location	Lanes	Lane widths (from left to right)	Speed limit (closed / open)	Factors
A1 – Beekbergen – Deventer-Oost	2+1	**3,10**|3,50|3,45	120 / 100	Zero alternative
A12 – Ede - Veenendaal	2+1	**3,00**|3,50|3,35	120 / 100	Width: Average
A12 – Woerden - Gouda	3+1	**2,75**|3,50|3,50|3,50	120 / 100	Width: narrow Lanes: 4
A12 – Gouwe-Zoetermeer	2+1	**2,75**|3,50|3,25	100 / 100	Width: narrow Speed: 100/100
A27 – Gorinchem - Noordeloos	2+1	**2,70**|3,00|3,25	100 / 80	Width: narrow Speed: 100/80

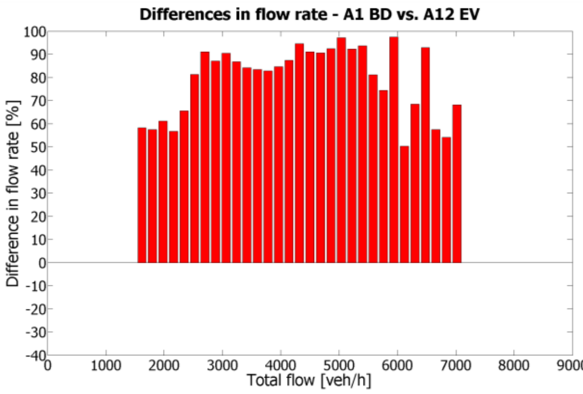
To determine the differences in occupancy, data of lane flow distributions are gathered for all sections as described in Table 7-3. In appendix 22, all lane flow distributions can be found. All plots of the differences between pairs of rush-hour lane sections are plotted in Figure 7.23. A total of 6 pairs are compared (note that the abbreviations represent the begin and end-junctions of the section):

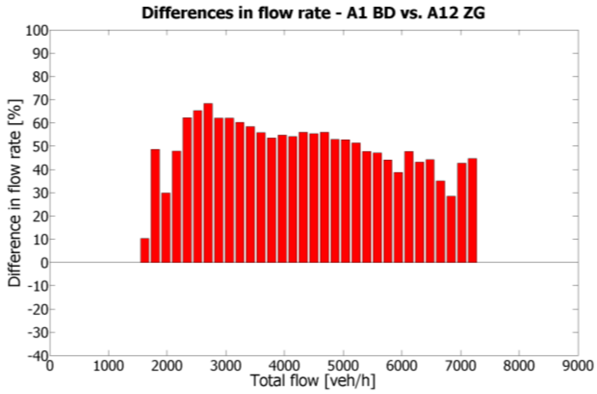
- A1 BD vs. A12 EV
- A1 BD vs. A12 ZG
- A1 BD vs. A27 GN
- A12 EV vs. A12 ZG
- A12 EV vs. A27 GN
- A12 ZG vs. A27 GN

Relative differences are plotted, i.e. an increase in occupation from 10% to 15% will be shown as the relative increase of 50% instead of the absolute increase of 5%. All intervals are plotted. The design factors 'speed limit' and 'lane width' will be analyzed together; the design factor '4 lanes' is analyzed separately.

The ranking of the 4 sections for flow fractions is as follows:

1 A1 between junction Beeksbergen and junction Deventer-Oost
2 A27 between junction Gorinchem and junction Noordeloos
3 A12 between junction Gouwe and junction Zoetermeer
4 A12 between junction Ede and junction Veenendaal





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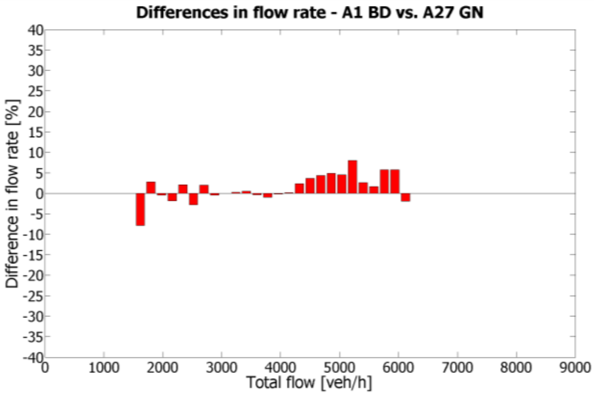

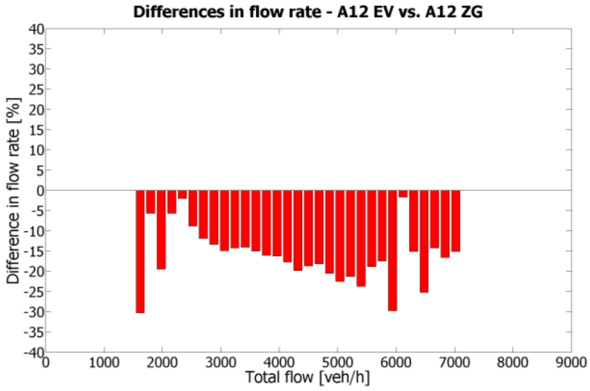

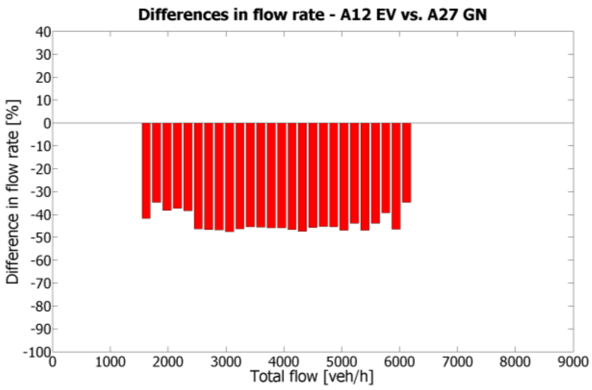

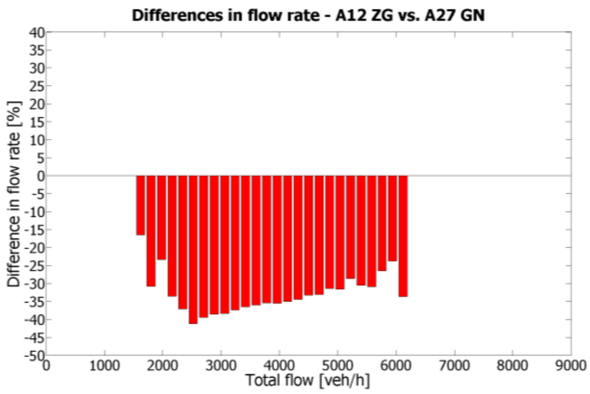

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Figure 7.23: Differences in flow rates of the pluslane sections

Speed limit / Lane width

The most noticeable aspect of comparing the lane flow distributions is the low flow rates at the A12 between junction Ede and Veenendaal. The fact that only 1 turbulence-free detector provides data makes it impossible to compare differences between detectors, so to make sure the data is reliable; the section between junction Veenendaal and junction Ede is also analyzed (this section has the same specifications). The differences are substantial (see Figure 7.24), so other factors that are not analyzed in this research can play a large role. It is expected that the large number of junctions on the sections plays a role. This reduces the turbulence-free length at the section and can have a large effect on the data. In paragraph 7.1.3, the differences between different locations on the section between Ede and Veenendaal are compared.

When focusing on the other 3 sections, it is interesting to see that a combination of the speed limit and the lane width is the most important factor that determines the occupation. The section at the A27 between junction Gorinchem and junction Noordeloos with the smallest width (2,70 m) and the speed limit of 80 km/h performs just as well as the section at the A1 between junction Beekbergen and junction Deventer-Oost. When the high speed limit of 100 km/h is combined with a small lane width of 2,75 m - as can be seen at the section on the A12 between junction Gouwe and junction Zoetermeer - flow rates drop. The relative differences can be as big as 60%.

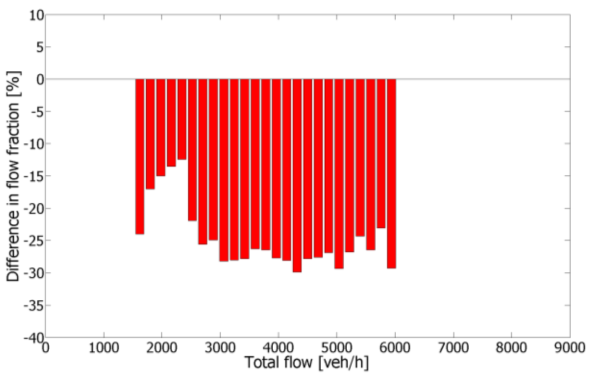


Figure 7.24: Differences in flow fraction of the pluslanes at the A12 between Ede and Veenendaal (north vs. south)

4 Lanes

The section with 4 lanes at the A12 between junction Woerden and junction Gouda is analyzed separately from the other sections. To analyze the occupation levels correctly, they are multiplied by the intensity levels, giving the 'intensity-share' for the lane (see paragraph 7.2.1 for a detailed description of the method). As can be seen in figure 7.25, the pluslane at the 4 lane section performs worst of all analyzed sections, except for the section at the A12 between junction Ede and junction Veenendaal. As mentioned before, the data from the latter section is considered biased by the relatively large amount of junctions at the section and therefore the relatively short turbulence-free length.

Intensity-shares are comparable with the section at the A12 between junction Gouwe and junction Zoetermeer. At lower intensities, the pluslane at the 4 lane section is less-occupied, whereas at higher intensities the 3 lane section is less-occupied. It is expected that the combination of the speed limit of 100 km/h and the narrow lane width of 2,75 m reduces the occupation rates at the 4 lane section.

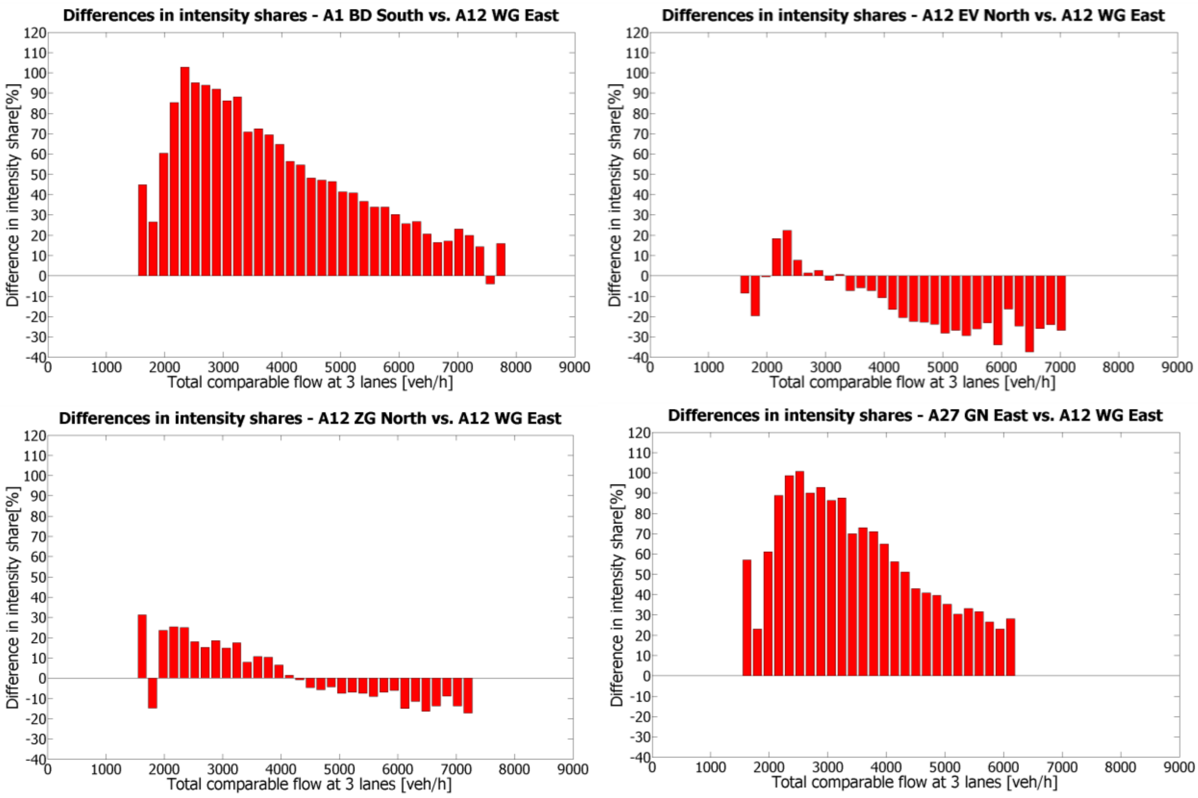


Figure 7.25: Differences in flow rates of the 4 lane section compared to the 3 lane sections

7.2.4 Pluslanes - Speeds

Speeds driven on the section are compared for relative differences per intensity interval. All intensity-speed relations are added to appendix 19. Relative speed differences of pluslanes are added to appendix 21. The same six pairs as in paragraph 7.2.3 are compared. All 3 design factors - speed limit, lane width, 4 lanes - are treated separately.

Speed limit

The section that shows the biggest differences in driven speeds is, as expected, the section with the lowest speed limit of 80 km/h. When regarding the comparison between the pluslane at the A1 and the section with 3 regular lanes at the A4 in paragraph 7.1.2, it can be seen that speeds on all pluslanes are lower than speeds at a regular left lane. At lower intensities, speed limits are not well-respected at the pluslane sections. At higher intensities, the speed decrease at the pluslane is proportional to the speed limit. The decrease in speed limit from 100 km/h to 80 km/h is 20%. The decrease in speeds at higher intensities is, as can be seen, also approximately 20%. This, however, only holds true for the pluslane. Speeds driven at the middle lane and left lane are up to 8% lower at the A1 section.

Lane width

The lane width of the section at the A12 between junction Gouwe and junction Zoetermeer is 2,75 m. Speeds driven at this section are up to 4% lower at the higher intensity levels when compared to the section at the A1 between junction Beekbergen and junction Deventer-Oost.
Data from the section at the A12 between junction Ede and junction Veenendaal is neglected. As mentioned before, the large amount of junctions at the section seems to have a large influence on the data.

4 Lanes

It is interesting to see that speeds at the section with 4 lanes are highest of all sections (see Figure 7.26). Speed differences are about 10% when comparing the different sections. This result is expected. Speeds increase at lanes situated further to the left (Hoogendoorn, 2012b). At the section with 3 lanes and a pluslane, this can also be observed. The narrow lane width of 2,75 m does not have an influence on the speeds driven at the pluslane.

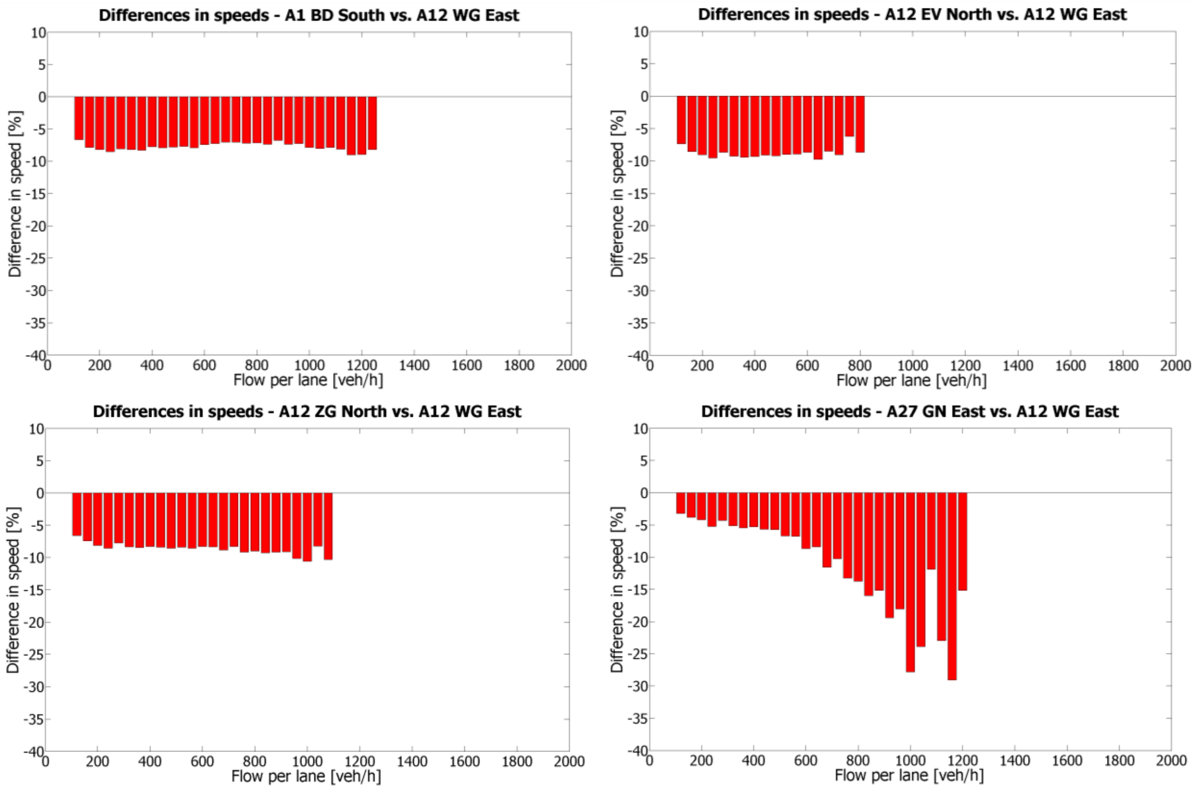


Figure 7.26: Speed differences of the 4 lane section compared to the 3 lane sections

7.2.5 Synthesis

This paragraph focused on analyzing the design factors that influence the performance of rush-hour lanes and pluslanes. Three design factors were analyzed: the lane width, the speed limit and the total number of lanes. The influence of all design factors will be discussed for rush-hour lanes and pluslanes separately. Also, a separation is made between the two performance indicators: occupation and speeds.

Rush-hour lanes - occupation

The speed limit as a design factor has the biggest influence on the occupation of rush-hour lanes. The section with the highest speed limit of 120 km/h performs worst of all analyzed sections (between 15% and 90% less occupation, when compared to the other rush-hour lane sections).
Two rush-hour lane sections at the A2 are analyzed to show the influence of lane widths. As all other design factors are the same. The occupation of the rush-hour lane with a lane width of 3,28 m is up to 10% lower at higher intensity levels when compared to the rush-hour lane with a lane width of 3,35 m. This indicates that lane width has an influence on the occupation.
A rush-hour lane section with 4 lanes in total (3+1) shows the same intensity share pattern than the A50 section, i.e. intensity shares stay constant for different intensity levels. At lower intensity levels, the intensity shares of the 4 lane section are therefore lower than the intensity shares at a rush-hour lane section with 3 lanes in total (2+1). At higher intensity levels, the differences can be neglected.

Rush-hour lanes - speeds

The speed limit as a design factor has the biggest influence on the speeds driven at rush-hour lane sections. The section with the highest speed limit of 120 km/h performs worst of all analyzed sections, however, the truck percentage at that section is also highest of all sections. A combination of the high truck percentage and the low overall occupation of this rush-hour lane reduces the speeds.
Two rush-hour lane sections at the A2 are analyzed to show the influence of lane widths. As all other design factors are the same. The speeds driven at the rush-hour lane section with a lane width of 3,28 m are up to 8% lower at higher intensity levels when compared to the rush-hour lane with a lane width of 3,35 m. This indicates that lane width has an influence on the speeds.
A rush-hour lane section with 4 lanes in total (3+1) does not show differences in free-flow speeds when compared to a rush-hour lane section with 3 lanes in total (2+1).

Pluslanes - occupation

A combination of a high speed limit of 100 km/h with a small lane width has the biggest influence on the occupation of pluslanes. The section with a speed limit of 100 km/h combined with a lane width of 2,75 m performs worst of all analyzed sections (between 30% and 70% less occupation). The pluslane section with a high speed limit of 100 km/h combined with a wide lane of 3,10 m shows the same occupation rates when compared to a section with a narrow lane of 2,70 m and a low speed limit of 80 km/h.

The pluslane section with a total number of 4 lanes (3+1) shows intensity shares that are comparable with the section with a combination of a high speed limit and a narrow lane width. As the lane width of the 4 lane-section is also narrow (2,75 m) and the speed limit is also high (100 km/h) it is expected that the lower intensity shares are caused by this combination rather than the addition of an extra lane.

Pluslanes - Speeds

The speed limit as a design factor has the biggest influence on the free-flow speeds at pluslanes. Speeds driven at the section with a speed limit of 80 km/h shows the lowest free-flow speeds of all sections. This, however, only holds for speeds driven at the pluslanes. Speeds driven at the middle lane and the left lane are higher at the section with a 80 km/h speed limit.

The section with a lane width of 2,75 m shows 4% lower speeds than the section with a lane width of 3,10 m.

Speeds driven on a pluslane at a section with a total of 4 lanes (3+1) are 10% higher than speeds driven on pluslanes at sections with 3 lanes.

In the next chapter, the best performing rush-hour lane section will be compared with the best performing pluslane section. Regarding the occupation, data is used from paragraph 7.1.1 and paragraph 7.1.2. The lane that resembles the representative regular lane the most is considered the best performing managed lane. Regarding the speeds, the section with the highest free-flow speeds driven at the lanes is considered the best performing section.

7.3 Rush-hour lanes vs. pluslanes

At this point, all aspects of performance have been analyzed. This section is meant to summarize the results and compare the results from the analysis of rush-hour lanes with the results from the analysis of pluslanes.
The main **hypotheses** of this section are:

Hypothesis 19: A pluslane section performs better than a rush-hour lane section regarding the speeds driven on the different lanes.
Hypothesis 20: A pluslane section performs better than a rush-hour lane section regarding the occupation of the lane.

In this section, the best performing rush-hour lane and pluslane are used, as they are assumed to show us what both managed lanes are capable of. The best performing sections are derived from the analyses in the previous paragraphs and are:

- The rush-hour lane at the A2 between junction Kerensheide and junction Vonderen
- The pluslane at the A1 between junction Beekbergen and junction Deventer-Oost

The meaning of performance in hypothesis 19 is clear: the section with the highest free-flow speeds is considered the best performing section. In hypothesis 20, however, performance has a somewhat more complicated definition. The rush-hour lane is compared to a regular right lane in paragraph 7.1.1 and the pluslane section of the A1 is compared with a regular left lane in paragraph 7.1.2. The lane that resembles the representative regular lane the most is considered the best performing lane regarding occupation. This part of the comparison can be seen as a recap of the aforementioned paragraphs.
Occupation of the rush-hour lane is always a minimum of 15% lower than the occupation of a regular right lane (see Figure 7.10). Occupation of the pluslane is comparable to the occupation of a regular left lane. At higher intensities, occupation rates of the pluslane even exceed the occupation rates of the regular left lane (see Figure 7.16).
When comparing the speeds driven at each section, speeds at the pluslane section are approximately 4% higher for the left lane and the middle lane.
Speeds driven on the rush-hour lane at the section of the A2 are higher than speeds driven on the right lane at the section of the A1. The percentages of trucks are 20% for the A2 section and 26% for the A1 section respectively. As differences on the right lanes are not very big it is assumed that these differences are caused by the differences in truck percentages (see Figure 7.27)

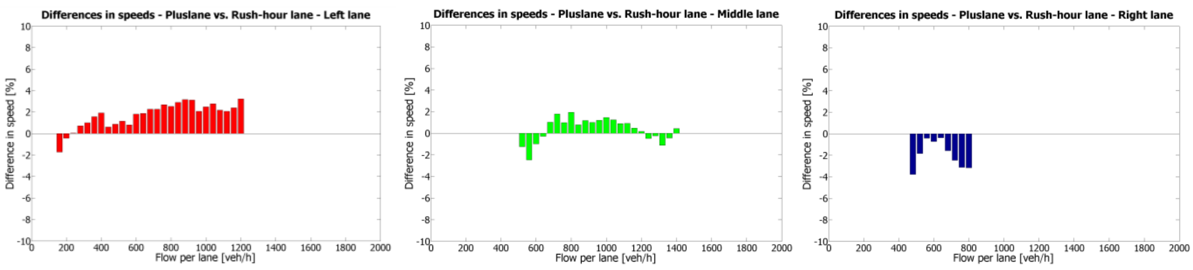


Figure 7.27: Speed differences when comparing the pluslane section at the A1 and the rush-hour lane section at the A2

7.3.1 Synthesis

Occupation of the rush-hour lane is always a minimum of 15% lower than the occupation of a regular right lane. Occupation of the pluslane is comparable to the occupation of a regular left lane. At higher intensities, occupation rates of the pluslane even exceed the occupation rates of the regular left lane.
When comparing the speeds driven at each section, speeds at the pluslane section are approximately 4% higher for the left lane and the middle lane. Speeds driven on the rush-hour lane at the section of the A2 are higher than speeds driven on the right lane at the section of the A1. As differences on the right lanes are not very big it is assumed that these differences are caused by the differences in truck percentages.

The analyses that are needed to answer the sub-questions A1, A2, A3, A4 and B1, as posed in paragraph 1.2 are now all performed. The next chapter concludes the ex-post evaluation by answering these sub-questions. The answers are given by proving or disproving the hypotheses as stated in the separate paragraphs of this section.
Also, a synthesis is made with the driving simulator study in the following section C.

8 Conclusion

8.1 Synthesis between sections

The ex-post evaluation focused on the performance of rush-hour lanes and pluslanes. 5 rush-hour lane sections and 5 pluslane sections are proven to be suitable for this research. Data of these sections was collected and filtered for this purpose.
In the first part of this section, the performance of a rush-hour lane is compared with a regular right lane and the performance of a pluslane is compared with a regular left lane. Also, the differences in performance of different locations at rush-hour lane and pluslane sections are analyzed.
The second part focused on the design factors that cause differences in performance. The three design factors that are tested are: the lane width, the speed limit and the total number of lanes.
The last part compared the best performing rush-hour lane with the best performing pluslane to give an advice to the preferred managed lane.

The rush-hour lane at the A50 between junction Ewijk and junction Valburg was also analyzed in this first part. This rush-hour lane section will be designed in the driving simulator to find the behavioral factors that underlie the results in the next section. Lane changing behavior and car following behavior are the microscopic indicators that link to the macroscopic performance indicators as used throughout this section.
The results are also used to make the virtual cars in the driving simulator behave realistically. This means that the same occupation rates will be used and that the speeds driven on the lanes will resemble speeds driven in reality.
The driving simulator study is set up in such a way that a change in the layout of rush-hour lanes can be analyzed for performance. Two design changes are analyzed for their influence on the occupation of the rush-hour lane: reduced signaling and broken markings.

8.2 Answering the sub-questions

To recap, the sub-questions for the ex-post evaluation are:

A1 - What is the performance of a rush-hour lane compared to a regular right lane?

A2 - What is the performance of a pluslane compared to a regular left lane?

A3 - What is the performance of different locations at rush-hour lane and pluslane sections?

A4 - What is the performance of a rush-hour lane compared to a pluslane?

B1 - What are the underlying design factors causing the differences in performance?

In this chapter, answers will be given to these sub-questions by confirming or rejecting hypotheses as stated in the previous chapters.

A1 - What is the performance of a rush-hour lane compared to a regular right lane?

Hypothesis 1: Speeds of traffic driving at a rush-hour lane section are structurally lower than speeds driven on a section with 3 regular lanes

Confirmed

Adding a rush-hour lane to a section with 2 regular lanes, making the configuration 2+1, mainly has an influence on the speeds driven at the left lane and the middle lane. Speeds driven on these lanes are minimally 5% lower than on a section with 3 regular lanes. Speeds on the rush-hour lane highly depend on the truck percentage at the analyzed section. Speeds are between 5% and 12% lower at a rush-hour lane. When a speed limit of 120 km/h is applied, speed differences are more substantial. At the middle lane, speeds are 10% lower and at the left lane, speeds are up to 14% lower at the rush-hour lane section.

Hypothesis 2: Traffic makes significantly less use of the rush-hour lane compared to a regular right lane

Confirmed

Two rush-hour lane sections where analyzed for this purpose. Both perform worse than a regular right lane. At lower intensities the difference in flow fraction can be as high as 120%. At higher intensities, the difference is approximately 15%.

The flow fraction at the middle lane is higher than the flow fraction at all rush-hour lanes for all intensity levels. This shows a natural dislike of traffic to make use of the rush-hour lane.

A2 - What is the performance of a pluslane compared to a regular left lane?

To answer this research question, two hypotheses where tested. The prove or disprove of these hypotheses will be treated separately here.

Hypothesis 3: Speeds of traffic driving at a pluslane section are structurally lower than speeds driven on a section with 3 regular lanes

Rejected

The differences in speeds are between 3% and 4% on the middle and right lane when comparing a section with 3 regular lanes with a pluslane section. At the pluslane, speed differences can be neglected at higher intensity levels. At lower intensity levels, differences are also 4%.
Speed limits are not well-respected in free-flow conditions for both tested sections.

Hypothesis 4: Traffic makes significantly less use of the pluslane compared to a regular left lane

Confirmed for low intensities

Flow rates are up to 30% lower for pluslanes, compared to a regular left lane. These differences, however, only occur at lower intensity levels. This difference is probably caused by slightly lower speeds on the pluslane. At higher intensity levels, flow rates at the pluslane are comparable with flow rates of a regular left lane. At one section, flow rates are up to 5% higher at the pluslane.

A3 - What is the performance of different locations at rush-hour lane and pluslane sections?

To answer this research question, four hypotheses where tested. The prove or disprove of these hypotheses will be treated separately here.

Hypothesis 5: Traffic makes significantly less use of the rush-hour lane at the start and the end of the section compared to a turbulence-free section.

Undecided

As not much information was available of the lay-outs at start and end sections of the rush-hour lanes, the research cannot prove the hypothesis. Results indicate that the lay-out influences the occupation rates much. At the rush-hour lanes it can be seen that at a start section where the rush-hour lane starts after an on-ramp, occupation rates are significantly lower than occupation rates at a turbulence-free section. At a section where the rush-hour lane starts before an on-ramp or ends before an off-ramp, occupation rates are higher than a turbulence free section.

Hypothesis 6: Traffic makes significantly less use of the pluslane at the start and the end of the section compared to a turbulence-free section.

Undecided

As not much information was available of the lay-outs at start and end sections of the rush-hour lanes, the research cannot prove the hypothesis. Data from start and end detectors at pluslanes show indecisive results. More detailed research should be performed to prove or disprove this hypothesis. It can be concluded that more research needs to be performed to answer this research question. For further information, see chapter 15.

A4 - What is the performance of a rush-hour lane compared to a pluslane?

To answer this research question, two hypotheses where tested. The prove or disprove of these hypotheses will be treated separately here.

Hypothesis 19: A pluslane section performs better than a rush-hour lane section regarding the speeds driven on the different lanes.

Rejected

Speeds driven on the best performing rush-hour lane section do not differ significantly from the speeds driven on the best performing pluslane section. The maximum relative difference is 4%.

Hypothesis 20: A pluslane section performs better than a rush-hour lane section regarding the occupation of the lanes.

Confirmed

The occupation rates of the best performing pluslane are compared with the occupation rates of a regular left lane. The differences are not significant. Pluslanes are only less occupied at low intensities.

The occupation rates of the best performing rush-hour lane are compared with the occupation rates of a regular left lane. The differences lie between 15% and 30%. At low intensities, differences are slightly higher than at high intensities.

B1 - What are the underlying design factors causing the differences in performance?

To answer this research question, twelve hypotheses where tested. The prove or disprove of these hypotheses will be treated separately here. At first, the hypotheses concerning rush-hour lanes will be discussed. Subsequently, the hypotheses concerning pluslanes will be discussed. Three design factors where tested in this research: lane width, total number of lanes and speed limit.

Rush-hour lanes

Hypothesis 7: If the total number of lanes increases, the occupancy of a section with a rush-hour lane decreases.

Confirmed for lower intensities

Intensity shares of the section with 4 lanes are comparable to intensity shares of sections with 3 lanes at higher intensity levels. At lower intensity levels, the section with 4 lanes show up to 30% lower intensity shares.

Hypothesis 8: If the total number of lanes increases, the speeds driven on a section with a rush-hour lane will not change.

Confirmed

Speeds driven on the rush-hour lane at a section with 4 lanes are the same as speeds driven on the section with 3 lanes between junction Hoevelaken and junction Barneveld.

Hypothesis 9: If the lane width decreases, the occupancy of a section with a rush-hour lane decreases.

Undecided

Two rush-hour lane sections had a smaller lane width: the A2 between junction Kerensheide and junction Vonderen and the A2 between junction Vonderen and junction Kerensheide. They both show highest occupation rates when compared to the other rush-hour lane setions. In that sense, lane width does not influence the occupation rates. When both sections are compared, however, the section with a lane width of 3,28 shows approximately 10% lower flow rates than the section with a lane width of 3,35 m.

Hypothesis 10: If the lane width decreases, the speeds driven on a section with a rush-hour lane will become structurally lower.

Undecided

At higher intensity levels, speeds driven on the section at the A2 with the smaller lane width are up to 7% lower than speeds driven on the A2 with a wider rush-hour lane. As lane widths do not differ that much (3,28 m compared to 3,35 m), the hypothesis cannot be proven by this research alone. It does, however, give an indication of the influence of lane width, as all other factors between the two sections are the same.

Hypothesis 11: If a speed restriction is set on a section with a rush-hour lane, the occupancy decreases.

Rejected

Occupation rates are lowest on the rush-hour lane section with the highest speed limit of 120 km/h. All other sections have speed limits of 100 km/h when the rush-hour lane is opened. Occupation rates are at least 20% higher at high intensity levels. Occupation rates at the section with a 120 km/h speed limit are not influenced by the intensity level. They remain constant at a rate of 17%.

Hypothesis 12: If a speed restriction is set on sections with a rush-hour lane, speeds will decrease proportionally to this speed limit.

Rejected

The speeds driven on the rush-hour lane are highly affected by the truck percentage on the section. The section with the highest speed limit has the lowest driven speeds.

Pluslanes

Hypothesis 13: If the total number of lanes increases, the occupancy of a section with a pluslane decreases.

Confirmed for low intensities

Occupancy is in this sense defined as the intensity share. The intensity share is comparable with the pluslane at the A12 between junction Zoetermeer and junction Gouwe. At higher intensity levels, the intensity share is between 10% and 30% higher at the pluslane with 4 total lanes. The lower intensity shares at the section with 4 lanes are caused by the combination of a high speed limit with a narrow lane width rather than the addition of an extra lane, as is also the case at the A12 section.

Hypothesis 14: If the total number of lanes increases, the speeds driven on a section with a pluslane will not change.

Rejected

Speeds driven on a pluslane at a section with a total of 4 lanes are structurally higher than speeds driven on a pluslane at sections with a total of 3 lanes. The increase is approximately 10%.

Hypothesis 15: If the lane width decreases, the occupancy of a section with a pluslane decreases.

Confirmed, combined with hypothesis 17

It cannot be said that a decrease in lane width alone has a big influence on the occupation. A combination of the lane width and the speed limit, however, does have a big influence on the occupation rates of the pluslanes. Flow rates can drop up to 60% and drop at least 30% when a section with speed limit of 100 km/h and a lane width of 3,10 is compared to a section with a speed limit of 100 km/h and a lane width of 2,75. Occupation rates stay the same when the same section with 100 km/h speed limit and a lane width of 3,10 m is compared to a section with a speed limit of 80 km/h and a lane width of 2,70 m.

Hypothesis 16: If the lane width decreases, the speeds driven on a section with a pluslane will become structurally lower.

Undecided

Speeds driven on a section with a lane width of 2,75 are up to 4% lower at high intensity levels when compared to a section with the same speed limit and a lane width of 3,10 m. This difference is too small to indicate structural lower speeds.

Hypothesis 17: If a speed restriction is set on a section with a pluslane, the occupancy decreases.

Confirmed, combined with hypothesis 15

It cannot be said that the speed limit alone has a big influence on the occupation. A combination of the lane width and the speed limit, however, does have a big influence on the occupation rates of the pluslanes. Flow rates can drop up to 60% and drop at least 30% when a section with speed limit of 100 km/h and a lane width of 3,10 is compared to a section with a speed limit of 100 km/h and a lane width of 2,75. Occupation rates stay the same when the same section with 100 km/h speed limit and a lane width of 3,10 m is compared to a section with a speed limit of 80 km/h and a lane width of 2,70 m.

Hypothesis 18: If a speed restriction is set on sections with a pluslane, speeds will decrease proportionally to this speed limit.

Partially confirmed

At high intensities, the speeds driven on the pluslane with a speed limit of 80 km/h are approximately 20% lower than speeds driven on the pluslane sections with a speed limit of 100 km/h. This is proportionally to the speed limit, as the decrease in speed from 100 km/h to 80 km/h is also 20%. However, at the middle lane and right lane, speeds are up to 10% higher on the section with the 80 km/h speed limit and those speeds therefore do not change proportionally to the speed limit.

8.3 Conclusion

Conclusions regarding performance

A pluslane shows the same occupation rates when compared to a regular left lane. Rush-hour lanes show a minimum of 15% lower occupation rates when compared to a regular right lane. At lower intensity rates, both rush-hour lanes and pluslanes show lower occupation rates. This is caused by the natural dislike of traffic to make use of the rush-hour lane and by speed differences at the pluslane.

Speeds driven on sections with a pluslane are not structurally lower than speeds driven on a section with 3 regular lanes. Speeds driven on a rush-hour lane section do not differ significantly from speeds driven on a pluslane section. Speeds driven at rush-hour lanes are highly affected by the truck percentage.

In this research, the differences in occupation rates between start and end locations at rush-hour lane and pluslane sections could not be confirmed. See chapter 15 for recommendations about further research that can be performed on this subject.

Differences in speeds can neglected when comparing the best-performing pluslane section to the best-performing rush-hour lane section.

Conclusions regarding design factors

Regarding rush-hour lanes, it can be concluded that the speed limit as a design factor has the highest influence on the performance. The rush-hour lane section with the highest speed limit of 120 km/h performs the worst of all sections.

Adding an extra lane to the cross section (making it 3+1) has a negative influence on the occupation of the rush-hour lane at low intensities. At high intensities, no significant differences were found. Adding an extra lane does not influence the speeds driven on rush-hour lanes.

The influence of lane width on performance cannot be proven in this research. The research does, however, give an indication about the negative influence of smaller lane widths on both occupation as well as speeds.

Regarding pluslanes, it can be concluded that adding a lane to the cross section (making it 3+1) has a negative influence on the intensity shares of pluslanes at low intensities. At high intensities, no significant differences were found. Adding a lane increases speeds driven at the pluslane with 10%.

Also, a high speed limit in combination with a narrow lane width has a negative influence on the performance of pluslanes. Narrow lane widths in combination with low speed limits (80 km/h) do not have a negative influence on performance. Also high speed limits (100 km/h) in combination with wide lanes do not have a negative influence on performance.

Section C

Driving simulator study

9 Experimental setup

9.1 Introduction

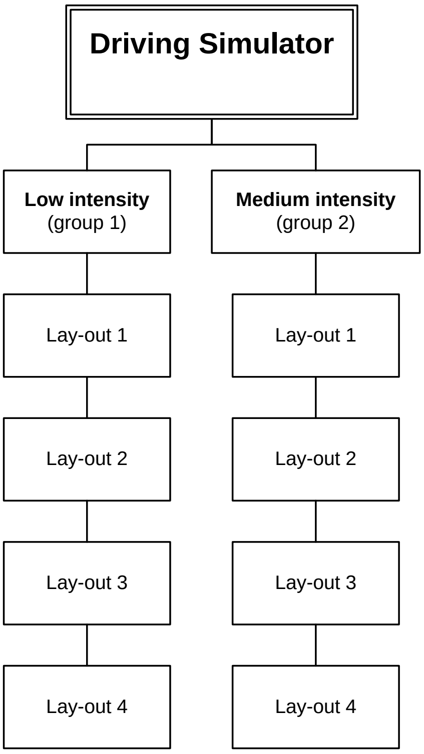
To gain detailed insight in the behavior of drivers on road sections with rush-hour lanes or pluslanes, detailed data is needed. As it was not possible to obtain disaggregated detector data nor was it possible to obtain camera data, the best way to get detailed data is to make use of a driving simulator. In this research, the use of a driving simulator is particularly beneficial, because different non-existent design factors have to be separately researched:

- the influence of markings on driving behavior
- the influence of the signaling system on driving behavior

Note here that the factor 'lane width' is left out of the research. The main reason for this is that the amount of needed participants for significant data would be too much for this thesis. Also, a lot of research is already performed on the subject albeit not in combination with rush-hour lanes. The experience of Raymond Hoogendoorn with driving simulator studies helped in defining the different sub phases. Because of feasibility reasons, the driving simulator tests will be performed with less detail as initially was planned. This results in a driving simulator test that only makes use of road sections with a rush-hour lane. For the driving simulator study, all factors should be the same for all participants, except for the experimental variable. In this case, the main variable is the lay-out of the rush-hour lane. The 4 lay-outs are:

1) Regular signaling with continuous markings
2) Regular signaling with broken markings
3) Decreased signaling with continuous markings
4) Decreased signaling with broken markings

Each participant will drive through 4 sections and each section contains a different rush-hour lane lay-out. An extra variable that is very important in this research is the difference in intensity. As it is assumed infeasible to create 8 different lay-outs and thus designing both factors (lay-out and intensity) as 'within participant'-factors, intensity will be designed as a 'between participant'-factor. This creates the scheme in Figure 9.1 for the driving simulator study to be performed:



	Lay-out					
	Signaling		Markings		Intensities	
	Reg.	Dec.	Cont.	Broken	Medium	High
Alternative 1	1	2	3	4	x	
Alternative 2	1	2	4	3	x	
Alternative 3	1	3	2	4	x	
Alternative 4	1	3	4	2	x	
Alternative 5	1	4	2	3	x	
Alternative 6	1	4	3	2	x	
Alternative 7	1	2	3	4		x
Alternative 8	1	2	4	3		x
Alternative 9	1	3	2	4		x
Alternative 10	1	3	4	2		x
Alternative 11	1	4	2	3		x
Alternative 12	1	4	3	2		x

Figure 9.1:Left: setup of the driving simulator study. Right: different alternatives as used in the driving simulator study

To prevent learning effects, counterbalancing is done by randomizing the order of the different lay-outs. In the scheme of Figure 9.1, the different alternatives are organized on the right. As can be seen, all participants are given the 'zero alternative' as the first drive. Intensities are organized as a 'between participants' variable, as also can be seen in Figure 9.1. This means that the first 6 participants all get low intensity and the second 6 participants get medium intensity etc. These intensity levels will later be used to compare the results from the driving simulator with the results from the ex-post evaluation.

As can be seen, 12 alternatives needed to be created in the driving simulator (6 of them have different design orders and the other 6 have the same orders but other scenarios). As the different lay-outs could not be drawn in one 3D-environment, every lay-out is created separately. Participants will drive one lay-out from start to end and then the next lay-out is loaded for them. This has the advantage that participants have a break between the different lay-outs. Also, only 4 different lay-outs needed to be created, as the order of loading them in can be changed for each participant.

The performance indicators that will be tested have been mentioned before in the ex-post evaluation (see Section B):

Table 9-1: Macroscopic- and microscopic performance indicators

Macro	Micro
Speeds	- Speeds per lane
Lane flow distributions	- Lane changes from and to the different lanes - Headways on the different lanes

These indicators are derived directly from the literature review (see section A). The influence of different lay-outs on the microscopic indicators will be tested in the driving simulator study. Also, the data is compared with the macroscopic data from the ex-post evaluation.
This phase of the project is divided into five sub-phases

- Creating the designs of road sections
- Programming the driving simulator
- Pilot-study
- Performing the simulations
- Analyzing the data

All these sub-phases will be discussed in the following paragraphs of this chapter.

The **goals** for this phase are:

- *To recreate an existing rush-hour lane section as realistically as possible*
- *To validate the data of the created rush-hour lane with data of the existing one*
- *To analyze the underlying behavioral aspects that cause differences in performance*
- *To create alternative lay-outs of rush-hour lanes in the simulator and analyze their performance*

9.2 The driving simulator

The description of the driving simulator is taken from (Hoogendoorn, 2012a).

The driving simulator used for this thesis consists of three screens that are placed at an angle of 120 degrees, a driver's seat mock-up and hardware and software interfacing of this mock-up to a central computer system. This central computer system consists of two personal computers that are connected through a Local Area Network (LAN). One of them has a controller with a Graphical User Interface and the other one is the Traffic personal computer.

From the driver's seat, the view of the driving environment consists of a projection of in total 210 degrees horizontally and 45 degrees vertically. The used software was developed by StSoftware. The software consists of several modules, namely: StRoadDesign, StScenario, StControl, StTraffic and StRender.

The driving environments are designed with StRoadDesign. This tool generates a geometrically correlated graphical and logical database required for the traffic module and the graphical rendering module.

The actual test drives are generated with StScenario. StScenario makes use of a scripting language. This scenario controls the module StControl, which provides control over the simulation module StTraffic. StTraffic finally computes the dynamic traffic system based on intelligent agents based technology. During the test drives, the graphics are rendered through StRender at a 60 fps frame rate.

9.3 Creating designs of road sections

From the road sections used in the ex-post evaluation, one road section containing a rush-hour lane was selected based on the following criteria:

- The stretch's length shouldn't be too long, as participants don't want to spend a lot of time on the highway section
- The stretch should contain at least one junction in between the start and the end junction
- The stretch should contain as less disturbing factors as possible (i.e. regular lane width, no speed limit, 2+1 lay-out)

The road section that perfectly fits all of these criteria is the rush-hour lane at the A50 between junction Ewijk and junction Valburg (see Figure 9.2).

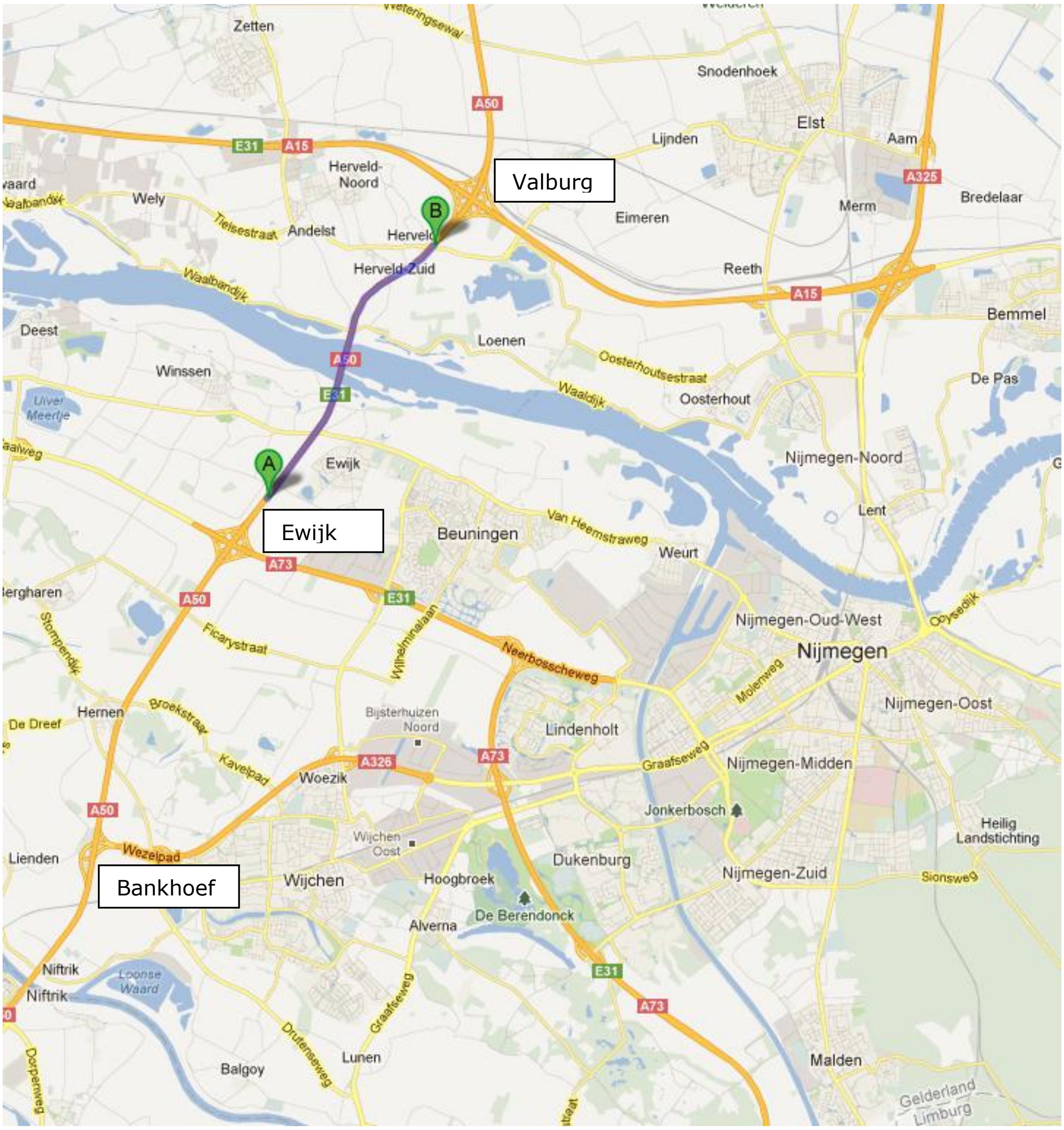


Figure 9.2: The A50 between junction Bankhoef and junction Valburg (source: maps.google.com)

The length of the rush-hour lane section is approximately 5 km. This road section should be designed in the driving simulator as realistically as possible. This means that the length, the lane widths, markings and signaling should all resemble the real life situation as close as possible. This design can be created using a 3D-modeling program. To let the participants get used to the simulator, the highway section before the rush-hour lane will also be created (between junction Bankhoef and junction Ewijk). This way, the participants will drive a total of approximately 10 km per lay-out.

The designs for the tests should also be made. A setup with both pluslane and rush-hour lanes is considered infeasible for the thesis and the choice is made to reduce the total number of tests by only testing the two factors 'influence of markings' and 'influence of signaling' for rush-hour lanes. Figure 9.3 shows the tests that need to be performed.

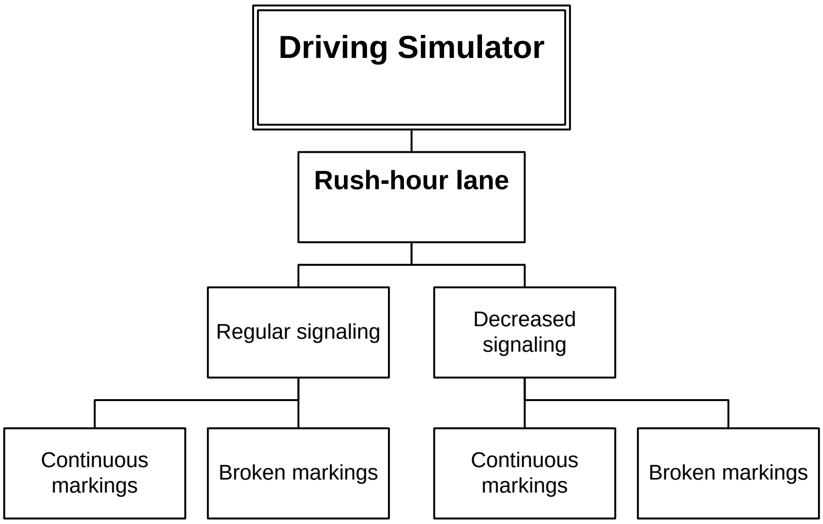


Figure 9.3: Driving simulator setup

As can be seen, four combinations are needed in the test. The initial idea was to divide the total number of participants into 2 groups that have different signaling systems as can be seen in Figure 9.3. This was done to cope with the problem that participants 'get used' to the scope of the research. However, the division into 2 groups leads to statistical problems, because the behavior between the groups can be very different. Therefore, only one group will be tested and all participants will drive through all 4 combinations of design elements (regular/decreased signaling and continuous/broken markings).
To cope with the 'getting used to the scope'-problem, the 4 sections with rush-hour lanes will be mixed for the different participants (counterbalancing). This way, the order of the 4 combinations between different signaling and markings will be different between participants.

The program StRoadDesign is used for the purpose of designing the simulated environment. This program is created by the company StSoftware in 1992 (Hoogendoorn, 2012a). The design is created by following 4 steps:

1. Investigating the A50
2. Creating a rough outline
3. Creating the surroundings
4. Creating the road signs

9.3.1 Investigating the A50

The A50 between junction Bankhoef and junction Valburg will be designed into the driving simulator. To gain information about the characteristics of this highway section, a combination of information sources is used. The coordinates of the highway are measured in the program Jedi that was also used in the ex-post evaluation. In this program, all roads are drawn using the RD- ("Rijksdriehoeks-") coordinate system. These coordinates can be used to make a replication of the A50 in the driving simulator. The coordinates are converted in such a way that the end of the onramp at Bankhoef will be situated at x,y = (0,0). The more detailed investigation will be explained at sections 3 and 4.

9.3.2 Creating a rough outline

Using the program StRoadDesign, the lay-out is built up of segments. As the program demands these segments to be connected with the same angles, some conversions from the original, measured coordinates had to be made. Especially when arcs were created, the program created its own coordinates. The translation is relatively small, however, if the original coordinate will be used for the next straight section, deviations in the lay-out will occur. To keep the lay-out as realistic as possible, the original coordinates of the next sections (after a corner) will be transformed to the new end-coordinate of the drawn corner.

All 4 layouts are made from this base design. The first section consists of a part of 6 kilometers of regular highway. Participants can get used to driving in the driving simulator in this area before driving onto the highway section with a rush-hour lane.

The length of the total section is approximately 10 km. The speed limit is 120 km/h for the whole section. Assuming an average speed of 100 km/h on the section, drivers will spend 7,2 minutes on the section. During the whole simulation, the section will be opened 4 times to let the participants experience the 4 alternative lay-outs. This means the total highway-time will add up to 28,8 minutes. In practice, the runs take an average of approximately 6 minutes each. It has to be taken into account here that participants wait approximately 1 minute before driving to let the traffic feeder produce enough traffic.

The biggest problem in designing the section into the driving simulator is the transition from regular shoulder to rush-hour lane. The shoulder is a lane that can't be driven. For programming it is not possible to assign traffic to the shoulder lane. Making it a regular lane with shoulder markings could bring a solution here. This, however, still brings the problem of the first off-ramp that starts the rush-hour lane. It is impossible to design road widening into StRoadDesign. As 2 drivable lanes should be converted to 3, this gives problems. Creating a connecting node doesn't solve this problem as the driving simulator then sees the splitted road as two separated carriageways.

Another solution is given by connecting a road section with 3 lanes and no shoulder to a prior road section with 2 lanes and a shoulder. By adjusting the markings and lane widths, the transition can hardly be seen in the driving simulator. This, however, raises another big problem. It all seems to work fine, but when a saved project is opened again, the program crashes! When saving the project, the program reconnects the two road segments in a wrong way. The left lane of the first segment is linked to the middle lane of the second segment and the right lane of the first is linked to the right lane of the second. Figure 9.5 shows the problem.

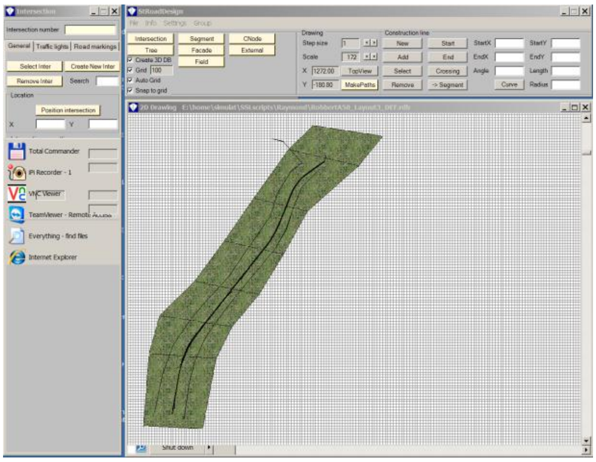


Figure 9.4: Overview of StRoadDesign

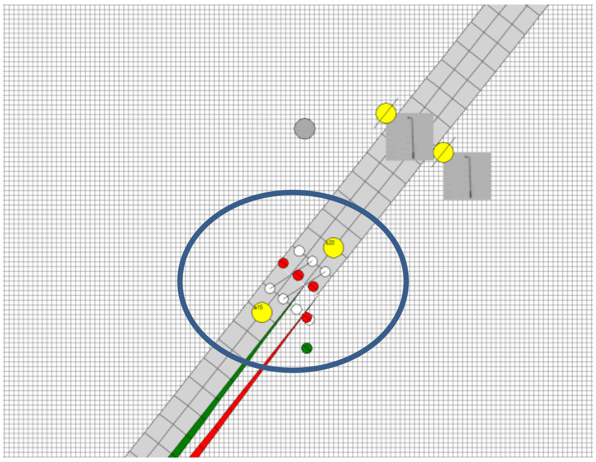


Figure 9.5: Logical connection problem in StRoadDesign

In the end all these extra measures to fit the 4 layouts together turned out to be useless, as they all resulted in malfunctioning simulations. The final solution was therefore to create 4 separate lay-outs. The problem of connecting a regular road section with 2 lanes and a hard shoulder (the regular highway section) to a new road section with 3 lanes and no hard shoulder (the section with the rush-hour lane) did work when it was applied in a small stretch. The only thing that went wrong was the fact that the last segment did not show up in the simulation and therefore the total length of the rush-hour lane section was reduced.

9.3.3 Creating the surroundings

The highway section is drawn in one direction, so no upcoming traffic is simulated. In StRoadDesign it is possible to add trees, light poles, barriers, etc. to the design. The design of this simulation is kept as simple as possible to reduce distractions. To prevent participants from getting bored, some extra features were added. At the beginning, a meaningless portal is added. After a while, the participants gets to an off-ramp that is indicated with a standard off-ramp sign ('Oostdorp'). Just before the rush-hour lane section, an on-ramp is added. This on-ramp is also present at the real A50. In Figure 9.6, a screenshot is shown of the start of the simulation. Figure 9.7 displays the beginning of the rush-hour lane section, including a comparison with the real situation in Figure 9.8.

Figure 9.6: Overview of driving simulator screen

Figure 9.7: Start of rush-hour lane section in the driving simulator

Figure 9.8: Start of rush-hour lane section in reality

9.3.4 Assumptions in design

As mentioned before, designing the driving simulator was done with the program *StRoadDesign* by StSoftware. The program lets the user create 2D environments that are rendered into 3D environments for the driving simulator. The basics of the program are easy to learn, however, the program has a lot of bugs that reduce the realism of the lay-outs. These bugs, amongst other things, have led to a number of assumptions in the design of the different lay-outs.

Markings do not align
At the start of the rush-hour lane section, a portal is located with 3 green signs and an extra sign that says 'rush-hour lane opened' is displayed. However, the markings at the start of the rush-hour lane do not align with each other. This may lead to a distraction by the participant, causing him or her to miss the information about the rush-hour lane. Several attempts have been made to align the markings at this location, but it seemed to be impossible. Also, it was considered more important to keep the lane widths of all lanes at the rush-hour lane constant and in line with reality (all 3,50 m). To align the markings, the lane widths of the preceding section in StRoadDesign were changed numerous times, without the desired result.

Matrix signs bigger than in reality
The 3 green-arrow matrix signs that are present at each portal in the different lay-outs are bigger than in reality. To be more precise: the green arrows are bigger than in reality. This was noticed by Rudi Kraaijeveld in the Pilot-study. It can influence the behavior of participants as the information they get will be clearer than in reality. This only affects the comparison of the driving simulator data with the real data. The comparisons between the different lay-outs will be unaffected.

Shorter rush-hour lane section
The rush-hour lane section is shorter than in reality. This is due to a bug in *StRoadDesign*. The last segment that was drawn into the program seemed to connect perfectly to the preceding segment, however, when rendered into a 3D environment the last segment disappeared completely. Added portals and signs stayed where they were, but the roadway was missing. The choice is then made to remove the segment and also remove the 'end of rush-hour lane'-sign. This means that the comparison of driving simulator data with real data cannot be compared at the end of the rush-hour lane.
Another downside of this bug is the fact that the ratio between lengths of the preceding part of regular highway and the part with the rush-hour lane is off. Participants will drive a relatively long time on the regular highway. This may lead to boredom of the participant. It is assumed that the effect of this will not be noticeable in the behavior of participants.

9.4 Programming

Within this step, the standard routines of Raymond Hoogendoorn will be used. They are altered to be made applicable for this project. The main focus point of programming the driving simulator was to create a realistic driving experience for the group of test persons.

This, however, creates the well-known problem that computer controlled cars have to behave realistically at the rush-hour lane sections, but the behavior at this rush-hour lane is a big part of this research and thus not yet known. In the beginning of the ex-post evaluation the representative road section is researched (see paragraph 7.1.1). The information about this road section can be used to program the behavior in the driving simulator.

The standard routines of Raymond Hoogendoorn are altered. They produce cars with different speeds, but use the standard lane changing / car following model from the simulator. Cars created with this model tend to stick left when overtaking. This has the disadvantage that a virtual car driving on the left overtakes very slowly or not at all. The two involved cars block the whole carriageway.

The program is altered to make sure that cars on the left overtake faster. The rules of the lane changing model that is created in this way are quite simple:

1) When driving on the right: If the distance to your first leading vehicle is smaller than a certain threshold (desire to change lanes) and the distance between the first rear on your left and the first leader on your right is above a certain threshold (gap acceptance) you should move to the left lane
2) When driving on the left lane: Accelerate up to 130 km/h to overtake the first vehicle on the right. Check if the gap between the first rear vehicle on the right and the first lead vehicle on the right is above a certain threshold (gap acceptance)

As the thresholds in the program are tweaked according to the behavior at tests, they do not represent any real life value. The values were first assumed to represent meters (for example: Participant[i].DisToFirstRearOnRightLane = 3 means distance to first rear on right lane is 3 meters), however, at the tests this turned out to be not the case.

This simple model did improve the speed of the overtaking maneuvers.

The intensities that are generated at the feeder are gained from the lane flow distribution as seen in the appendix 22. It contains data of a turbulence-free detector at the A50 section between junction Ewijk and junction Valburg.

Traffic is generated at two feeders, the first one generates the traffic of the left and middle lane (initially the left and right lane), the second one generates the traffic at the rush-hour lane. The intensity can be controlled by setting the 'in-between-time' (in other words: the time headway) of generated vehicles. The assumption is made that 75% of traffic used left and middle lanes and 25% uses the rush-hour lane at both intensities (see also paragraph 9.4.1). At the intensity level of 3000 veh/h, this gives an in-between time of 1.6 s (intensity of 2250 veh/h) for the first feeder and 4.8 s (intensity of 750 veh/h) for the second feeder. At the intensity level of 4000 veh/h, the in-between times are respectively 1.2 s (intensity level of 3000 veh/h) and 3.6 s (intensity level of 1000 veh/h) for feeder 1 and feeder 2.

Figure 7.7 shows a plot of the lane flow distribution at a reliable detector with no turbulence. As can be seen, the average percentage of occupancy at the rush-hour lane is about 18% in these graphs.

Speeds are programmed into the driving simulator according to the intensity-speed distributions as shown in Figure 7.3. These are derived at the ex-post evaluation for the rush-hour lane section at the A50. As can be seen, the average speed at the rush-hour lane is about 95 km/h, at the middle lane it is about 100 km/h and at the left lane between 115 and 120 km/h.

As mentioned before, a lane changing model was programmed into the simulator. This model was made to force the speeds to the virtual traffic. In practise, however, speeds turn out to be fairly constant and about 115 km/h for the middle lane, 120 km/h for the left lane and 95 km/h for the rush-hour lane. The downside of these speeds is the small speed difference between left lane and middle lane, causing overtaking maneuvres to take some time.

9.4.1 Assumptions in programming

Due to combinations between the design limitations in *StRoadDesign* and the limitations of the programming of virtual traffic scenarios, some assumptions had to be made.

Intensity levels

The intensity levels used for the simulations are 3000 veh/h ('low') and 4000 veh/h ('medium'). The idea at first was to increase the 'medium' intensity to 4500 veh/h, but this caused vehicles to behave unrealistically. The difference between the two levels of intensity is therefore smaller than originally intended.

Also, the ratio between the intensity of traffic on the rush-hour lane and traffic on the other two lanes is 25% / 75%, whereas measurements of the real situation show a distribution that is closer to 18% / 82% (see appendix 22). The problem with programming this ratio into the driving simulator is the assumption that no virtual traffic makes lane changes from and to the rush-hour lane.

A big problem with programming the intensity levels is the fact that some programmed vehicles are leaving the highway on the offramp that is meant to represent junction 'Ewijk'. Planning the whole route for each vehicle did not help. Also, using the command 'route := straight' at every segment did not change a thing. The downside of this weird bug in the programming is that it decreases the intensity of the traffic generated by feeder 1. The ratio between traffic on the left and middle lanes and the rush-hour lane is therefore different than in reality. As the amount of cars leaving the highway changes every simulation run, the difference in intensities is different for each participant. This highly influences the results.

Traffic drives only at the left lane at the beginning of rush-hour lane

At the section just before the start of the rush-hour lane, traffic is assigned a preferred lane of '1'. In the programming language this means all traffic prefers to drive in the left lane. This is done deliberately to separate traffic on the rush-hour lane from traffic on the other 2 lanes (left and middle). As traffic on the rush-hour lane has a preferred lane of '0' during the whole simulation (they all keep right, also see assumption 'Constant intensity at rush-hour lane') adding a rule to all traffic driving left separates the two traffic feeders. At first this was tried by putting one feeder into a list of virtual traffic, but this didn't work.

A lot of participants notice the weird behavior at the start of the rush-hour lane. It can have a negative effect in two ways:

- It can distract the participant from the first portal with green arrows and the first sign 'rush-hour lane opened'
- It can 'force' the participant to also move to the left lane as he or she is mimicking the behavior of the other traffic. This can prevent them from making the change to the rush-hour lane further in the simulation

No trucks drive at the right lane

The plan was to create half of the traffic created by the feeder at the rush-hour lane as a truck. This was a truck percentage of 12,5% could be reached, which is assumed to be rather low for the A50. As can be seen in appendix 23, the percentage of trucks at the A50 is 30%.

However, the feeder did not produce any trucks. Several tweaks in the types of cars that were produced didn't work. The end result is a feeder that only produces cars that drive with a speed between 90 and 100 km/h. In other words, half of the cars represent the speed of trucks driving in the Netherlands.

This can have a negative effect on the results in that sense that the visual appearance of trucks can make participants ignore the rush-hour lane more. It is assumed that introducing trucks on the rush-hour lane reduces the usage of this lane as people tend to dislike driving behind trucks.

Constant intensity at rush-hour lane

To keep the intensity constant at the rush-hour lane, no lane changing from and to the rush-hour lane is allowed by virtual traffic. The traffic feeder at the rush-hour lane produces cars with a constant in-between time to guarantee constant intensity. Diversity in traffic is created by randomizing the speeds of the traffic generated at the rush-hour lane. This creates platoons and gaps on the rush-hour lane.

The downside of this decision is the fact that traffic on the other lanes can behave counter-intuitive. In practice it seems to behave rather realistically in the sense that participants only meet a few virtual cars on the rush-hour lane section. If the virtual cars 'decide' not to use a big gap at the rush-hour lane it is still considered realistic.

Slow overtaking

By forcing traffic to drive 130 km/h on the left lane, the plan was to get rid of 'left-sticking' traffic. This forcing, however, did not work. The lane changing model that is created for this simulation did increase the speed driven on the left lane, but still the speed difference between an overtaking car and the car on the right lane can be rather small. Overtaking maneuvers can therefore take a frustrating amount of time. Also, the speed of the middle lane is at an average of 115 km/h. The difference between the speeds at the rush-hour lane (appr. 95 km/h) is therefore rather big. This fact influences the usage of the rush-hour lane. Participants tend to stay at the middle lane longer because of the higher speeds.

Excessive brake lighting

Some virtual vehicles tend to use their brake lights very often. It can be confusing for a participant. In practice it has never occurred at the rush-hour lane section, so it is assumed not to affect the data.

Traffic feeder rush-hour lane

The feeder that generates the traffic driving on the rush-hour lane instantly creates a vehicle at the beginning of the rush-hour lane. This is done to prevent this traffic to first merge into the stream created by feeder 1 and then immediately changing to the rush-hour lane. It is told to the participants that this phenomenon happens. The first 5 seconds of data are removed in MATLAB. Traffic (both virtual, as well as the main participant) is assumed to be stable after that period.

9.5 Pilot-study

Directly after the design and programming phases are completed, a pilot study was carried out. In this study, two experts drove in the simulator to test the realism of the simulation. The first expert is dr. ir. Raymond Hoogendoorn. He performed several researches with the help of the same driving simulator that is used in this research.
The second expert is ir. Rudy Kraaijeveld. As the successor of Bert Helleman at Rijkswaterstaat, Rudi Kraaijeveld is the new expert in the field of managed lanes.
The question they were asked at the end of the simulation run was: 'Did you find the simulation realistic and, if not, what should be changed?'

Raymond Hoogendoorn noticed the traffic using the off-ramp. After telling him that the traffic was all told to drive straight on, he said that this was due to some bug in the core software. He also faced the same problem in one of his researches and did not manage to find the cause of it.
Besides that, he found the simulated vehicles to behave realistically. His advice was to start with the real simulations.

Rudi Kraaijeveld mentioned that the behavior of the vehicles at the rush-hour lane section was realistic. He did see some weird behavior before the rush-hour lane section. This weird behavior is also mentioned in the assumptions in paragraph 9.4.1 and was needed in order for the traffic to behave realistically at the rush-hour lane section.
Furthermore, he mentioned that the matrix signs looked bigger than in reality. This is true, the matrix sign itself is the same size as reality, but the arrow inside the matrix sign is bigger. The sign was created from a google picture. After Rudi noticed it, a search was performed for other, more realistic pictures of the green arrow. These were not found, so the aberrant sign is added to the assumptions section in paragraph 9.3.4.
The last remark was that the transition from the regular highway section to the rush-hour lane section was a bit off. The markings do not align. As the width of the lanes at the rush-hour lane section is considered a priority, the widths of the lanes at the preceding section were changed to align the markings. A lot of different configurations have been tried, but the markings never perfectly aligned. In the definitive version, the markings are used that aligned in the best possible way. As this can have some influence on the behavior of the participant, it is added as an assumption in paragraph 9.3.4.

9.6 Participants

In total, 24 participants have driven the complete simulation. Each participant drove through 4 lay-outs. The only condition that changed for the participants was the intensity: 'low' or 'medium'. In Table 9-2, the information of the participants is organized.

Table 9-2: Descriptives of the participants in the experiment

Conditions	n	Mean age (SD) (years)	Mean driving experience (SD) (years)
Low intensity	12 (10 male, 2 female)	38,08 (13,36)	19,00 (13,36)
Medium intensity	12 (8 male, 4 female)	40,83 (20,58)	20,58 (19,19)

A complete summary of all participants can be found in appendix 24.

9.6.1 Assumptions regarding participants

Ratio male/female not optimal

As can be seen, the ratio male/female overall is 3/1 (67% / 33%). Statistics at (CBS, 2010) show that the normal ratio is between 58% / 42% and 54% / 46% when looking at distance and time travelled per day respectively.

Total number of participants low

A total of 24 people participated in the research. The main reason that the amount of participants is rather low is the fact that it was too time-consuming for this thesis work to make more people drive the simulation. In the end, all 12 alternatives are driven twice.

Filtering of participants

For each participant, the whole simulation is watched for errors. If anything out of the ordinary happened in the simulation, it was noted. Not much went wrong during the simulations. The most important noted aspect was the fact that a large amount of virtual vehicles left the highway and therefore the traffic situation at the rush-hour lane section was far from realistic. For every participant where this happened, data from that layout is filtered out. In appendix 24 it is noted for what participants this was the case.

9.7 Data structure

During the simulations data will be collected of the participant. The driving simulator has a data-collection rate of 10 Hz. The following variables are tracked (the variables in **bold** are used in this research):

- **Time (in seconds from the start of the simulation)**
- **Time interval (in seconds)**
- **Velocity (in m/s)**
- Acceleration (in m/s^2)
- Lateral velocity (in m/s)
- Distance to segment (related to the segment numbers created in StRoadDesign)
- **Lateral position (related to the rightmost part of the highway, including hard shoulder)**
- Segment number (the current segment on which the participant is driving)
- **Path number (the current path on which the participant is driving)**
- Indicated signal (0 if off; 1 if left; 2 if right)
- Steering wheel (in degrees compared to straight)
- Gas (amount of pressure on gas pedal)
- Brake (amount of pressure on brake pedal)
- TLC (Time-to-line crossing, if crossing left edge line sign is positive, if crossing right edge line, sign is negative)
- Distance to intersection (related to intersection numbers created in StRoadDesign
- **Time headway (between the participant and the first leading vehicle)**
- Time to collision (not used in this research)
- Time to collision_opp (not used in this research)
- **Leader distance (distance headway in meters between participant and the first leading vehicle)**
- Leader velocity (velocity in m/s between participant and the first leading vehicle)
- Approacher distance (distance headway in meters between participant and the first approaching vehicle)
- Approacher velocity (velocity in m/s between participant and the first approaching vehicle)
- Yaw rate (the angular velocity around the vertical axis in m/s)
- X-position (x-coordinate of current position of participant)
- Y-position (y-coordinate of current position of participant)

Data is written to so called '.DA0'-files. These files are first opened with StDataProc, a program to process the data. Because the analyses that can be performed with this program are rather limited, the data is converted to ASCII-format. Files are then written to a '.dat'-format that can be opened with WordPad or read by MATLAB.

9.8 Synthesis

The experimental setup in the preceding chapter describes the methodologies used in this part of the research. The driving simulator used in this research is located at the Delft University of Technology. The software for the simulator is developed by StSoftware.

The design in the driving simulator is created with StRoadDesign. The highway section at the A50 between junction Bankhoef and junction Valburg is designed into the driving simulator. To analyze the influence of the signaling repetition and the markings, 4 layouts are created:

1) Regular signaling with continuous markings
2) Regular signaling with broken markings
3) Decreased signaling with continuous markings
4) Decreased signaling with broken markings

Results from the ex-post evaluation are used to program realistic virtual traffic into the driving simulator. The distribution of traffic is derived from the lane flow distributions and the speeds driven on the section are derived from the intensity-speed relations.

For a detailed description of the assumptions that are made in the design and in the programming a reference is made to paragraphs 9.2 and 9.3.

A total of 24 participants drove all 4 layouts in the simulation. Some layouts are filtered out because virtual traffic behaved unrealistically.

The next chapter of this section shows the results of the driving simulator study. The results are sub-divided into 2 paragraphs.

Paragraph 10.1 shows the **behavioral factors** that influence the performance of the rush-hour lane at the A50.

Paragraph 10.2 focuses on possible **changes in the design** of rush-hour lanes. As mentioned before, two factors are tested for their influence on the performance of the rush-hour lane: reduced signaling and broken markings. The influence of these two design factors is covered separately.

10 Results

The driving simulator study is used to give an answer to two research questions in particular. To recap, they are stated again below:

- *What are the underlying **behavioral factors** causing the differences in performance of rush-hour lanes?*
- *What **changes** can be made **to the design** of a rush-hour lane to improve its performance?*

The two parts of the research questions that identify the need of the driving simulator are highlighted: 'behavioral factors' and 'changes in the design'. These two terms are used to organize the results of the study.

To gain insight in the microscopic factors that cause the differences in performance of a rush-hour lane, the data from the driving simulator study is compared with data from the ex-post evaluation. As layout 0 is designed to resemble the real A50 section between junction Ewijk and junction Valburg, a validation of the driving simulator data with data from the A50 section would be a logic step here. However, as mentioned before (see paragraph 9.3.1), the intensity levels vary randomly between participants and are thus not known. Comparing with the real, macroscopic data is therefore not possible. In other words, the goal of validating the data from the driving simulator study with data from the ex-post evaluation is not reached. Behavioral factors and changes in the design will still be researched in the chapter 10.1 and chapter 10.2. The research method is described at the beginning of each chapter.

10.1 Behavioral factors - car-following

The behavioral factors that are still reliable in this research are the distance and time headways of the participants, or, in other words, the car-following behavior of the participants. Car-following behavior is used to test the following hypothesis.

The main hypotheses of this section are:

Hypothesis 21: The incentive of using the rush-hour lane at a speed limit of 120 km/h is low

Analyzing the headways at the 3 lanes gives insight in the car-following behavior. The definition of time headways is gained from (Hoogendoorn, 1998):

A time headway of a vehicle is defined as the period between the passing moment of the preceding vehicle and the vehicle considered

In the driving simulator, the time headway between the participant and the first leading vehicle is recorded 10 times per second during the simulation. As was derived in the literature review, headways are directly related to capacity. The definition of capacity is:

The capacity of a single lane of a road at a specific cross-section is the inverse of the mean time headway of constrained vehicles since it is assumed that, during capacity conditions of a road, all drivers are constrained drivers (Minderhoud, 1996)

This definition shows the importance of the division between drivers in constrained conditions (following) versus drivers in unconstrained conditions (leading). When the time headways are plotted per lane for all participants, the difference between leading and following can be shown (see Figure 10.1).

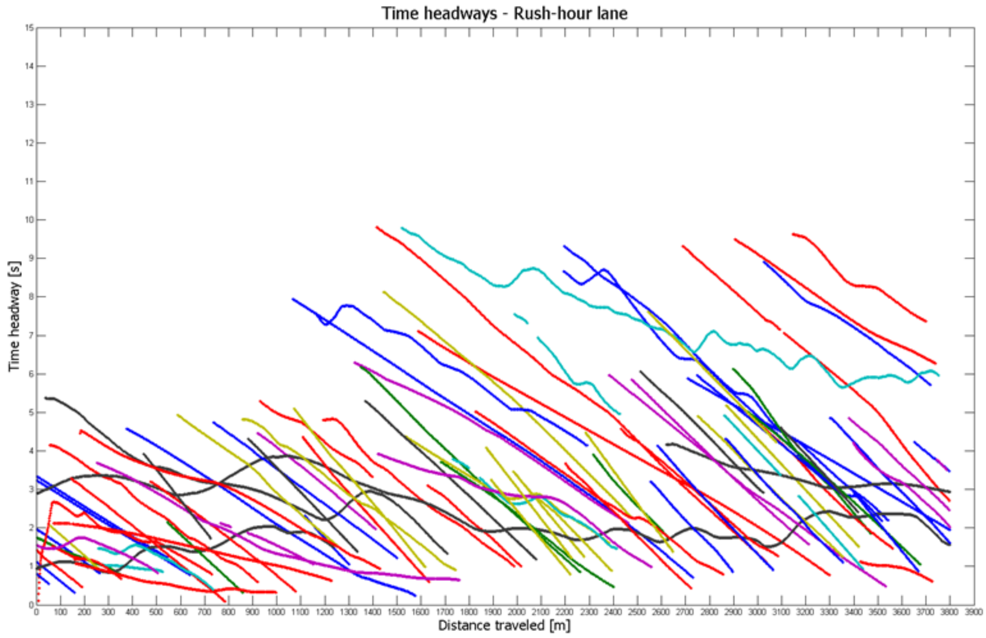


Figure 10.1: Time headways of participants driving at the rush-hour lane

As can be seen from Figure 10.1, two kinds of patterns can be distinguished. Leading vehicles keep a constant speed and their headway therefore decreases linearly with the speed difference between the first leading vehicle. When the time headway becomes too small, a lane change is made to the middle lane. Following vehicles show a different pattern. At first, they are leading vehicles and thus their headway decreases linear. As they approach the first leading vehicle, and a lane change is not possible, they adjust their time headway to a comfortable, desired value. Accelerating and decelerating causes an oscillating pattern in the time headways. From the literature review, this is known as ‘penduling’ (Leutzbach, 1986). Followers adjust their speeds continuously around the desired headway value, even though the leading vehicle has a constant speed.

What also can be seen from Figure 10.1, almost all participants are in leading state when driving at the rush-hour lane. To explain this fact, the main factors influencing car-following and lane-changing behavior should be reviewed. In (Knoop, 2010) it is mentioned that the two main factors influencing a lane change are 1) the desire to change lanes and 2) the possibility to change lanes. These two factors are respectively translated into 1) decision models and 2) gap acceptance models. A well-known decision model is the model of ‘slugs’ and ‘rabbits’ by (Daganzo, 2002). Rabbits have a higher maximum speed (V_f) than slugs (v_f). At free-flow conditions, a so-called ‘2-pipe-regime’ is operational. This can be compared with the situation on the rush-hour lane section. Speeds on the shoulder lane (i.e. the rush-hour lane) are equal to v_f and speeds at the middle lane and left lane are approximately equal to V_f.

Virtual cars at the rush-hour lane drive at an average speed of approximately 95 km/h, whereas the speed limit allows participants to drive 120 km/h. Speeds on the rush-hour lane are gained from the ex-post evaluation and are this low because of the trucks driving on it. In the literature review it is found that the most important factors that influence the lane changing process and therefore the lane flow distributions are the speed limit and the road layout (assuming stable traffic conditions), see Figure 10.2. These two combined determine the desired speed of each participant. As the desired speed for most participants lies higher than the speeds driven on the rush-hour lane, making a lane change to the rush-hour lane will only happen if the desired speed can be maintained for some time. The headway to the first leader after a lane change to the rush-hour lane will therefore be large. The results from the ex-post evaluation also support the hypothesis that the maximum speed (and as a result the desired speed) is an important factor affecting the lane flow distribution. The rush-hour lane section at the A50 between junction Ewijk and junction Valburg has a speed limit of 120 km/h - whereas the other investigated stretches have a limit of 100 km/h - and it has the lowest occupation rates of all rush-hour lane sections.

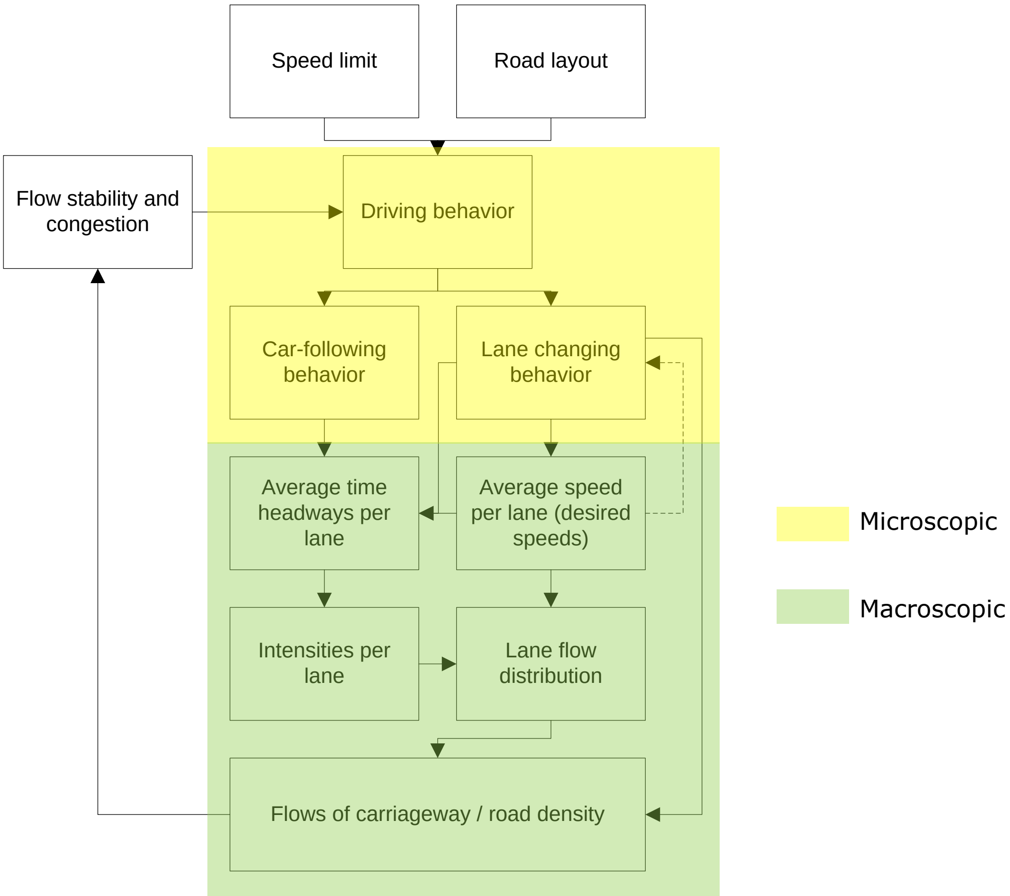


Figure 10.2: Macroscopic- and microscopic performance indicators

10.1.1 Synthesis

The behavioral factors that underlie the results of the ex-post evaluation regarding the rush-hour lane at the A50 are covered in the preceding part. Validation with the real situation was not possible, because the intensity level of the different simulations changed due to random vehicles leaving the highway section. As the validation was not possible, only car-following behavior was analyzed as this microscopic data is most reliable.
Traffic can be sub-divided into two states: following or leading. At the simulation, it turns out that the participants driving at the rush-hour lane are almost all in leading state. In the literature review it was found that the road layout and the speed limit are the most important factors influencing the driving behavior. The difference between the desired speed of the participants and the average speeds driven on the rush-hour lane (95 km/h) is large. This is caused by the high speed limit of 120 km/h and matches the results from the ex-post evaluation that the occupation rates at the A50 section were lowest of all rush-hour lane sections.

The influence of changes in the design on the occupation of the rush-hour lane is analyzed in the next chapter. Two factors are tested for their influence on the performance of the rush-hour lane: reduced signaling and broken markings. The influence of these two design factors will be covered separately.

10.2 Changes in the design

The driving simulator is the perfect tool to research an alternative design of rush-hour lanes. In this case, two factors were altered from the real situation in a total of 4 layouts:

Layout 0: regular signaling and continuous markings (real situation)
Layout 1: reduced signaling and continuous markings
Layout 2: regular signaling and broken markings
Layout 3: reduced signaling and broken markings

The main hypotheses of this section are:
Hypothesis 22: Decreasing the signaling has a negative effect on the occupancy of rush-hour lanes
Hypothesis 23: Applying broken markings has a positive effect on the occupancy of rush-hour lanes

When looking at the cumulative distributions of headways for all three lanes in Figure 10.3, it can be seen that time headways on the rush-hour lane are generally larger than on the other two lanes. Headways on the left lanes are smallest. When regarding the fact that these headways are related to the intensities on each lane, it resembles the patterns of the lane flow distributions as they are found in the ex-post evaluation. At the ex-post evaluation, the occupation of the rush-hour lane was lowest. The occupation of the middle lane is also lower than the left lane, especially at higher intensities. Referring back to the scheme of Figure 10.2, these headways are an indication of the intensities of the lanes. The main assumption for the continuation of this chapter is that the distribution over the different lanes resembles reality. An extra indication for the reliability of the occupation rates is the fact that flow fractions stay approximately constant for all intensity levels at the A50 section (see paragraph 7.1.1).

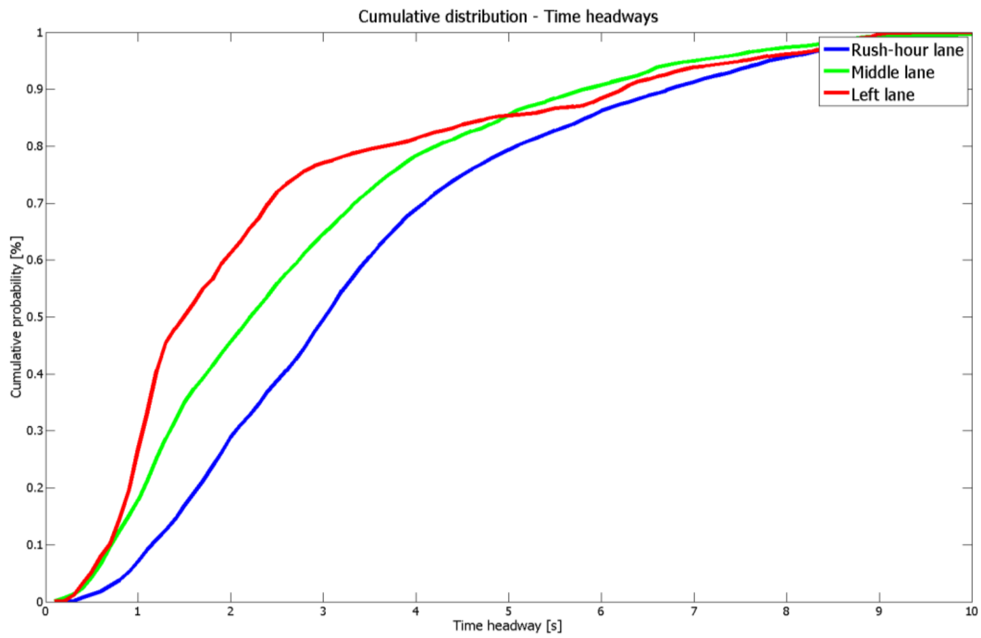


Figure 10.3: Cumulative distribution of time headways per lane

Assuming that the occupations of the lanes are realistic, the focus will now lie on the occupation of the rush-hour lane. To determine the occupation rate of a certain lane, the first step is to determine the lane at which the participant is located at a certain distance. This data is derived from data about the lateral position of the participant. In Figure 10.4, a graph is shown of the lateral position of all participants at the rush-hour lane section. To define the current lane of each participant, intervals are defined for the lateral position at each lane:

- Left lane: Lateral positon > 6 m
- Middle lane: 2.5 m < Lateral position < 5.2 m
- Rush-hour lane: Lateral position < 1.2 m

Note that these values have been derived on sight from the graph, as no data was known of the limits of each lane (the widths of the lanes did not match the values of the lateral position for some reason). This has the benefit that if the lateral position is not within one of these intervals, the participant is either performing a lane change maneuvre or drives outside the roadway. Note here that data from the first 60 m on the rush-hour lane section is filtered out and that the end-limit of driving is 3800 m (appr. 200 m before the end).

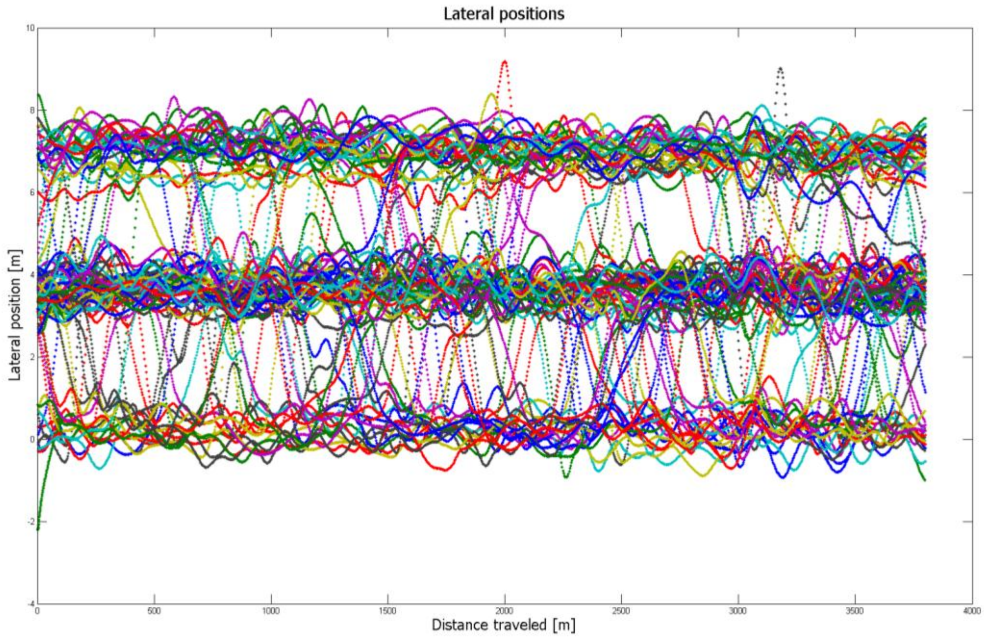


Figure 10.4: Lateral positions of all participants

Occupation is determined by comparing the distance driven on the rush-hour lane to the total distance driven on one of the three lanes in total (and thus neglecting the distance driven while making a lane change). Another possibility is to check the total time spent on each lane and compare it with the total time spent on one of the three lanes in total. This, however, has the downside that it is highly affected by the speed at which the participant is driving. Total distance driven is the same for all participants, whereas total time driven differs as speeds differ.
When zooming in on the process, the method becomes clear. In Figure 10.5, a fictive trajectory of a participant is drawn.

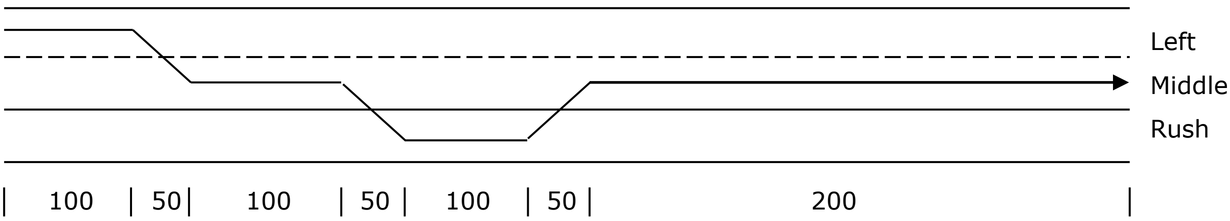


Figure 10.5: Fictive trajectory: At the bottom, the distances traveled in m.

Total distance traveled in this situation is 650 m. When distance of lane changing is neglected, the distance traveled is 500 m. The occupation rates for all lanes are as follows:

- Left lane: 100 / 500 = 20 %
- Middle lane: 300 / 500 = 60 %
- Rush-hour lane: 100 / 500 = 20 %

As the extreme low intensities at the rush-hour lane section are removed (see paragraph 9.6.1 and appendix 24), it is possible to compare the occupation rates of the rush-hour lane between combinations of layouts. Two factors will be compared in the following paragraph for the influence on the occupation: signaling and markings.

10.2.1 Signaling

In the literature review (see section A) it is described that the signaling system of the rush-hour lane is considered well-understandable. The most recent study of (XTNT, 2011) even shows that the sign 'rush-hour lane open' is not needed and that the green arrow / red cross combination provides sufficient information. None of the studies, however, mention the influence of the repetition of information.

When looking at the influence of signaling placement, combination of layouts 0 and 2 (regular signaling) are compared with the combination of layouts 1 and 3 (reduced signaling). Regular signaling is measured from Google Earth at an in-between distance of approximately 600 m. This is drawn into the driving simulator in both layouts 0 and 2. The other two layouts have only half of the signaling portals, thus making the in-between distance approximately 1200 m.

Mean occupation rates are determined using the method described earlier for the mentioned combinations and give the boxplots as provided in Figure 10.6 on the next page. As can be seen from the boxplots, the mean occupation percentages are the same for both combinations of layouts. To perform a student t-test on the data the data is first proven to be normally distributed by performing a Kolmogorov-Smirnov-test. In this test, the empirical cumulative distribution function of occupation means is compared to a normal cumulative distribution function with estimated mean and standard deviation values. The data of layout 0 and 2 combined is normally distributed with a sample size of 28, a mean of 0,18 and standard deviation of 0,11 ($p < 0,05$). Data of 1 and 3 combined is normally distributed with a sample size of 29, a mean of 0,16 and standard deviation of 0,08 ($p < 0,05$).

To test if there is any significant difference between the two combinations of layout, a student t-test is performed. The test statistic is calculated using the following formula:

$$t = \frac{\overline{X_1} - \overline{X_2}}{\sqrt{\frac{s_1^2}{n_1} + \frac{s_2^2}{n_2}}} \text{ and the degrees of freedom, d.f.} = \frac{\left(s_1^2/n_1 + s_2^2/n_2\right)^2}{\left(s_1^2/n_1\right)^2/(n_1 - 1) + \left(s_2^2/n_2\right)^2/(n_2 - 1)}$$

For the sample sizes, means and standard deviations as mentioned before, t = 0,783 and d.f. = 44
To be significant at a confidence level of 95%, the test statistic should be 2,021 (at 40 d.f.). The mean occupation rate of the layout combinations with regular signaling do not differ significantly from the mean occupation rate of the layout combinations with reduced signaling. It should be noted here that the correlations between the factors are ignored (i.e. no MANOVA test is performed to analyze the correlation as it was apparent that the influence of the factors was small).

10.2.2 Markings

When looking at the influence of markings, the combination of layouts 0 and 1 (continuous markings) are compared with the combination of layouts 2 and 3 (broken markings). The data of layout 0 and 1 combined is normally distributed with a sample size of 30, a mean of 0,16 and standard deviation of 0,09 ($p < 0{,}05$). Data of 2 and 3 combined is normally distributed with a sample size of 27, a mean of 0,17 and standard deviation of 0,11 ($p < 0{,}05$). The student t-test as described before is also performed on these two samples:

t = 0,373 and d.f. = 50.

To be significant at a confidence level of 95%, the test statistic should be between 2.000 (at 60 d.f.) and 2,021 (at 40 d.f.). The mean occupation rate of the layout combinations with continuous markings do not differ significantly from the mean occupation rate of the layout combinations with broken markings.

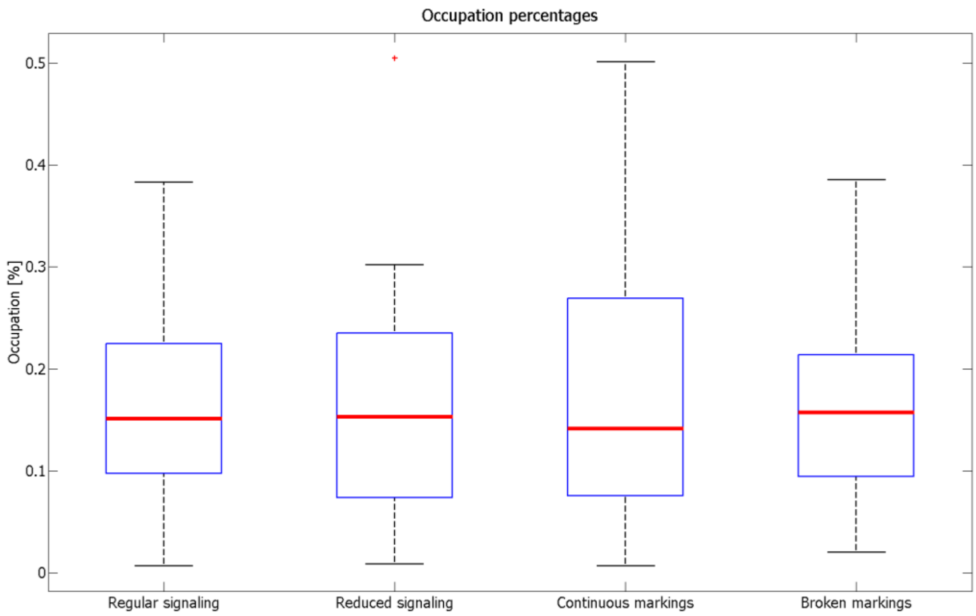


Figure 10.6: Occupation percentages per design factor

10.2.3 Synthesis

Two design factors are analyzed for their influence on the occupation of the rush-hour lane: reducing the signaling and adding broken markings instead of continuous markings. Occupation is determined by comparing the distance driven on the rush-hour lane to the total distance driven on one of the three lanes in total (and thus neglecting the distance driven while making a lane change).
Both design factors do not influence the occupation of a rush-hour lane at a section with a speed limit of 120 km/h. It is shown in the ex-post evaluation that this speed limit as a design factor has a large negative influence on the occupation. The behavioral factors causing this influence are elaborated in the previous chapter.

The analyses that are needed to answer the sub-questions B2 and B3, as posed in paragraph 1.2 are now all performed. The next chapter concludes the driving simulator study by answering these sub-questions. The answers are given by proving or disproving the hypotheses as stated in the separate paragraphs of this section.

11 Conclusion

11.1 Synthesis between sections

The first part of the driving simulator study was focused on gaining insight in the behavioral factors that explain the results from the ex-post evaluation. The link between macroscopic and microscopic indicators, as derived from the literature review in section A was used for this purpose. Virtual traffic was programmed into the driving simulator by using the results from the ex-post evaluation in section B. Because intensities were not constant for the simulations, a validation with the real situation was not possible and only car-following behaviour was analysed.

In the second part of the driving simulator study, the influence of changes in the design of rush-hour lanes is analyzed. Two design factors are analyzed for their influence on the occupation of the rush-hour lane: reducing the signaling and adding broken markings instead of continuous markings.

The next section in this research is added to summarize all conclusions of the research. Throughout this report, all chapters are linked together by using syntheses. The last section starts with a summary of all syntheses. In other words, all findings will be summarized and the link between the findings will be made clear.
After this last synthesis, the main conclusion for the research is given. The answer to the main research question will be provided here. Recommendations following from this conclusion for the implementation of rush-hour lanes or pluslanes in the future, will be given after that.
The report will be finished with the recommendations for further research.

11.2 Answering the sub-questions

To recap, the sub-questions for the driving simulator study are:

B2 - What are the underlying behavioural factors causing the differences in performance of rush-hour lanes?
B3 - What changes can be made to the design of a rush-hour lane to improve its performance?

In this chapter, answer will be given to these sub-questions by confirming or rejecting hypotheses as stated in the previous chapters.

B2 - What are the underlying behavioral factors causing the differences in performance of rush-hour lanes?

Hypothesis 21: The incentive of using the rush-hour lane at a speed limit of 120 km/h is low
Confirmed
The speed difference between the rush-hour lane and the other 2 lanes is high. At the rush-hour lane, traffic drives with an average speed of 95 km/h. Because the desired speed of the participants lies higher than the speeds driven on the rush-hour lane, a lane change to the rush-hour lane is only made when the desired speed can be maintained for some time. This is backed up by the fact that almost all participants where in leading state when driving on the rush-hour lane.

B3 - What changes can be made to the design of a rush-hour lane to improve its performance?

Hypothesis 22: Decreasing the signaling has a negative effect on the occupancy of rush-hour lanes
Undecided
No difference in occupation was found between the layouts with the regular signaling, compared to the layouts with decreased signaling. However, the main factor influencing the occupation, as found in the ex-post evaluation, is the speed limit. The high speed limit in the driving simulator was therefore not suited to draw conclusions about this hypothesis.

Hypothesis 23: Applying broken markings has a positive effect on the occupancy of rush-hour lanes
Undecided
No difference in occupation was found between the layouts with the continuous markings, compared to the layouts with broken markings. However, the main factor influencing the occupation, as found in the ex-post evaluation, is the speed limit. The high speed limit in the driving simulator was therefore not suited to draw conclusions about this hypothesis.

11.3 Conclusion

Conclusions regarding behavioral factors

As only a rush-hour lane section with a speed limit of 120 km/h is tested in this research, the conclusion about this part of the research is limited. The low occupation rates at the high speed limit are caused by the high speed differences between the rush-hour lane and the other two lanes. As trucks are driving on the rush-hour lane, the average speed on that lane is 95 km/h at the tested section. The high speed limit increases the desired speeds of other traffic. The incentive of using the rush-hour lane is therefore low. In chapter 15 it is explained how further research can give a more concise answer to this part of the main research question.

Conclusions regarding changes in the design

The conclusion about this part of the research cannot be given by this research alone. It can be said that changing the markings and reducing the signaling does not have an influence on the occupation of a rush-hour lane when a speed limit of 120 km/h is operational. In chapter 15 it is explained how further research can give a more concise answer to this part of the main research question.

Section D

Conclusions and recommendations

12 Research synthesis

Throughout the report, syntheses have been made. This chapter is meant to summarize those syntheses and therefore summarize the findings of this research and make a connection between all sections of this research.

Findings are documented here separately for the 2 main phases of the research: the ex-post evaluation and the driving simulator study. This is done to keep things organized and is in line with the setup of the research. Connections between phases will be mentioned for every part of the research. The connections can also be found in Figure 1.1 in paragraph 1.3.2.

Ex-post evaluation

Regarding performance of rush-hour lanes and pluslanes, several steps have been taken to come to results. At first, a summary was made of all rush-hour lane and pluslane sections in the Netherlands. This summary is filtered for sections that are useful for this research. Data of 120 days (between 01-01-2011 and 01-05-2011) is collected of the sections. The data is filtered for wrong detector data, holidays and weekend days and aggregated to 5 minute data. Only free-flow data (speeds above 80 km/h) is used for the research. The rush-hour lane and pluslane sections that are used for this research are summarized in Table 6-2 and Table 6-3.

Performance - rush-hour lane compared to right lane

The first part of the ex-post evaluation is aimed at analyzing the differences in performance between a rush-hour lane and a right lane. As performance is in this research defined by occupation rates (lane flow distributions) and speeds (intensity-speed relations), these where compared. These performance indicators are derived from the *literature review* in section A.

The regular 3 lane sections that are used for this purpose are the A16 between junction s-Gravendeel and junction Klaverpolder with a speed limit of 120 km/h and the A4 between junction Leidschendam and junction Zoeterwoude-Dorp with a speed limit of 100 km/h.

Two rush-hour lane sections are used for the comparison: the best-performing rush-hour lane section, located at the A2 between junction Kerensheide and junction Vonderen and the rush-hour lane at the A50 between junction Ewijk and junction Vonderen. This last section will also be designed into the *driving simulator* to find the behavioral factors that underly the results.

Results are shown in Figure 7.4 and 7.6. As can be seen from these figures, the occupation rates of both rush-hour lanes are far lower than at the regular right lanes. The relative differences range between 15% and 120%. The low occupation rates at the A50 section are explained in the *driving simulator study* in section C.

When regarding speeds, the rush-hour lane section with a speed limit of 120 km/h at the A50 has lower free-flow speeds than the section with 3 regular lanes and a speed limit of 120 km/h at the A16. Differences lie between 10% and 14% (Figure 7.2). The section at the A2 with a 100 km/h speed limit shows smaller relative differences in speed with a maximum difference of 5% (Figure 7.3).

Performance - pluslane compared to left lane

The same is done for pluslanes, comparing the pluslane at the A1 between junction Beekbergen and junction Deventer-Oost with the left lane at the A4, as mentioned before. As can be seen in Figure 7.9, flow fractions at the pluslane are much lower at low intensities. However, at high intensities differences are much smaller. The left lane even has about 5% lower flow fractions compared to the pluslane.

When regarding speeds, the pluslane section with a speed limit of 100 km/h at the A1 has lower speeds than the section with 3 regular lanes and a speed limit of 100 km/h at the A4. The differences are, however, small with a maximum of 5% (see Figure 7.8). At higher intensities, the speed differences between the section with a regular left lane and the section with a pluslane can be neglected.

Performance - different locations at rush-hour lane and pluslane sections

Different locations on rush-hour lane and pluslane sections are analyzed for their occupation rates. For all sections mentioned in Table 6-2 and Table 6-3, data is collected - when possible- of detectors located at the start and the end of the section and compared with the data from a detector at a turbulence-free section. Information about the lay-outs at the start and the end, as well as the detector data was scarce.

At rush-hour lane sections, it was interesting that the lay-out of the start and -end seems to have a big influence on the occupation rates. When the rush-hour lane starts before an on-ramp or ends before an off-ramp, as is the case at the A50 section, it is occupied up to 50% more than a turbulence-free section. If the start of the rush-hour lane is situated after an on-ramp, as is the case on the A1 section, it is occupied up to 60% less than a turbulence free section.

Pluslane sections show mixed results. At sections where an on-ramp is located downstream of the detector, traffic makes room for the merging traffic and thus moves further to the left. This causes an increase in occupation rates of the pluslane at those locations. More detailed research should be performed to gain insight in the influence of different lay-outs at the start and the end of rush-hour lane and pluslane sections.

Performance - design factors regarding rush-hour lanes

The next part was focused on the design factors that have an influence on the occupancy rates and free-flow speeds at rush-hour lanes and pluslanes. The three design factors that are researched are: the lane width, the total number of lanes and the speed limit. At first, the influence of these design factors on the performance of rush-hour lanes is analyzed.

The rush-hour lane at the A50 between junction Ewijk and junction Valburg has a permanent speed limit of 120 km/h and performs worst of all rush-hour lanes with occupation rates that are at least 20% lower when compared to a regular right lane. The behavioral aspects that underly this low performance are analyzed in the *driving simulator study* in section C.

At the A2, two rush-hour lane sections are analyzed: the east section between junction Kerensheide and junction Vonderen and the west section between the same junctions. The only factor that makes them different is the smaller lane width of the westbound section. As can be seen from the plots, the occupation rates at higher intensities are up to 10% lower at the

westbound section. This indicates a negative influence of smaller lane widths. In Figure 7.20, the A50 is compared with the A2 eastbound section and also the two A2 sections are compared, showing the large differences.
The section with at total number of 4 lanes at the A13 between junction Berkel & Rodenrijs and junction Delft-Zuid is analyzed separately. Intensity shares are analyzed and are well comparable with the sections with 3 lanes at higher intensity levels. The lower flow rates at low intensities shows that the preferred lane at low intensities is the middle right lane instead of the rush-hour lane. In Figure 7.21, the intensity shares of the A1 between junction Hoevelaken and junction Barneveld are compared with intensity shares at the A13.
Speeds at rush-hour lanes are highly affected by the truck percentage at the section. The speeds driven at rush-hour lane on the section at the A50 between junction Ewijk and junction Vonderen with a speed limit of 120 km/h are lowest of all sections. The truck percentage at that section is 30% (see appendix 23). Speeds were expected to be higher on the middle lane and the left lane. However, when the section at the A50 is compared with the section at the A2 between junction Kerensheide and junction Vonderen, speeds are lower on all lanes at the A50 section, as can be seen in appendix 20.
Speeds on the section with a total number of 4 lanes are comparable with speeds driven on the rush-hour lane at the A1 section, as can be seen in Figure 7.22.

Performance - design factors regarding pluslanes

The same analyses as mentioned before have been done for the pluslane sections. When a narrow lane is combined with a low speed limit, as is the case at the section on the A27 between junction Gorinchem and junction Noordeloos. The lane width is 2,70 m at this section and the speed limit is 80 km/h when the pluslane is opened. This rush-hour lane shows approximately the same occupation rates when compared to a wide pluslane with a high speed limit of 100 km/h at the A1 between junction Beekbergen and junction Deventer-Oost, as can be seen in Figure 7.22. However, when another pluslane with a lane width of 2,75 m and a speed limit of 100 km/h at the A12 between junction Gouwe and junction Zoetermeer is compared with the A1 section, occupation rates are up to 70% lower, as can be seen in Figure 7.22.
The section with 4 lanes at the A12 between junction Woerden and junction Gouda is analyzed separately from the other sections. Results are comparable with the A12 between junction Gouwe and junction Zoetermeer. It is expected that the combination of the speed limit of 100 km/h and the lane width of 2,75 m influences the occupation rates at this section as well. At lower intensities, the intensity shares of the 4 lane section are up to 30% lower.
Speeds at the pluslanes are, as expected, mostly affected by the speed limit. Sections with the same speed limit do not show significant differences in speeds. The section at the A27 between junction Gorinchem and junction Noordeloos with a 80 km/h speed limit shows the lowest speeds. The maximum differences can be seen when the section is compared with the A1 between junction Beekbergen and junction Deventer-Oost (see appendix 21). Speeds at the pluslane differ up to 20%. Speeds at the middle lane and the left lane are, however, up to 8% lower at the A1 section.

Lane widths do not have an influence on the speeds driven at pluslane sections. Speeds are up to 4% lower at the section on the A12 with a lane width of 2,75 m, compared to the section at the A1 with a lane width of 3,10 m.
When the section with 4 lanes is compared with the other sections, it shows that speeds are highest of all sections. It can be seen that the narrow lane width of 2,75 m does not influence the speeds driven at the section. Speeds differ up to 10% (see Figure 7.26).

Performance - rush-hour lanes vs. pluslanes
In the last part of the ex-post evaluation a general comparison is made between the performance of rush-hour lanes compared to pluslanes. For this purpose, the best performing rush-hour lane at the A2 between junction Kerensheide and junction Vonderen and the best performing pluslane at the A1 between junction Beekbergen and junction Deventer-Oost are used.
Occupation rates of the pluslane at the A1 are well-comparable with the occupation rates at a regular left lane. At higher intensities, they even exceed the values of the regular left lane by 5%.
Occupation rates of the rush-hour lane at the A2 are always at least 15% lower than the occupation rates at a regular right lane (see Figure 7.4 and Figure 7.6).
Regarding speeds, the differences can be neglected (see Figure 7.27).

Driving simulator study

The driving simulator used for this study is situated at the Delft University of Technology. The A50 between junction Bankhoef and junction Valburg is designed into the driving simulator as a zero alternative, to compare data from the driving simulator with data from the *ex-post evaluation* in section B. Three other alternative layouts are created to test the influence of signaling and markings on the performance. This makes for a total of 4 layouts:

0) Regular signaling with continuous markings (zero alternative)
1) Regular signaling with broken markings
2) Decreased signaling with continuous markings
3) Decreased signaling with broken markings

Two intensity levels were created: low (3000 veh/h) and medium (4000 veh/h). These two intensity levels did not stay constant between simulations, because traffic randomly left the highway section. The differences of intensity levels between participants make validation with reality impossible. Because the validation was not possible, only car-following behavior was analyzed as this microscopic data is most reliable. This is one of the main microscopic factors that underlies the macroscopic lane flow distributions and intensity-speed relations, as is derived in the *literature review* in section A.
The driving simulator was used to find the behavioral factors that underlie the results from the ex-post evaluation. Also, it is used to analyze what changes in the lay-out of a rush-hour lane can improve performance. Findings will be summarized for these 2 aspects separately.

Behavioral factors

Two patterns can be distinguished when looking at the time headways of all participants in Figure 12.16. Leading vehicles keep a constant speed and their headway therefore decreases linearly with the speed difference between the first leading vehicle. When the time headway becomes too small, a lane change is made to the middle lane.

Traffic can be sub-divided into two states: following or leading. From the simulation, it turns out that the participants driving at the rush-hour lane are almost all in leading state. In the *literature review* it was found that the road layout and the speed limit are the most important factors influencing the driving behavior. The difference between the desired speed of the participants and the average speeds driven on the rush-hour lane (95 km/h) is large. This is caused by the high speed limit of 120 km/h and matches the results from the *ex-post evaluation* that the occupation rates at the A50 section were lowest of all rush-hour lane sections.

Changes in the design

To analyze the differences between layouts, occupation is determined by comparing the distance driven on the rush-hour lane to the total distance driven on one of the three lanes in total (and thus neglecting the distance driven while making a lane change). When zooming in on the process, the method becomes clear. In Figure 10.5, a fictive trajectory of a participant is drawn.

Total distance traveled in the given situation is 650 m. When distance of lane changing is neglected, the distance traveled is 500 m. The occupation rates for all lanes are as follows:

- Left lane: 100 / 500 = 20 %
- Middle lane: 300 / 500 = 60 %
- Rush-hour lane: 100 / 500 = 20 %

The influence of reducing the number of signaling portals and applying broken markings instead of continuous markings at the rush-hour lane is analyzed in the driving simulator as these design factors are not implemented at existing rush-hour lanes. These design factors could therefore not be analyzed in the *ex-post evaluation.*

To analyze the differences in occupation between regular signaling and reduced signaling, the layouts are combined. Data from layouts 0 and 1 is compared with data from layouts 2 and 3. To analyze the differences in occupation between continuous markings and broken markings, data from layouts 0 and 2 is compared with data from layouts 1 and 3. Knowing the influence of broken markings on the performance of rush-hour lanes is interesting for Rijkswaterstaat, because broken markings will be implemented in the new managed lane called 'schakelstrook' (switching lane) as can be seen in the *literature review*. The current signaling at rush-hour lanes is clear to road users, as is also shown in the *literature review*. Reducing the signaling is interesting for Rijkswaterstaat, as it reduces the costs of the measure.

Figure 10.6 shows the results. No significant differences are found between the layout-combinations. See chapter 15 for the further research that can be performed on this subject.

13 Main conclusion

Using the methodologies as described in the previous chapter, it is possible to give answer to the main research question. To recap, the main research question of this thesis is:

What is the performance of rush-hour lanes and pluslanes, what are the behavioral factors and design factors causing differences in performance and what changes can be made to the design of rush-hour lanes to improve the performance?

The first part of the main research question relates to the **performance** of rush-hour lanes and pluslanes. Conclusions will be structured by the different aspects of performance that were covered in this research.

Performance - Rush-hour lane vs. right lane and pluslane vs. left lane

- A pluslane shows the same occupation rates when compared to the same intensity levels at a regular left lane
- Rush-hour lanes show a minimum of 15% lower occupation rates when compared to the same intensity levels at a regular right lane.
- At lower intensity rates, both rush-hour lanes and pluslanes show lower occupation rates. This is caused by the natural dislike of traffic to make use of the rush-hour lane and by speed differences at the pluslane.
- Speeds driven on sections with a pluslane are not structurally lower than speeds driven on a section with 3 regular lanes.
- Speeds driven on a rush-hour lane section do not differ significantly from speeds driven on a pluslane section.
- Speeds driven at rush-hour lanes are highly affected by the truck percentage.

Performance - Different locations at rush-hour lane and pluslane sections

- The differences in occupation rates between start and end locations at rush-hour lane and pluslane sections could not be confirmed in this research. See chapter 15 for recommendations about further research that can be performed on this subject.

Performance - Rush-hour lane vs. pluslane

- Speeds do not differ significantly when comparing the best-performing rush-hour lane section with the best-performing pluslane section

Performance - Design factors

- Regarding rush-hour lanes, it can be concluded that the speed limit as a design factor has the highest influence on the performance. The rush-hour lane section with the highest speed limit of 120 km/h performs the worst of all sections.
- Adding an extra lane to the cross section (making it 3+1) has a negative influence on the occupation of the rush-hour lane at low intensities. At high intensities, the differences can be neglected.
- Regarding rush-hour lanes, adding an extra lane to the cross section does not influence the speeds driven on that section.
- The influence of lane width on performance of rush-hour lanes cannot be proven in this research. The research does, however, give an indication about the negative influence of smaller lane widths on free-flow speeds and occupation rates at rush-hour lanes.
- Regarding pluslanes, it can be concluded that adding a lane to the cross section (making it 3+1) does not have an influence on the intensity shares (and therefore the occupation) of pluslanes.
- A high speed limit in combination with a narrow lane width has a negative influence on the performance of pluslanes. Narrow lane widths in combination with low speed limits (80 km/h) do not have a negative influence on performance. Also high speed limits (100 km/h) in combination with wide lanes do not have a negative influence on performance.

The second part of the research question relates to the **behavioral factors** that underlie differences in performance. The conclusions about these behavioral factors will now be described.

Behavioral factors

As only a rush-hour lane section with a speed limit of 120 km/h is tested in this research, the answer to this part of the research question is limited. The low occupation rates at the high speed limit are caused by the high speed differences between the rush-hour lane and the other two lanes. As trucks are driving on the rush-hour lane, the average speed on that lane is 95 km/h at the tested section. The high speed limit increases the desired speeds of other traffic. The incentive of using the rush-hour lane is therefore low. In chapter 15 it is explained how further research can give a more concise answer to this part of the main research question.

The last part of the research relates to possible **changes in the design** of rush-hour lanes that can improve the performance of them. The conclusion about changes in the design will now be described.

Changes in the design

The answer to this part of the main research question cannot be given by this research alone. It can be said that changing the markings and reducing the signaling does not have an influence on the occupation of a rush-hour lane when a speed limit of 120 km/h is operational. In chapter 15 it is explained how further research can give a more concise answer to this part of the main research question.

14 Recommendations

Recommendations can be given from the conclusions in the previous chapter. To keep this chapter organized, recommendations are separately described for rush-hour lanes and pluslanes or marked as general.

General recommendations

- Pluslanes perform better than rush-hour lanes when regarding occupation, so the implementation of a pluslane is recommended over a rush-hour lane in this sense. Policy makers should, however, weigh the costs against the benefits as pluslanes are also more expensive.

Recommendations regarding rush-hour lanes

- When implementing a rush-hour lane it is highly discouraged to apply a speed limit of 120 km/h at the section because occupancy of the rush-hour lane decreases significantly. This is mainly caused by the large differences in speed on the rush-hour lane compared to the other 2 lanes. The speed limit also reduces speeds at the middle and left lane by 10%.
- When analyzing speeds on rush-hour lanes, it should be noted that the speeds driven on the rush-hour lane are highly affected by the percentage of trucks driving at the section.

Recommendations regarding pluslanes

- When implementing a pluslane, it is highly encouraged to combine narrow lane widths (smaller than 2,80 m) with low speed limits (80 km/h) and to combine high speed limits (100 km/h) with wider lanes (3,10 m is recommended). Combining high speed limits with narrow lane widths significantly reduces the occupation of the pluslane.
- This fact also applies at pluslane sections with a total number of 4 lanes.

15 Further research

From the conclusions, the following further research topics are recommended:

Ex-post evaluation

- More detailed research can be done to the influence of the design factors. More rush-hour lane and pluslane sections could be included to give a more detailed picture of the influence of design factors. Also, other performance indicators can be used. A very important aspect that is not treated in this research is the difference between the before and after situation. Analyzing differences in the before and after situation of different rush-hour lane and pluslane sections gives good insight in the performance of them. Research that has been performed on this subject should be combined to quantify the influence of each design factor. With this, it may be possible to setup a model that can predict the performance of a rush-hour lane or pluslane design before implementation.
- More research needs to be performed on the effects of different start and end layouts on the performance of rush-hour lanes and pluslanes. This can be done with a driving simulator study or with on-site measurements. Current detectors are not spread densly enough over the network to draw concise conclusions. Starting a rush-hour lane right after an on-ramp, for example, is expected to have a negative influence on the occupation of the rush-hour lane. In fact, a bottleneck is created, because traffic first merges from 3 lanes to 2 and then it spreads out again over 2 lanes and a rush-hour lane.

Driving simulator study

- Changes in the design can be tested with a new driving simulator study. It is recommended to use a speed limit of 100 km/h instead of 120 km/h. It is interesting to see if broken markings really have a positive effect on the occupation of rush-hour lanes. This is also in line with plans of Rijkswaterstaat to implement a switching lane. Also, it is intereseting to see if reduced signaling has a negative effect on the occupation of rush-hour lanes. This can be an underpinning for the reduction of the amount of portals by Rijkswaterstaat
- Possible (fast) changes that increase realism in the current driving simulator study:
    - Remove the off-ramp, so traffic intensities remain constant
    - Reduce the speed limit to 100 km/h.
    - Simulate free flow and congestion

When implementing these changes, more detailed research can be performed on the behavior of traffic at rush-hour lanes. The models in the driving simulator at the Delft University of Technology are not suited for this kind of research, as results are highly affected by the virtual traffic that is programmed into the driving simulator and these models are not realistic enough. It is recommended to use a recently updated driving simulator with good traffic models to increase the realism. The large amount of assumptions in this research are mainly the cause of the old driving simulator software.

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Appendices

16 - Rush-hour lanes and pluslanes in the Netherlands

17 - Data collection MATLAB

18 - Detector locations

19 - Intensity-speed graphs

20 - Lane flow distributions

21 - Truck percentages

22 - Participants

16 Rush-hour lanes and pluslanes in the Netherlands

Rush-hour lanes

Roadnr.	From	To	Open since	Length (km)	Speed limit	Lane widths (from left to right) Lane 1	Lane 2	Lane 3	Lane 4	Data (days)
A1	Muiden-Oost	Muiderberg	29-04-11	1,364	P 100	3,00	3,50	3,35	**3,25**	305
A1	Bussum	Eemnes	01-11-11	4,660	P 100	3,25	3,40	**3,35**		119
A1	Eemnes	Bussum	01-11-11	4,520	P 100	3,25	3,40	**3,35**		119
A1	Hoevelaken	Barneveld	08-04-08	7,142	120/100	3,35	3,50	**3,50**		1421
A2	Vonderen	Kerensheide	11-01-11	15,380	120/100	3,25	3,40	**3,35**		413
A2	Kerensheide	Vonderen	31-05-11	17,400	120/100	3,25	3,40	**3,28**		273
A4	Nieuwe Meer	Badhoeverdorp	31-05-11	2,450	P 100	3,25	3,40	3,40	**3,35**	273
A4	Badhoeverdorp	Nieuwe Meer	31-05-11	2,600	P 100	3,25	3,40	3,50	**3,35**	273
A6	Muiderberg	Almere Stad - West	29-04-11	3,895	P 100	3,20	3,50	3,40	**3,25**	305
A7	Zaamdam	Purmerend-Zuid	12-12-07	7,851	120/100	3,25	3,40	**3,35**		1539
A9	Diemen	Holendrecht	15-11-10	3,250	P 100	3,25	3.40	**3,35**		470
A9	Holendrecht	Diemen	15-11-10	2,800	P 100	3,25	3,40	**3,35**		470
A9	Badhoeverdorp	Raasdorp	01-03-11	2,770	P 100	3,25	3,35	**3,35**		364
A9	Raasdorp	Velsen	01-03-11	3,370	120/100	3,25	3,40	**3,35**		364
A9	Velsen	Raasdorp	01-03-11	7,960	120/100	3,25	3,40	**3,35**		364
A9	Uitgeest	Alkmaar	06-10-11	8,900	120/100	3,25	3,40	**3,35**		145
A9	Alkmaar	Uitgeest	06-10-11	10,070	120/100	3,20	3,40	**3,35**		145
A10	Amstel	Nieuwe Meer	31-05-11	2,700	P 100	3,25	3,40		**3,35**	273
A10	Nieuwe Meer	Amstel	31-05-11	3,620	P 100	3,25	3,40		**3,35**	273
A13	Berkel & Rodenrijs	Delft-Zuid	16-04-07	4,968	P 100	3,25	3,40		**3,35**	1779
A27	Everdingen	Lunetten	16-02-11	5,000	P 100	3,50	3,50	**3,35**		377
A50	Beekbergen	Waterberg	24-06-11	18,900	120/100	3,50	3,50	**3,50**		1745
A50	Waterberg	Beekbergen	24-06-11	18,916	120/100	3,50	3,50	**3,50**		1745
A50	Ewijk	Valburg	20-06-98	4,794	P 120	3,50	3,50	**3,50**		1745

Pluslanes

Roadnr.	From	To	Open since	Length (km)	Speed limit	Lane widths (from left to right) Lane 1	Lane 2	Lane 3	Lane 4	Lane 5	Data (days)
A1	Beekbergen	Deventer-Oost	24-02-06	13,807	120/100	**3,10**	3,50	3,45			1745
A1	Deventer-Oost	Beekbergen	24-02-06	12,290	120/100	**3,10**	3,50	3,45			1745
A4	Nieuw Vennep	Hoofddorp	18-10-99	2,551	P 120	**3,34**	3,27	3,21	3,53	3,54	1745
A12	Veenendaal	Ede	27-04-09	8,311	120/100	**3,00**	3,50	3,35			1745
A12	Ede	Veenendaal	27-04-09	7,000	120/100	**3,00**	3,50	3,35			1037
A12	Zoetermeer	Gouwe	18-01-10	10,700	P 100	**2,75**	3,50	3,25			1745
A12	Gouwe	Zoetermeer	18-01-10	11,200	P 100	**2,75**	3,50	3,25			771
A12	Woerden	Gouda	01-12-10	16,950	120/100	**2,75**	3,50	3,50	3,50		771
A12	Zoetermeer	Zoetermeer-Centrum	08-11-11	4,100	120/100	**2,75**	3,50	3,45			112
A27	Houten	Everdingen	29-11-99	4,888	100/80	**2,70**	3,00	3,25			1745
A28	Ommen	Zwolle-Zuid	13-12-04	6,219	100/80	**2,80**	3,25	3,25			1037
A28	Zwolle-Zuid	Ommen	13-12-04	6,280	100/80	**2,80**	3,25	3,25			1745
A27	Gorinchem	Noordeloos	09-10-06	5,489	120/100	**2,75**	3,50	3,45			1745

17 Data collection MATLAB

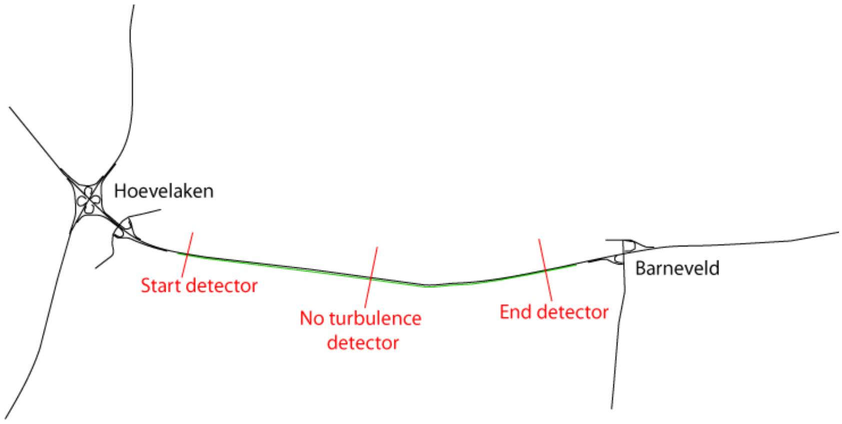
```
clearvars -except roads;
clc;
tic;
connectToProject;

s = selectionHandler.selectedDataObjects;

%% Input!

% In Jedi:
% - first set a start date (for example 01-jan-2011)
% - select the road section of which data needs to be collected (including
%   all detectors! has to be done AFTER setting start date for some reason)
% - check the position id of a link on the road section ('R' or 'L')

% State the name of the data-file to be saved
t = 'Plus_A12_ZG_S_20110101_20110501_120.mat';

% Insert number of days to import into data.
days = 120;

% Insert position ('R' for right; 'L' for left, see Jedi)
pos = 'R';

%% Data collection!

% Search links within selection
for i = 0:s.size()-1;
    dobj = s.get(i);

    % if selected object is a link
    if dobj.myType == 2

        roadnr = double(dobj.roadNumber);
        id = double(dobj.myElement.id);

        % Combine link id with roadnumber
        roads(id) = roadnr;

    end
end

now = project.timeCurrent;

% Create structure for the dataset
% data{days} = [];

Renum(1,max(roads)) = 0;

data{max(roads)} = [];

a = 0;

for i = 1:days
    project.changeTime(project.timeFrom, project.timeTo, now, 1);

    % Filter holidays and weekend days
    if project.timeCurrentDayIsHoliday == 0 && project.timeCurrentDOW < 6

        for d = 0:s.size()-1
            dobj = s.get(d);
```

```
            % Object is detector and is on 'position' carriageway (R or L;
            % right or left in Jedi)
            if dobj.myType == 104 &&
dobj.myElement.parents.get(0).parents.get(0).myDataObjects.get(0).position == pos

                % Give detector the id of the carriageway measurementpoint
                id_det = double(dobj.myElement.id-dobj.laneNumber);
                id_link = double(dobj.myElement.parents.get(0).parents.get(0).id);
                rw = roads(id_link); % Link detector id with link id
                if rw == 0
                    break
                else
                    g = 0;
                    for k = 1:size(Renum,1)
                        if Renum(k,rw) == id_det
                            index = k;
                            g = 1;
                        end
                    end
                    if g == 0
                        a = size(find(Renum(:,rw)>0),1)+1;
                        Renum(a,rw) = id_det;
                        index = a;
                    end
                end

                data{rw}.days{i}.carr{2,index} = id_det;

                % Only peak hour data is used (0600-1000 and 1530-1930)
                int1 = 360;
                int2 = 600;
                int3 = 930;
                int4 = 1170;
                int = [int1:int2 int3:int4];

                % Write the flow vector to the dataset. Flow is in veh/min
                if size(double(dobj.flow),1) ~= 0
                    data{rw}.days{i}.carr{1,index}.det{dobj.laneNumber}.F =
                    double(dobj.flow(int));
                else
                    data{rw}.days{i}.carr{1,index}.det{dobj.laneNumber}.F =
                    zeros(size(int,2),1);
                end
                % Write the speed vector to the dataset. Speed is in km/h
                if size(double(dobj.speed),1) ~= 0
                    data{rw}.days{i}.carr{1,index}.det{dobj.laneNumber}.V =
                    double(dobj.speed(int));
                else
                    data{rw}.days{i}.carr{1,index}.det{dobj.laneNumber}.V =
                    zeros(size(int,2),1);
                end
            end
        end
    end

    % Add 1 day (in milliseconds)
    now = now + 86400000;
end

% Save the datafile
save(t,'data');

toc;
clearvars -except roads data Renum;
```

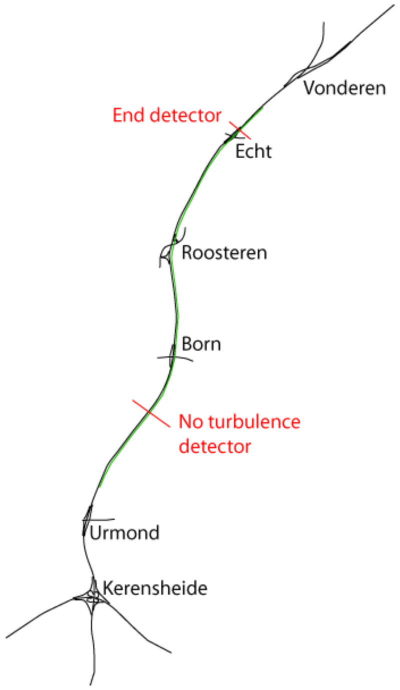
18 Detector locations

Rush-hour lanes

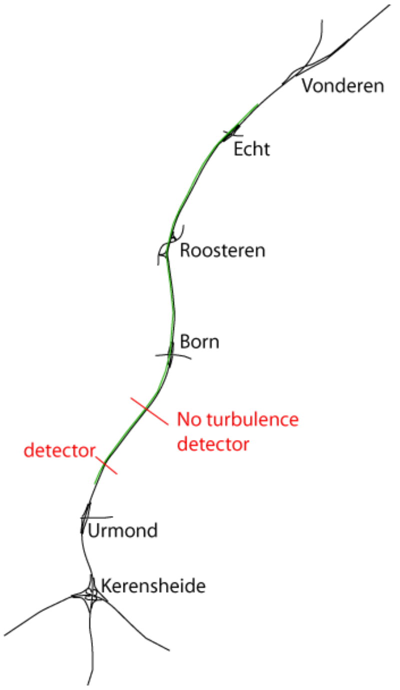
A1 - Hoevelaken-Barneveld



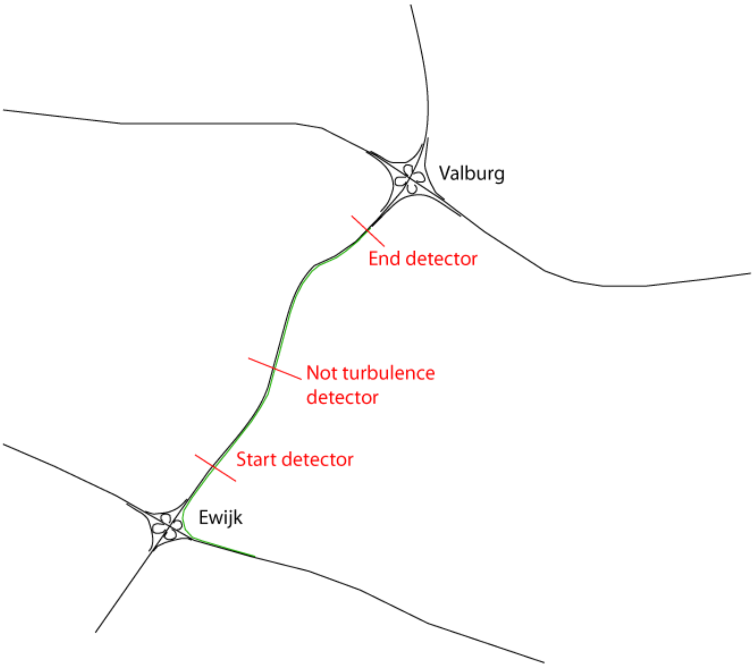
A2 - Kerensheide-Vonderen



A2 - Vonderen-Kerensheide

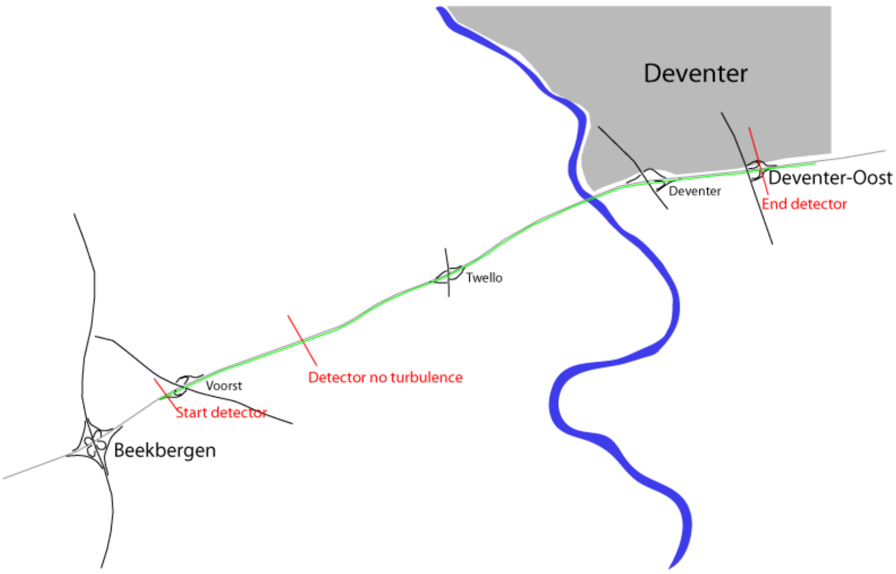


A50 - Ewijk-Valburg

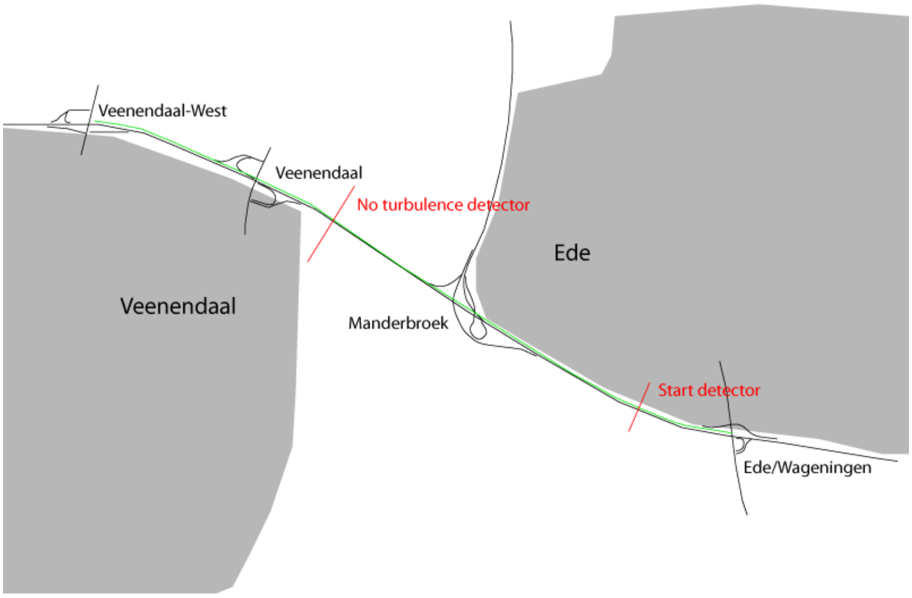


Pluslanes

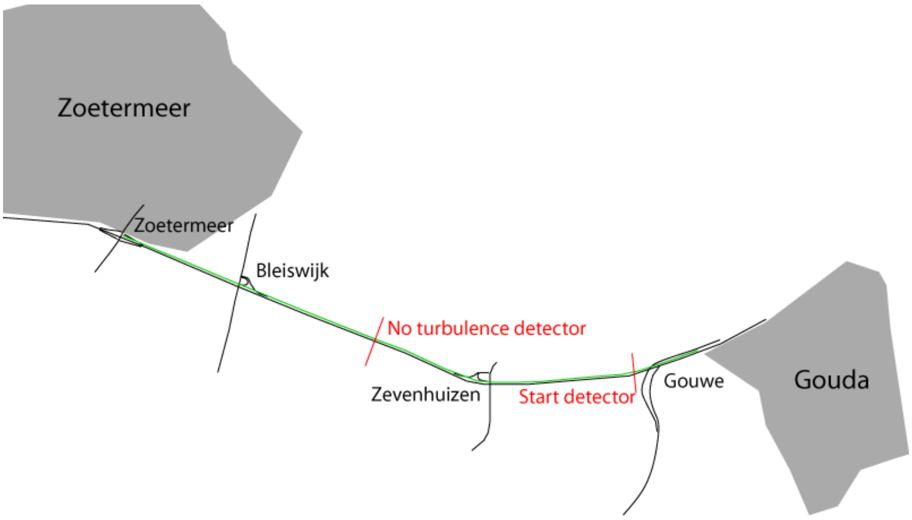
A1 - Beekbergen-Deventer-Oost



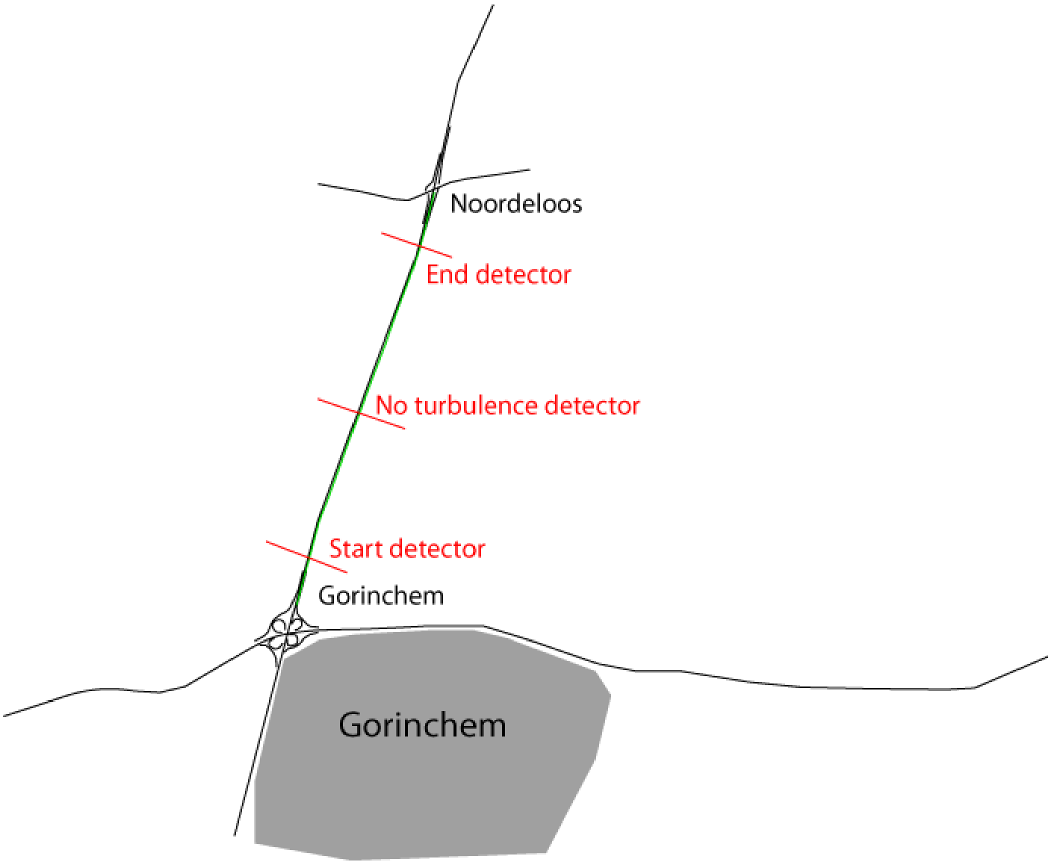
A12 - Ede-Veenendaal



A12 - Gouwe-Zoetermeer



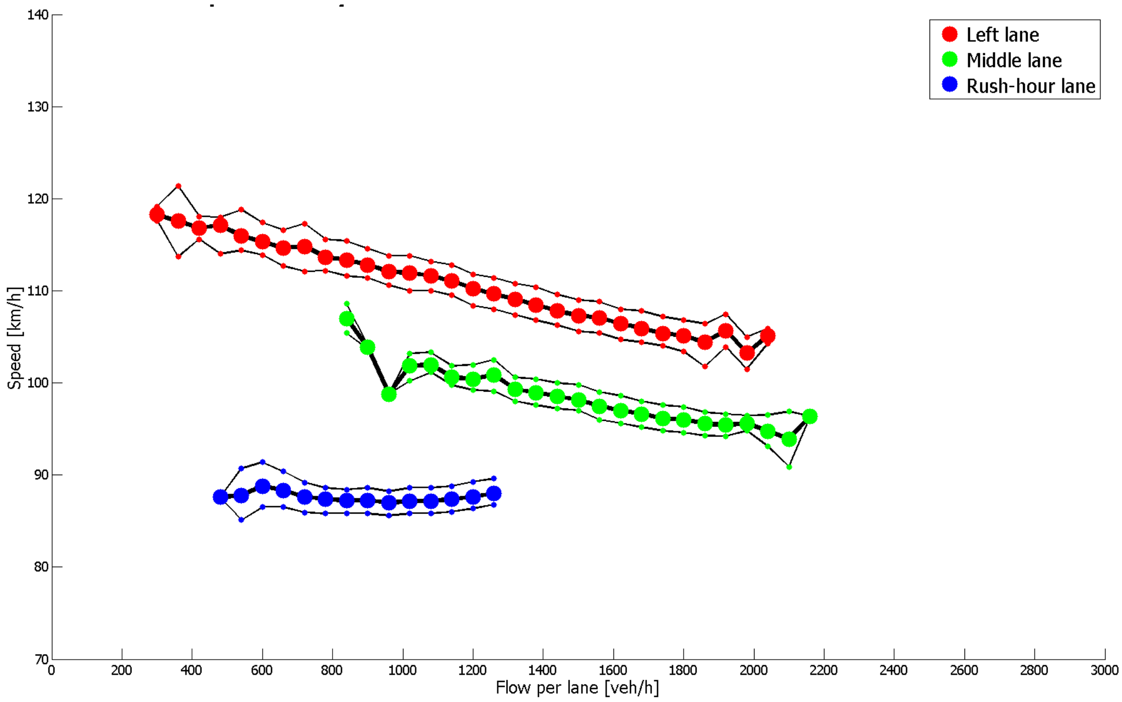
A27 - Gorinchem - Noordeloos



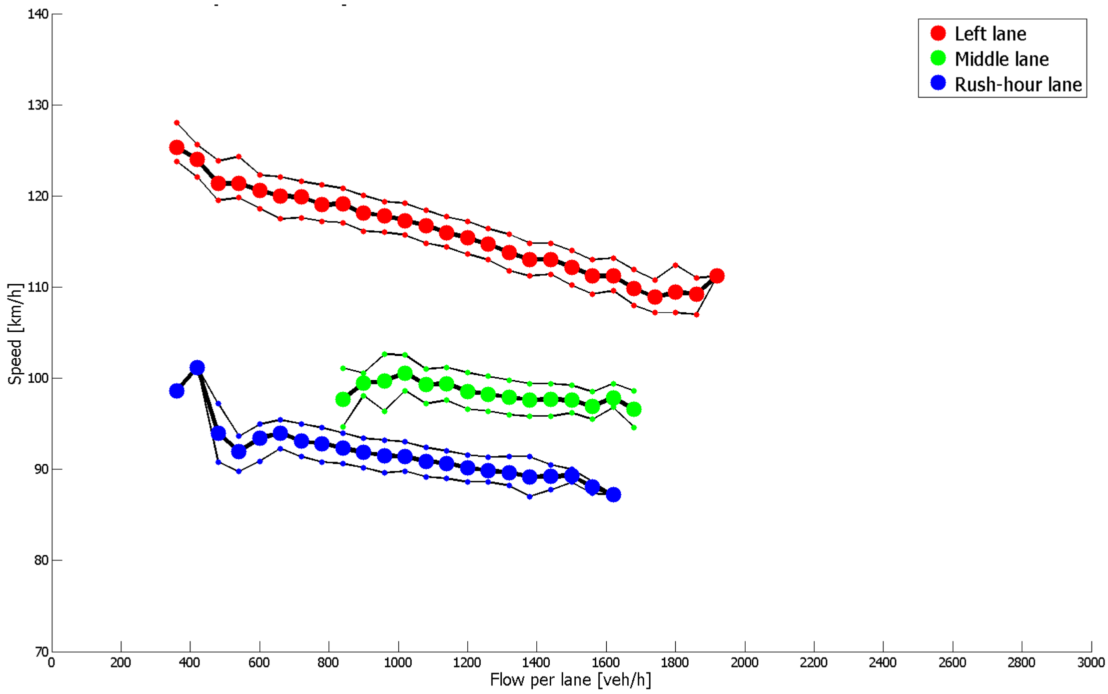
19 Intensity-speed graphs

Rush-hour lanes

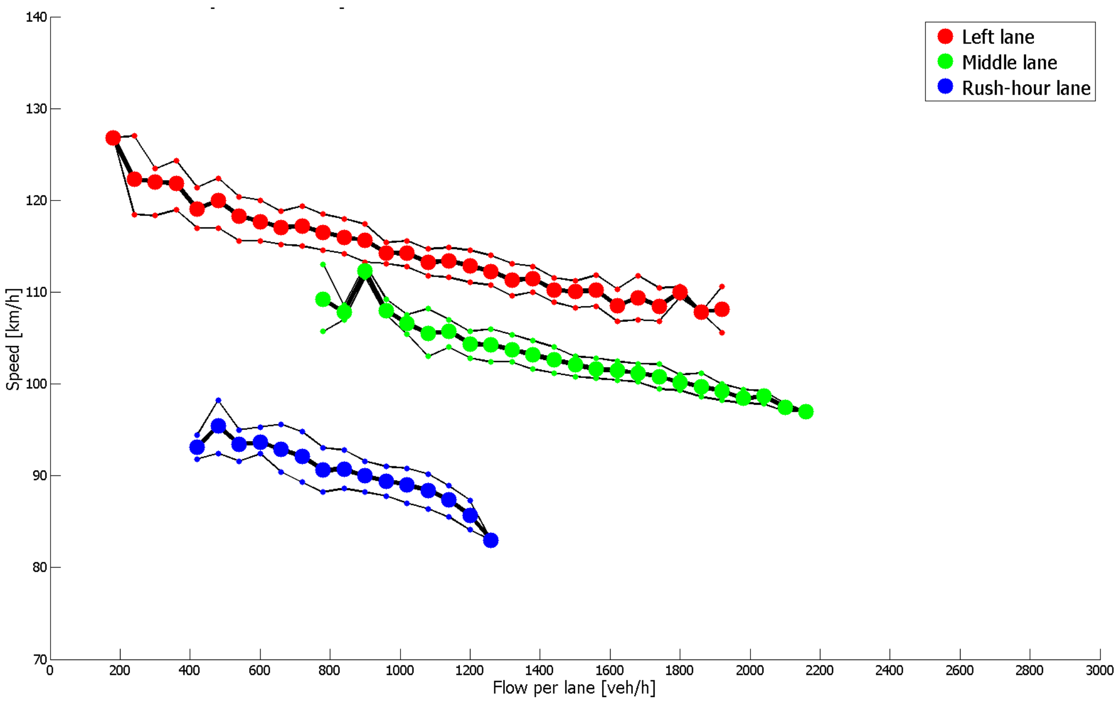
A1 - Hoevelaken-Barneveld



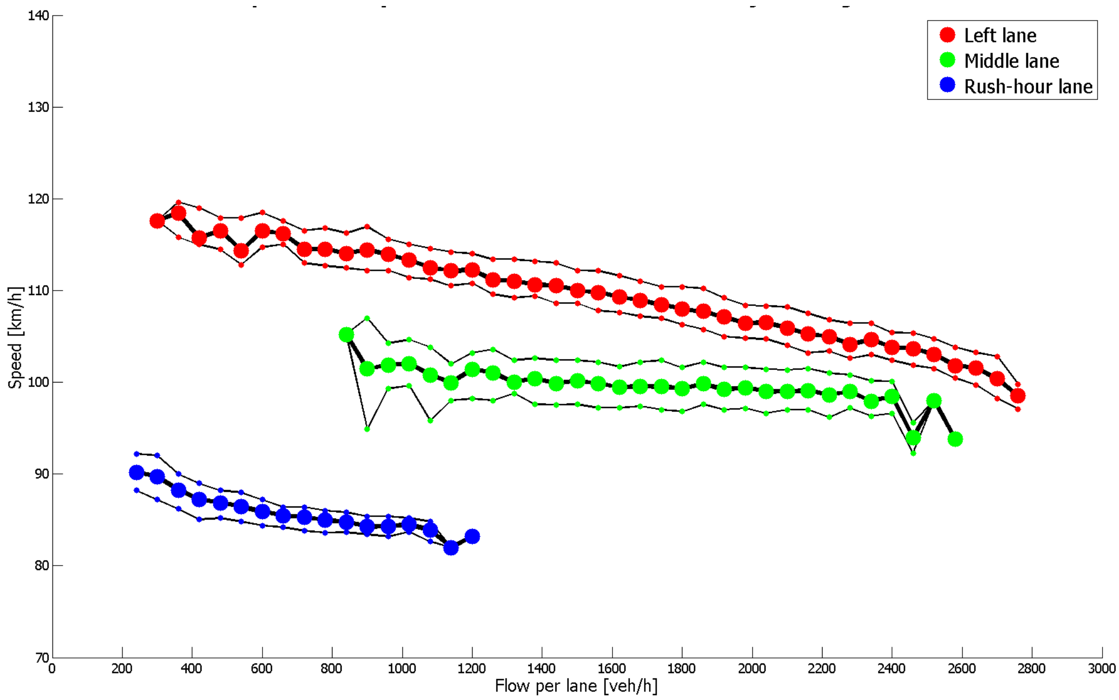
A2 - Vonderen-Kerensheide



A2 - Kerensheide-Vonderen

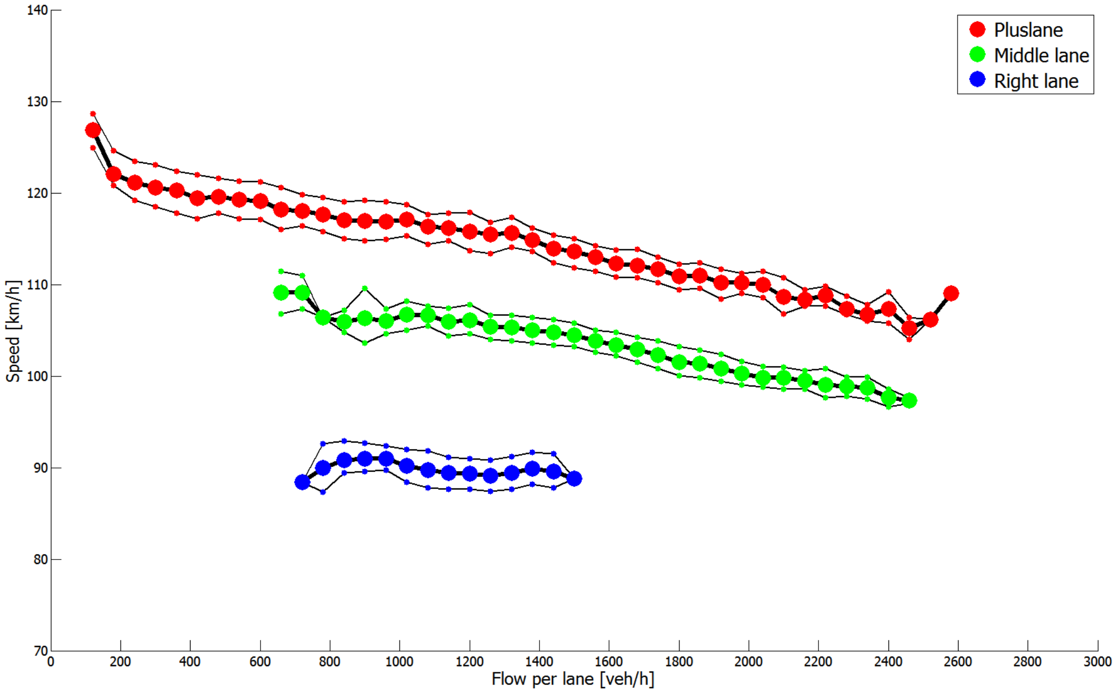


A50 - Ewijk-Valburg

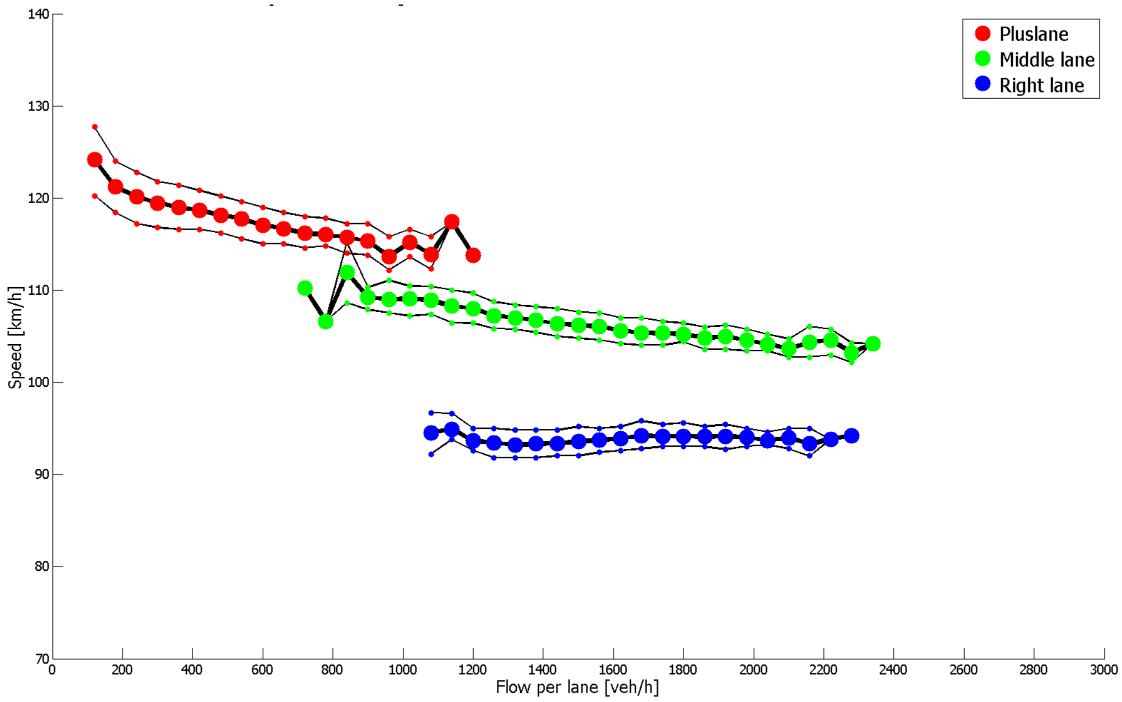


Pluslanes

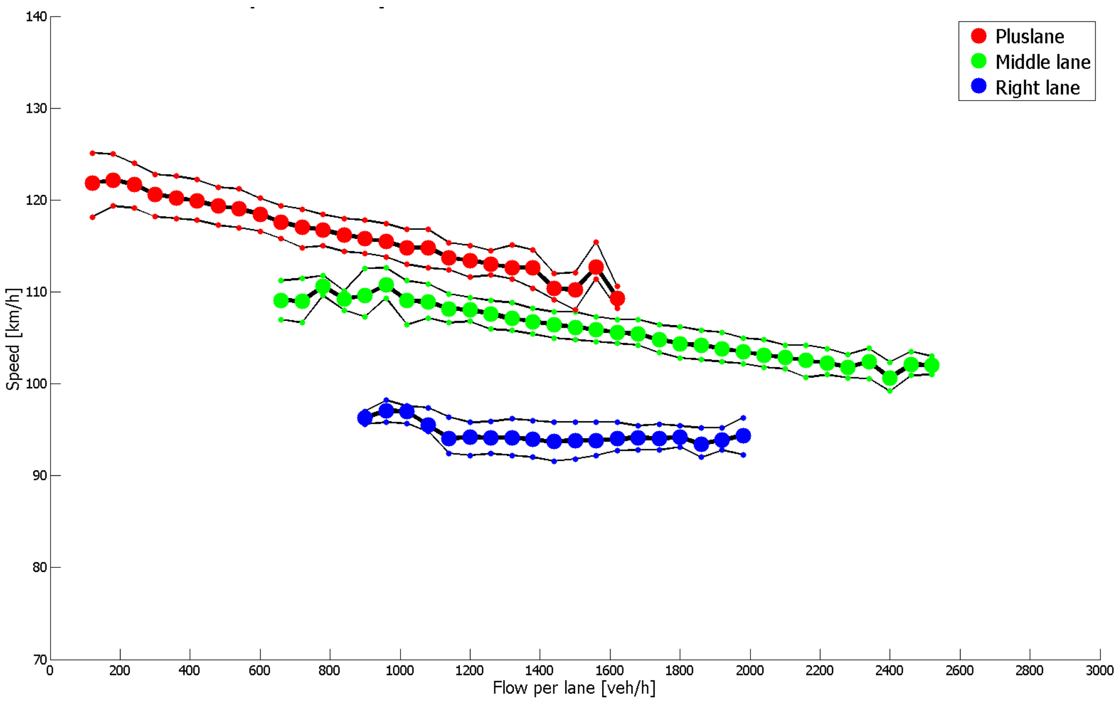
A1 - Beekbergen-Deventer-Oost



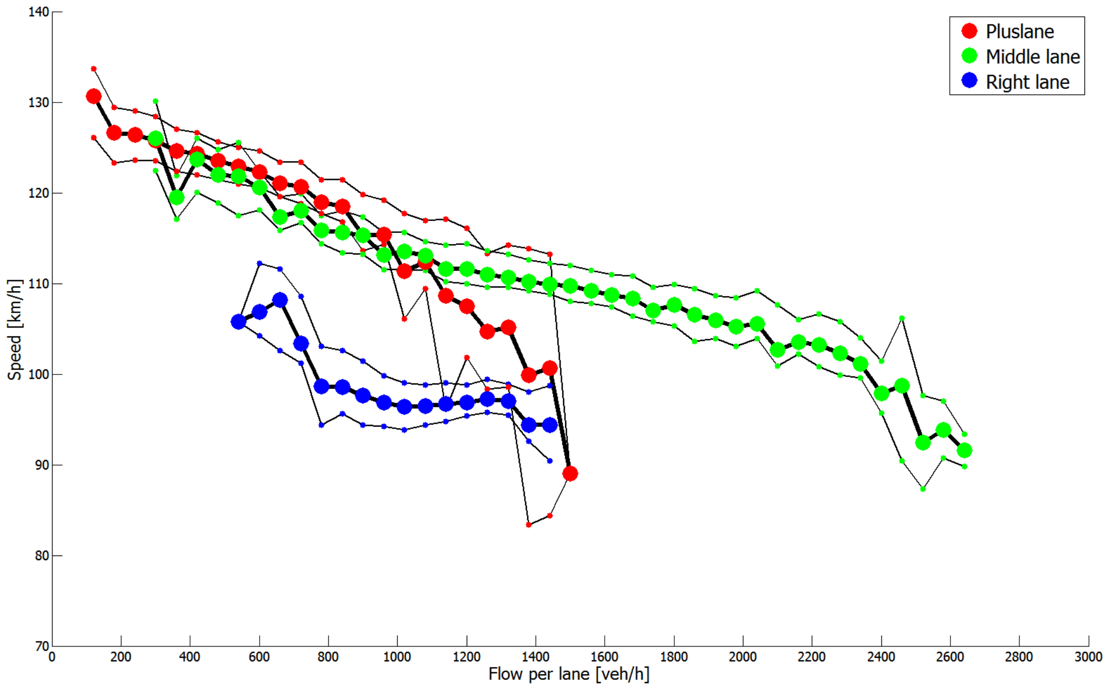
A12 - Ede-Veenendaal



A12 - Zoetermeer-Gouwe

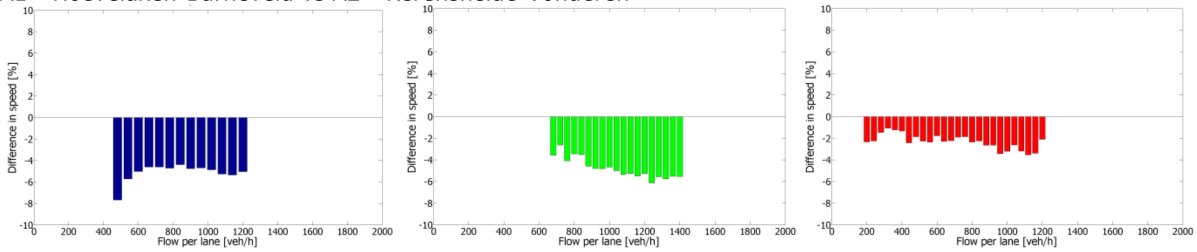


A27 - Gorinchem-Noordeloos

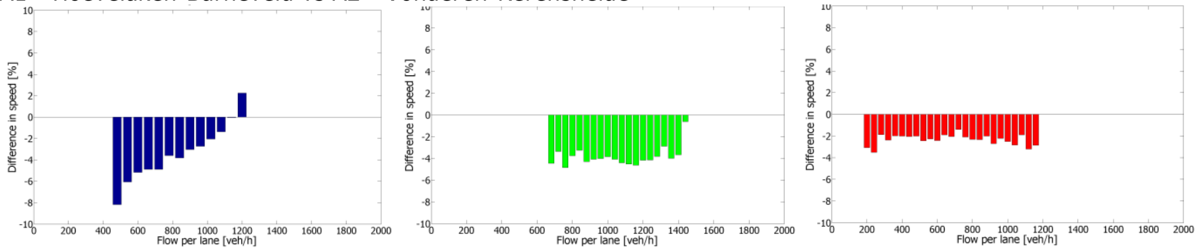


20 Speed differences rush-hour lanes

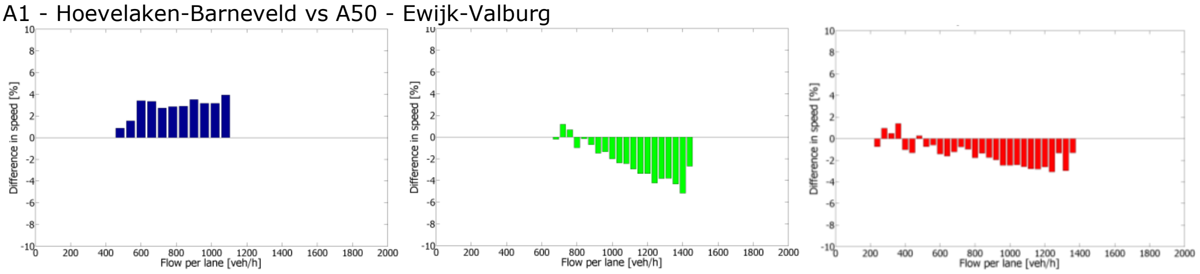
A1 - Hoevelaken-Barneveld vs A2 - Kerensheide-Vonderen



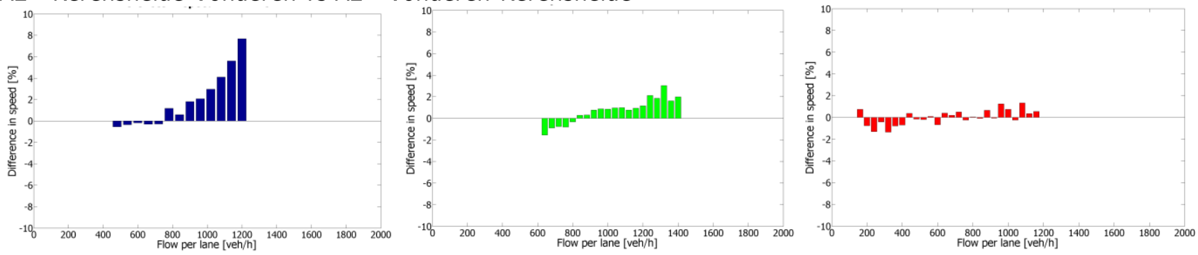
A1 - Hoevelaken-Barneveld vs A2 - Vonderen-Kerensheide



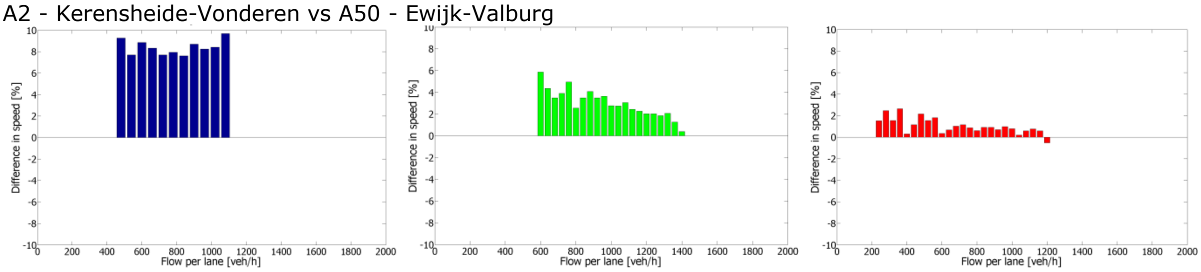
A1 - Hoevelaken-Barneveld vs A50 - Ewijk-Valburg



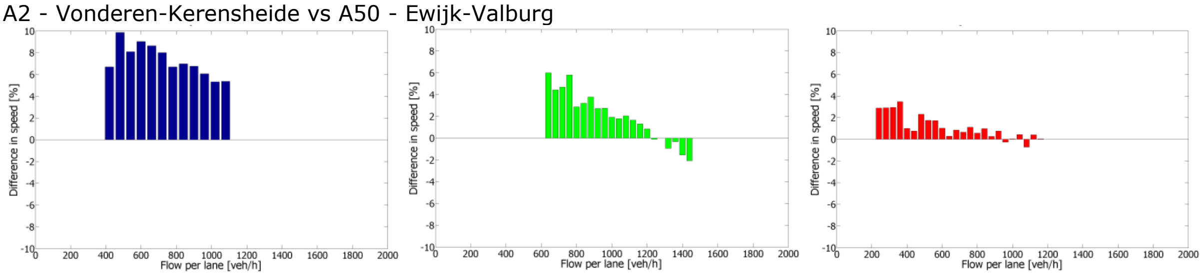
A2 - Kerensheide-Vonderen vs A2 - Vonderen-Kerensheide



A2 - Kerensheide-Vonderen vs A50 - Ewijk-Valburg

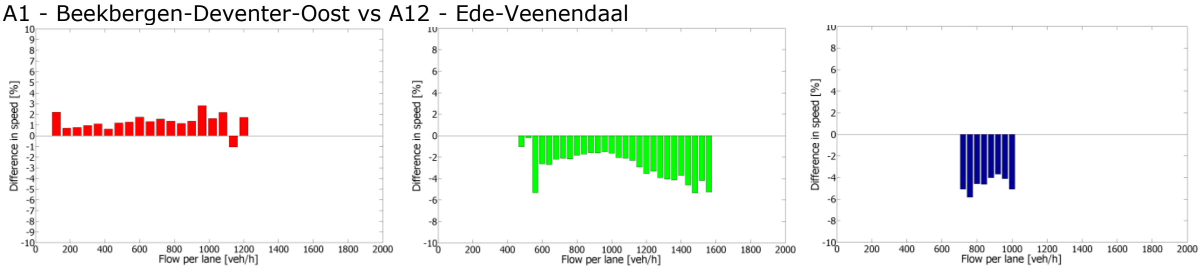


A2 - Vonderen-Kerensheide vs A50 - Ewijk-Valburg

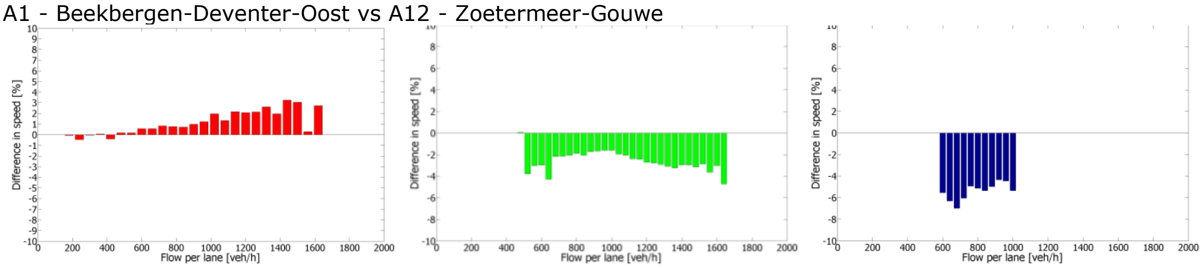


21 Speed differences pluslanes

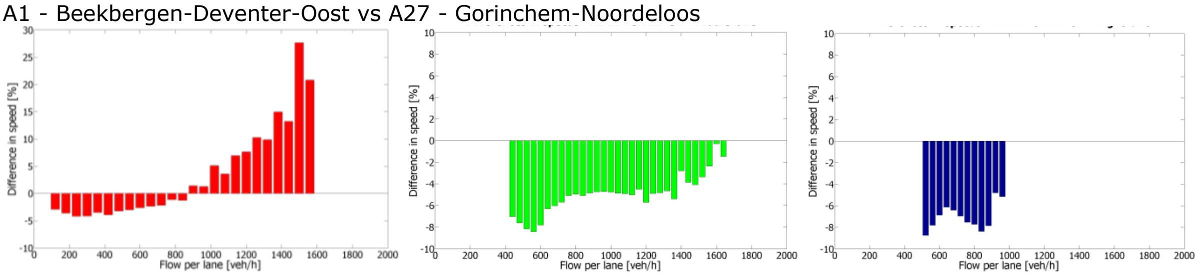
A1 - Beekbergen-Deventer-Oost vs A12 - Ede-Veenendaal



A1 - Beekbergen-Deventer-Oost vs A12 - Zoetermeer-Gouwe

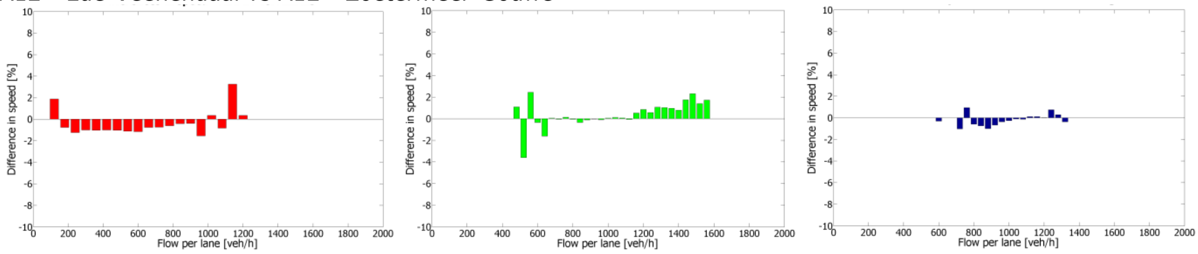


A1 - Beekbergen-Deventer-Oost vs A27 - Gorinchem-Noordeloos

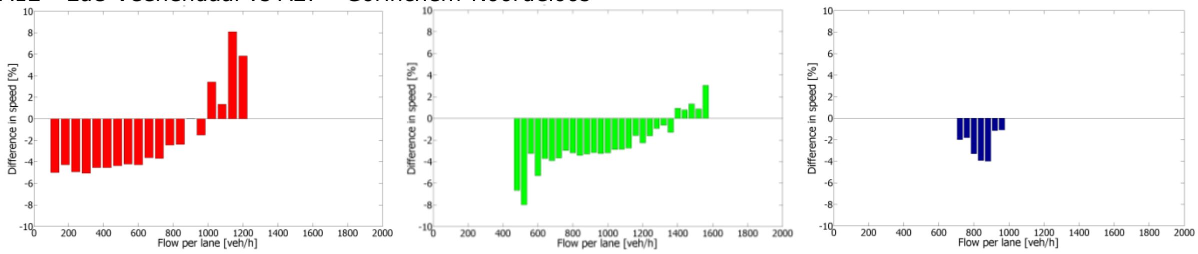


** Note the difference in scale*

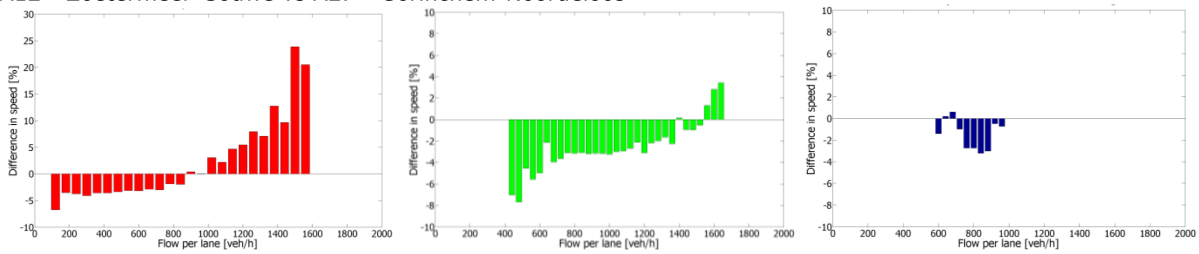
A12 - Ede-Veenendaal vs A12 - Zoetermeer-Gouwe



A12 - Ede-Veenendaal vs A27 - Gorinchem-Noordeloos



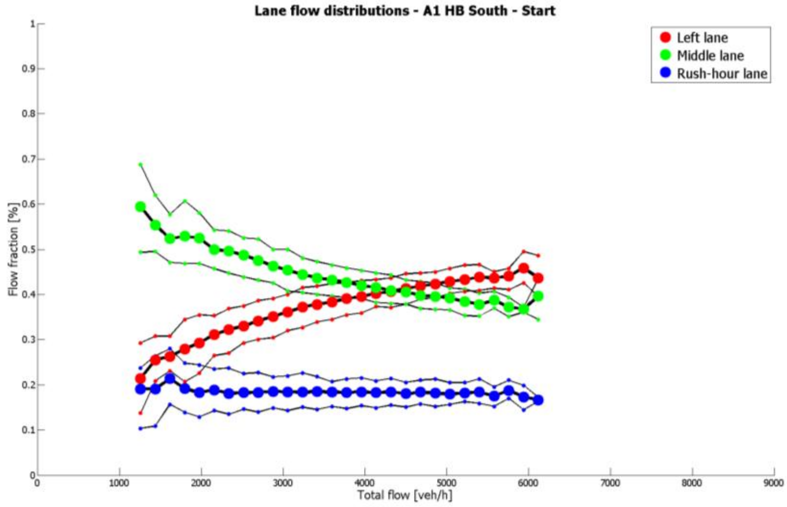
A12 - Zoetermeer-Gouwe vs A27 - Gorinchem-Noordeloos

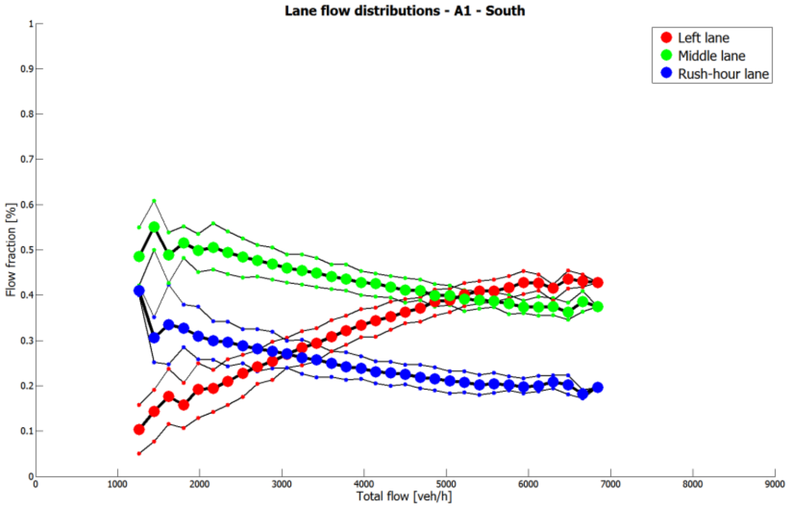


22 Lane flow distributions

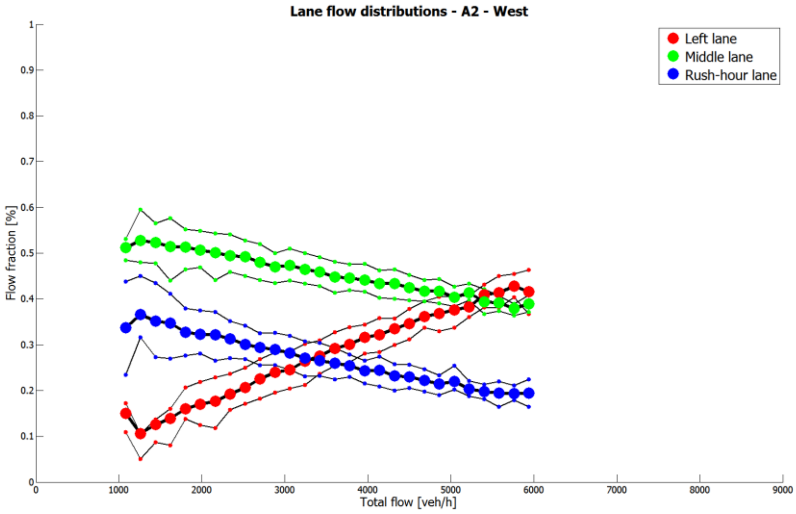
Rush-hour lanes

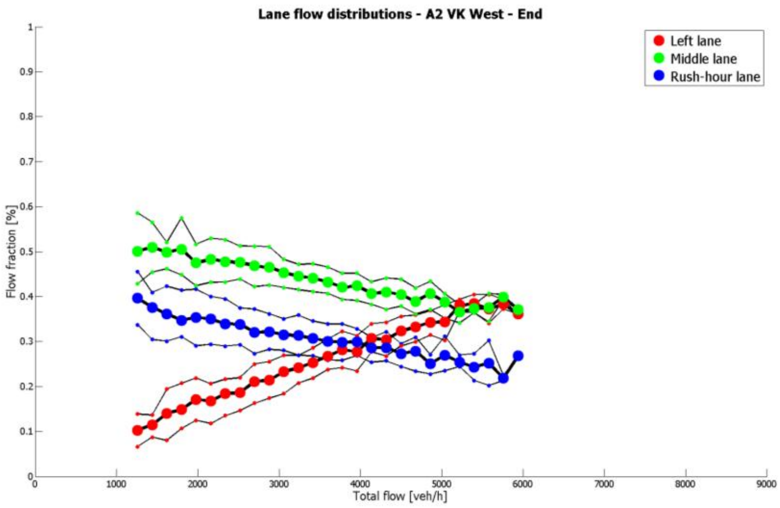
A1 - Hoevelaken-Barneveld



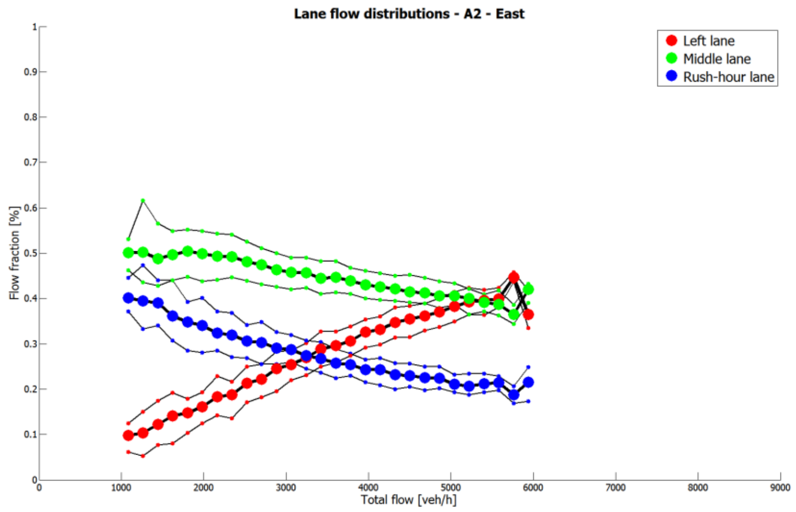


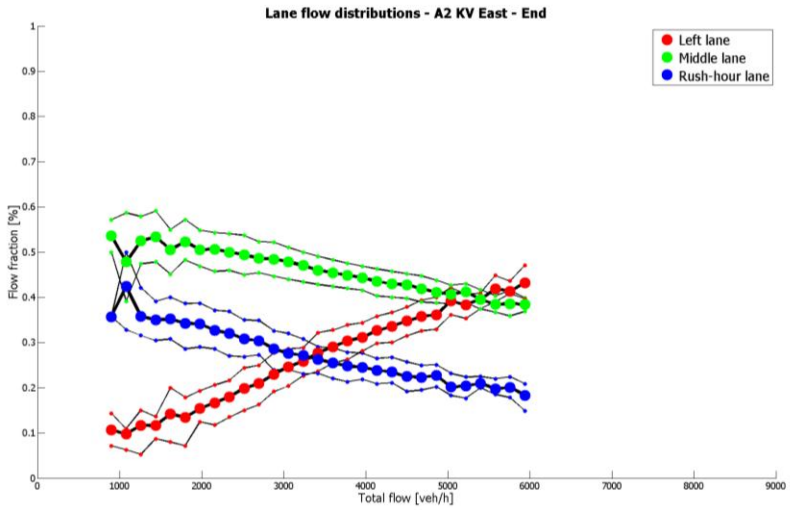
A2 - Vonderen-Kerensheide



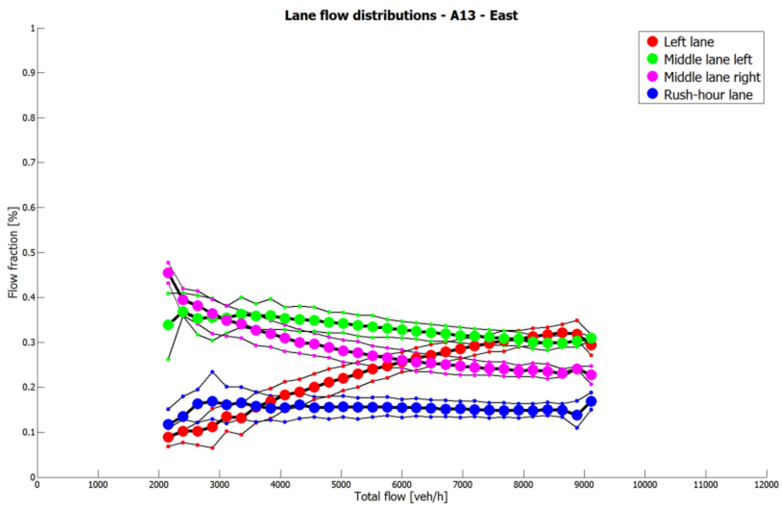


A2 - Kerensheide-Vonderen

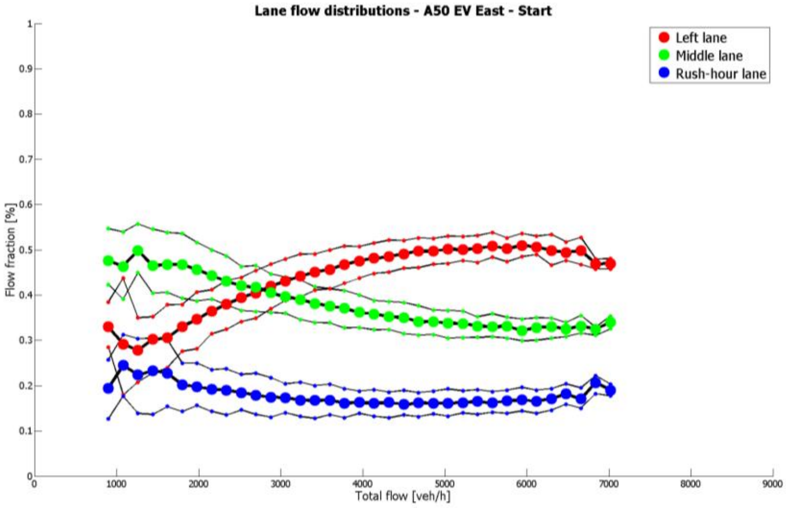


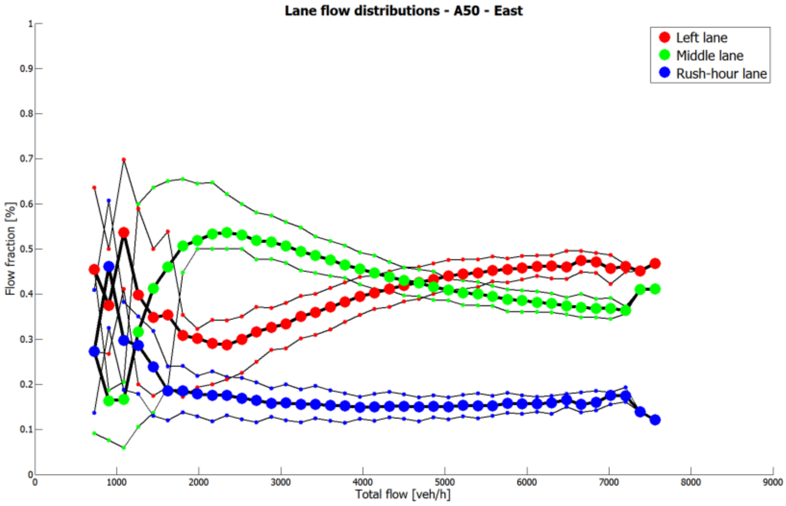


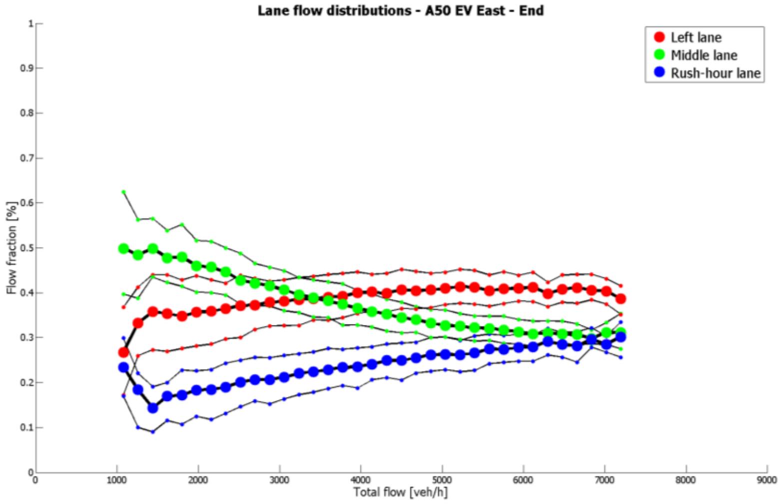
A13 - Berkel & Rodenrijs-Delft-Zuid



A50 - Ewijk-Valburg

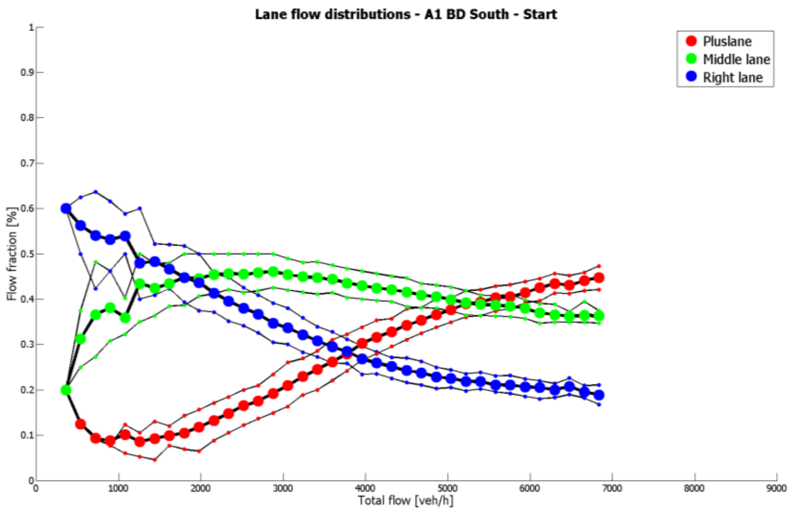


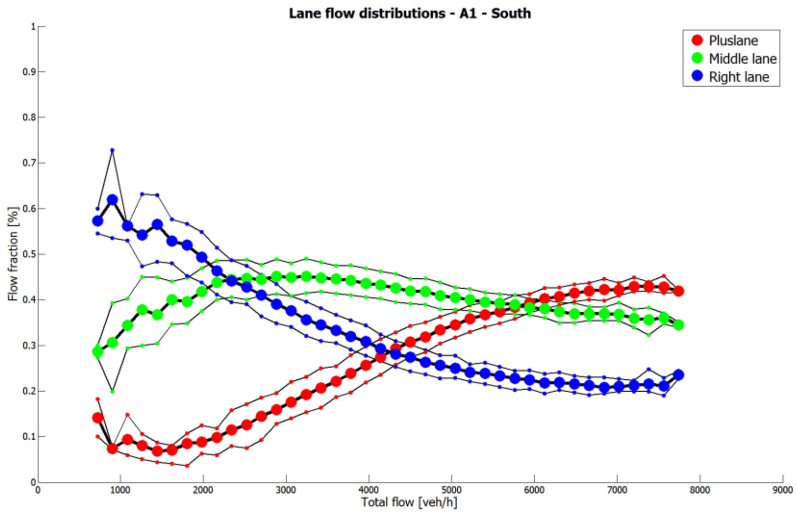


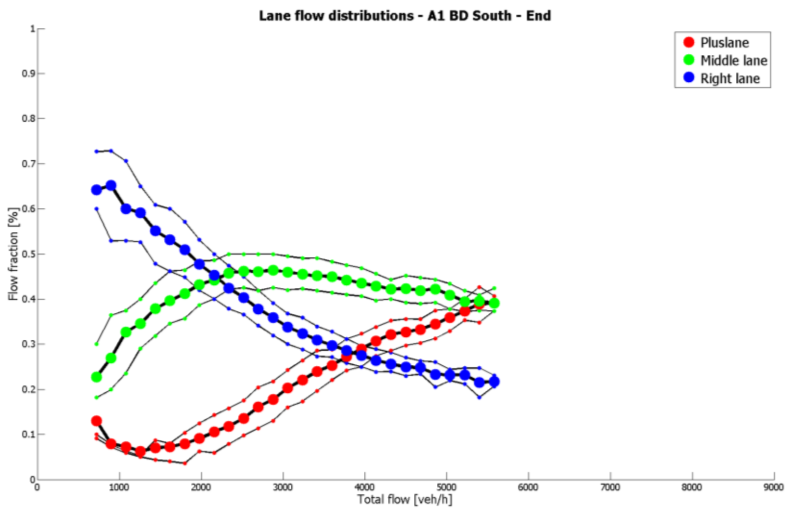


Pluslanes

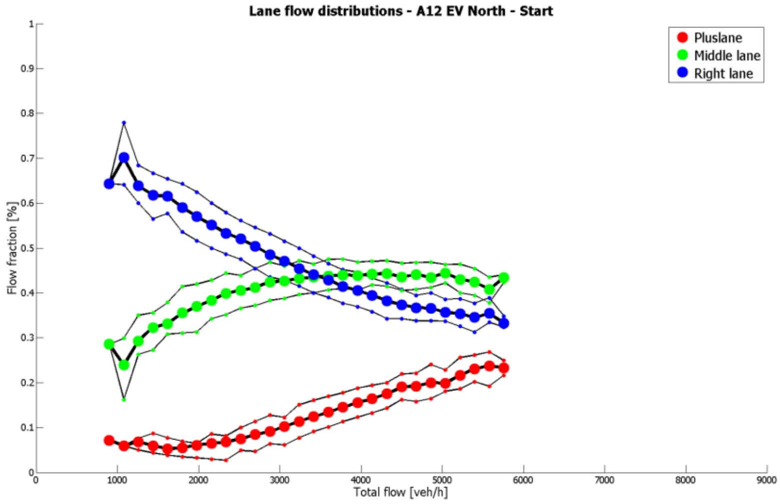
A1 - Beekbergen-Deventer-Oost

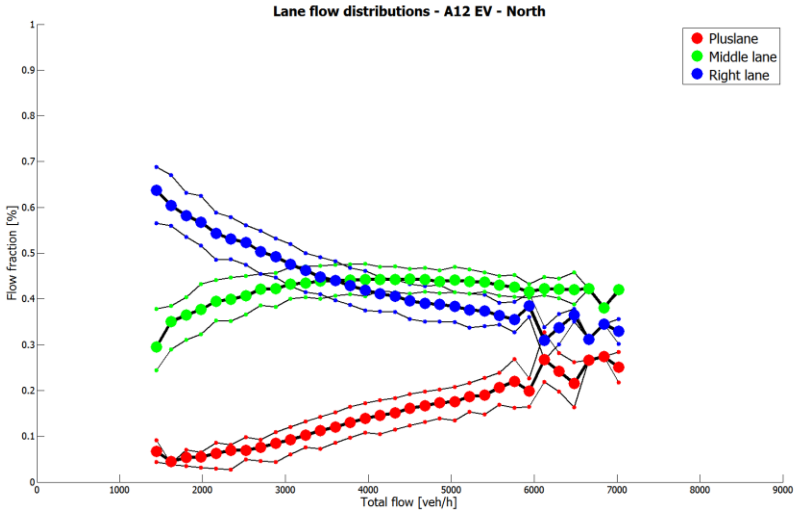




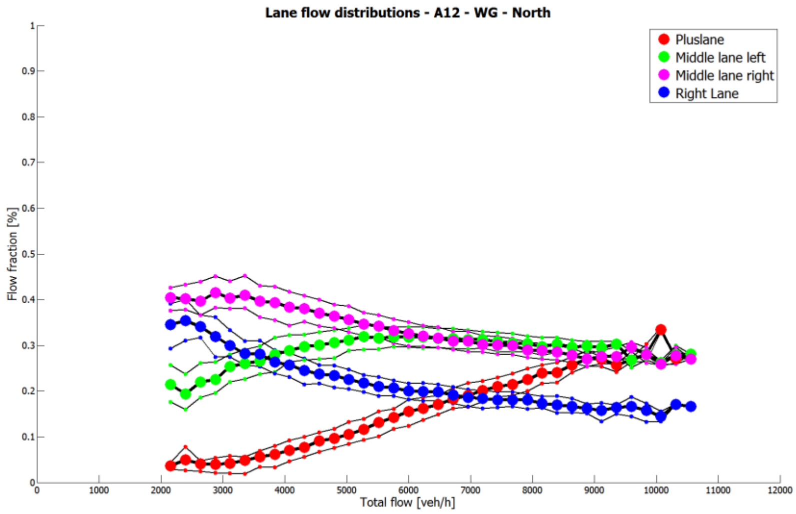


A12 - Ede-Veenendaal

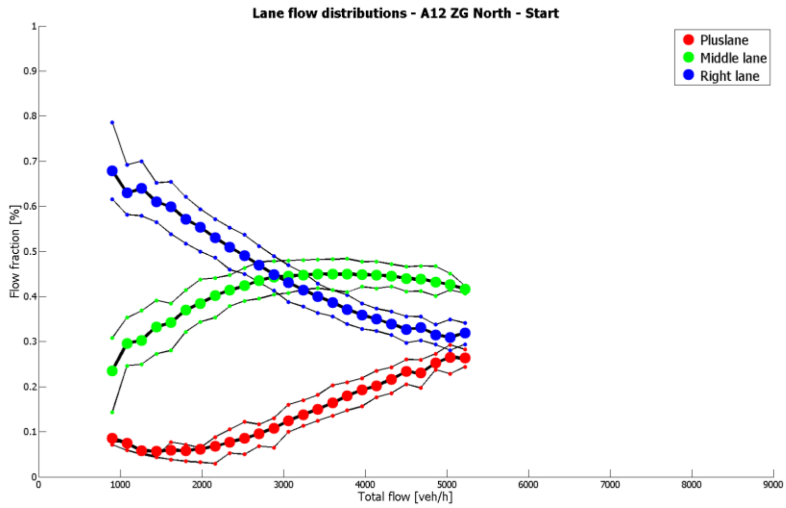


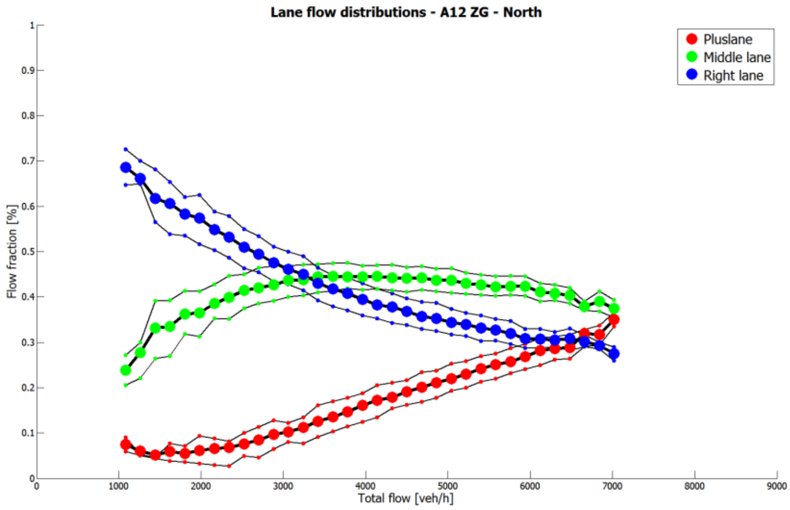


A12 - Woerden-Gouda

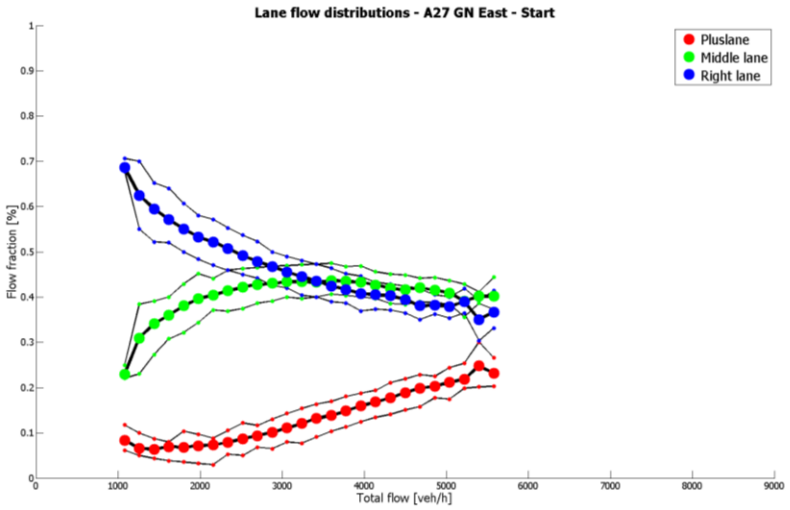


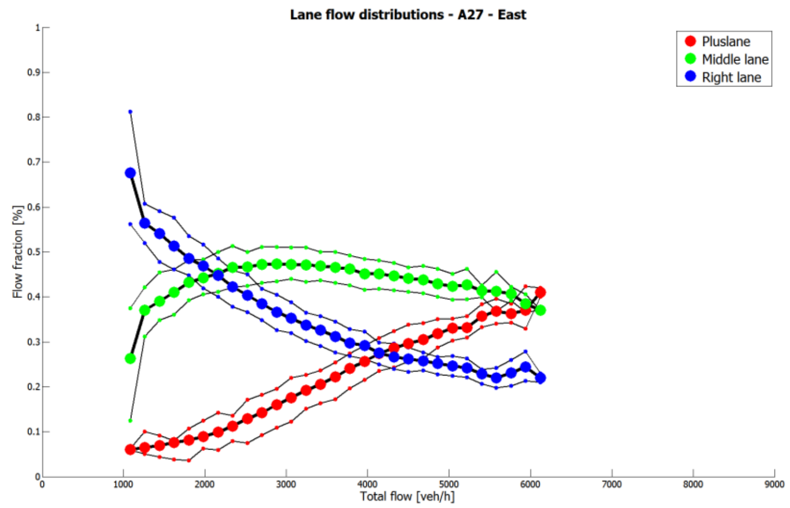
A12 - Zoetermeer-Gouwe

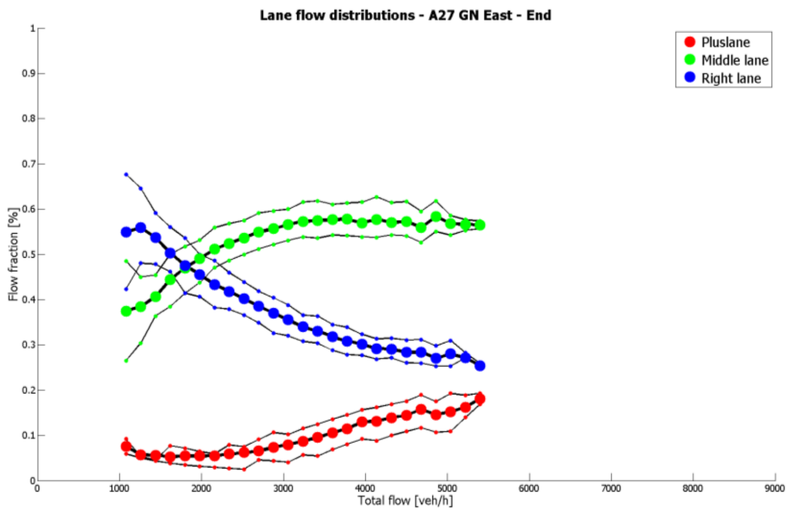




A27 - Gorinchem-Noordeloos







23 Truck percentages

Truck percentages are derived from Figure 21.1 and Figure 21.2. They are collected from a research performed by (Bogaerts, 2006). Also, they are compared with values from literature if possible.

Figure 23.1: Truck percentages predicted for 2020

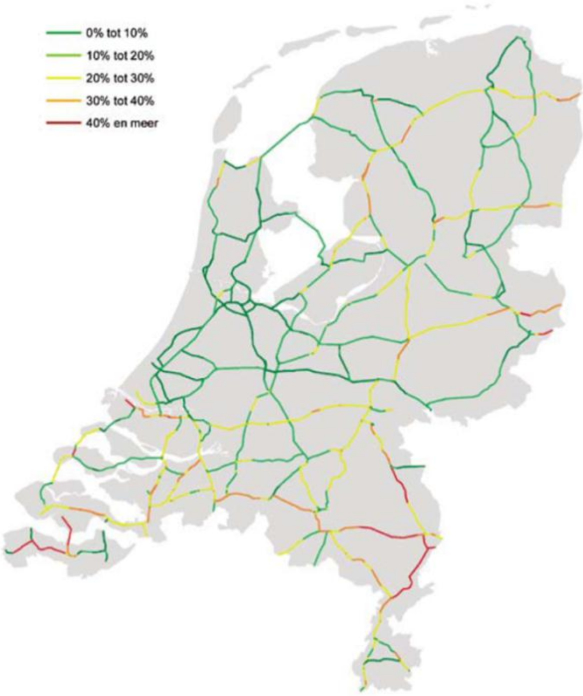


Figure 23.2: Truck percentages 2004

3 Lane section	Truck % 2004	Truck % 2020	Truck % lit*
A4 Leidschendam - Zoeterwoude-Dorp	0 - 10	0 - 10	-
A16 ‘s-Gravendeel - Klaverpolder	10 - 20	20 - 30	-

Rush-hour lane section	Truck % 2004	Truck % 2020	Truck % lit*
A1 Hoevelaken - Barneveld	10 - 20	0 - 10	14% (MER,2006)
A2 Kerensheide - Vonderen	10 - 20	20 - 30	20% (MER,2010)
A2 Vonderen - Kerensheide	10 - 20	20 - 30	20% (MER,2010)
A13 Berkel & Rodenrijs - Delft-Zuid	0 - 10	0 - 10	-
A50 Ewijk - Valburg	20 - 30	20 - 30	30% (TN,2005)

Pluslane section	Truck % 2004	Truck % 2020	Truck % lit*
A1 Beeksbergen - Deventer-Oost	20 - 30	20 - 30	26% (VR)
A12 Ede - Veenendaal	10 - 20	0 - 10	15% (TN,2001)
A12 Zoetermeer - Gouwe	0 - 10	0 - 10	10% (MER,2003)
A12 Woerden - Gouda	0 - 10	0 - 10	-
A27 Gorinchem - Noordeloos	10 - 20	0 - 10	-

* ‘Truck % lit’ shows the truck percentages as found in literature. Indicated behind the % value is the type of document where the truck percentage is found. WAB = wegaanpassingsbesluit (road change decision, literal translation), MER = Milieu-effectrapportage (environmental impact assessment), TN = trajectnota (route note, literal translation), VR = Verkenningsrapport (exploring report)

24 Participants

nr.	Gender	Age	Experience	Layout order	Intensity level	Comments
1	Male	43	25	0123	low	
2	Male	26	8	1032*	low	Layout 0 failed first time
3	Male	28	8	0213	low	Layout 2 filtered out*
4	Male	57	35	0231	low	
5	Male	44	25	0312	low	
6	Male	24	6	0321	low	
7	Male	62	41	0123	medium	
8	Male	25	7	0132	medium	Layout 2 filtered out
9	Male	24	6	0213	medium	Layout 3 filtered out
10	Male	28	10	0231	medium	
11	Male	45	26	0312	medium	Layout 0 filtered out
12	Male	27	9	0321	medium	
13	Female	23	5	0123	low	
14	Male	54	36	0132	low	Layout 3 filtered out
15	Female	31	7	0213	low	
16	Male	24	6	0231	low	
17	Male	50	32	0312	low	Layout 0 filtered out
18	Male	53	35	0321	low	Layout 0 and layout 3 filtered out
19	Female	53	31	0123	medium	
20	Male	25	5	0132	medium	
21	Male	76	58	0213	medium	
22	Female	24	6	0231	medium	Layout 0 and layout 2 filtered out
23	Female	25	1	0312	medium	
24	Male	25	6	0321	medium	Layout 0 and layout 3 filtered out

* Layout filtered out because of crash at the rush-hour lane, not because of low intensities