The development of CCC advices and the effects on traffic flow and safety

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Preface

This report is written to present the results of a six months research performed at TNO as part of the master thesis of the master Transport Infrastructure and Logistics. The research contains the design and micro-simulation of advices for drivers in a (nearly) congested area due to a lane-drop. The advices are to be used by a system called Connected Cruise Control (CCC). This research indicates which advices should be given by CCC and what the influence will be on the traffic situation.

It was great to have the opportunity to do my master thesis on this topic since I was able to learn many things, and the subject is very interesting. CCC shows promising results, so maybe I will have it in my own car one day. I started my thesis with learning the programming language java, in which the ITS modeler is written. Many thanks to my supervisors Wouter Schakel and Gerdien Klunder and many members of the TNO department of Smart Mobility who helped me to understand this language until I was able to write code on my own.

Once the model was running and the output could be analyzed it saved lots of time that I had learned to work with Matlab. Thanks again to Gerdien Klunder and to Jos Carriere and Damir Vukovic who helped me to learn the Matlab language and way of thinking.

Eline Jonkers and Tanneke Ouboter helped me to better interpret the model outcomes, many thanks to them as well.

I also like to thank my supervisors Marjan Hagenzieker, Wouter Schakel, Gerdien Klunder and Bart van Arem for their valuable support during the report writing stage.

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Ewald Harmsen
Abstract
The current study focused on which advices should be given by an in-car system, Connected Cruise Control, (CCC) to drivers in a nearly congested situation in case of a lane drop. Using a micro simulation with a specially adapted vehicle model, a highway with a lane drop and cars as the only user class was modeled. Three advices were found to have a positive effect on the traffic situation: a lane change advice to go to the right-lane for drivers on the middle-lane, a speed advice for drivers on the left-lane, and a headway advice for drivers on the middle-lane. These three advices are found to have already an impact for small penetration rates. With a penetration rate of 40% and a compliance rate of 100% the vehicle loss hours decreased with 67.5%, and the maximum measured flow increased with 4.06%. With trucks implemented the advices still have a positive influence on the traffic situation. Given the fact that CCC can be installed in cars easily, and the positive results of the current study, CCC is worth investing in.
Summary

Congestion is a problem on many highways in the Netherlands, and it is expected that the traffic demand will increase. This will cause a doubling of the time drivers loose in congested traffic situations, while the amount of emissions increases as well, both in small particles as in CO$_2$ and NO$_x$ (Vlieger, et al., 2000).

Connected Cruise Control (CCC), which is currently in the developing stage, aims to limit these negative effects by optimizing the traffic flow during (nearly) congested situations. CCC will give advices to individual drivers by use of an in-car system, but it is not yet known which advices should be given. This study focus is on the advices to be given at a lane drop location.

The main research question is:

*How can the traffic flow be improved at a lane drop location using CCC?*

This research question is divided into three sub-questions:

- What are good triggers for the CCC system?
- Which lanes should receive which CCC advice?
- How does the CCC penetration rate influence the traffic flow?

To answer these questions a micro-simulation study was performed. 6.6 km of the highway between Rotterdam and Gouda was simulated, including the lane drop from three to two lanes nearby Nieuwerkerk aan den Ijssel. As reference day the 8th of June 2009 was used. On this day congestion due to the lane drop occurred between 6.10 and 7.30 AM. The simulation excluded the existence of trucks and the on- and off-ramp to Nieuwerkerk aan den Ijssel since, at this stage, it was considered too complicated to measure the advice effects in these situations.

The simulation was performed with the help of the micro-simulation tool Paramics. The ITS modeler plugin as developed by TNO in combination with the Lane change Model with Relaxation and Synchronization (LMRS) (Schakel, et al., 2011) is used to implement the CCC advices.

Three advices given to drivers were tested on several lanes: a lane change advice to change to the lane at the right, a headway advice and a speed advice. These advices were given to CCC drivers which are up to three km before the lane drop. The headway and lane change advice were only given when the speed of the driver was above 100 km/h.

The CCC system started to give advices when two out of the following conditions were met:

- Flow on all lanes exceeds 4020 veh/h.
- Flow on middle- or left-lane exceeds 2040 veh/h.
- Speed on middle- or left-lane is below 80 km/h.

The CCC system stopped giving advices when all following conditions were met:

- Flow on all lanes below 3480 veh/h.
- Flow on middle- and left-lane below 1800 veh/h.
- Speed above 90 km/h.

These flows and speeds were measured by four detectors which are located up to one km before the lane drop.

It was found that a lane change advice and a headway advice to CCC drivers on the middle-lane in combination with a speed advice to CCC drivers on the left-lane have the largest positive effect on traffic.
flow. The headway advice holds that drivers increase their headway to three seconds, and the speed advice holds that drivers decrease their speed to the speed on the lane to their right.

It was found that the above described CCC advices show positive effects for all tested penetration rates. The smallest tested penetration rate, 2%, showed a small positive effect. The higher the penetration rates the more the decrease of congestion. With a maximum penetration rate of 40%, an increase of maximum flow of 4.06% was found and a vehicle loss hours reduction of 67.5%, from 13.16 h in the basic situation to 4.28 h in the situation with 40% penetration, see figure 1. These results fit well in the outcomes of the studies on other systems which aim to optimize traffic flow, which show results of up to 60% travel time reduction and a capacity gain of up to 25% (van Driel & van Arem, 2010; Minderhoud, 1999). In reality these results will be (slightly) less positive because of the used compliance ratio of 100% in this study, which most probably does not reflect the real situation.

The average speed increased due to CCC which could mean a decrease in safety. However, the standard deviation in speed, the speed difference between lanes, the density difference between lanes, and the percentage of Time To Collisions smaller than 4 seconds decreased, which could be beneficial for safety. However, no conclusion can be made on the effect of CCC on safety, since it is not known how these negative and positive effects on safety interact with each other in reality.

Results showed that the advices as defined in the current study were very sensitive to the presence of trucks or a busy on- and off-ramp in the neighborhood of a lane drop. It is therefore advised to do extra research on how to deal with these factors.

As the current study had very positive results, especially for an informative system which does not influence a car directly, it shows that CCC is worth investing in.

![Figure 1: Indicator values per CCC penetration rate](image-url)
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1. Introduction

Congestion is a problem on many highways in the Netherlands. Although the amount of vehicle km decreased during the last few years, an increase of 12% to 17% vehicle km is expected between the year 2011 and 2015 (Francke, et al., 2010). This increased traffic demand will cause an expected increase of vehicle loss hours of 4% to 30%, while the amount of emissions increases as well, both in small particles as in CO₂ and NOₓ (Vlieger, et al., 2000). The effect of increasing traffic volumes at safety is not clear, as found by a literature study done by Marchesini & Weijermans (2010). At the rear and the front of congested area’s more accidents occur but in the queue itself less accidents seem to happen.

The means by which this congestion problem is tried to be minimized includes not only the building of new roads, but a better use of the existing roads as well. One of the ways to improve road utilization is the use of Advanced Driver Assistance Systems (ADAS). These in-vehicle systems try to optimize the traffic flow, safety or comfort by implementing smart technology into individual cars. Some of these systems, like the adaptive cruise control (ACC), take over certain driving tasks. In case of ACC this means that the driver does not have to manually accelerate to reach the desired speed or brake in case of a predecessor with a lower speed. Others, like route navigation with congestion information, only give messages to the driver. The driver can make a decision based on this information, which possibly decreases the travel time.

An in-vehicle system which supports the driver to anticipate the predicted downstream traffic situation is not yet available (Klunder, et al., 2011). Connected Cruise Control (CCC) is developed to fill this gap. This system will give lane specific advices to the driver, based on the predicted traffic situation several km ahead. These advices will help drivers to anticipate future problems and perform actions based on that. The main aim of CCC is to improve the traffic flow.

CCC is still in the developing phase and it is not yet known when the advices should be given in order to receive the desired traffic situation on time, to which lanes which advices should be given, or what the effects of the advices are. The minimum penetration rate the CCC system needed to have a significant influence on the traffic situation is also an unknown factor. This research aims to fill in this knowledge gap for one specific situation, a lane drop from three to two lanes, by use of a simulation study.

The central research question for this study is:

*How can the traffic flow be improved at a lane drop location using CCC?*

To further specify this research question, several sub-questions were formulated:

- What are good triggers for the CCC system?
- Which lanes should receive which CCC advice?
- How does the CCC penetration rate influence the traffic flow?

Although this research focused mainly on traffic flow, some indicators to study the safety effects were implemented as well. These outcomes are presented, but no extra research to improve the safety was performed.

This document is organized as follows. In chapter 2 a specific literature review consisting of a description of ADA systems, how they are studied in a simulation, the results of these studies, and the relevance for
this study is given. Chapter 3 gives the methodology as used for this study. In chapter 4 the CCC implementation is described. Chapter 5 gives the experimental plan. Chapter 6 describes the results of verification and validation and the results of the experiments. In chapter 7 the research outcomes are discussed. Chapter 8 gives the final conclusions and recommendations.
2. Literature review

This chapter describes several Advanced Driver Assistance (ADA) Systems from literature in order to create an overview of which types of systems exist, which methodology was used to study them, and what the measured effects on the traffic situation and safety are. The focus of this chapter is on studies on traffic flow improvement with the use of a traffic simulation tool. This chapter concludes with a section on what can be learned from the described methodologies and a section about which results can be expected for this study.

2.1. ADA systems overview

There is currently a wide range of ADA Systems available or in development. This range varies from route guidance systems, which give information on the route to follow, to the Intelligent Parking Assist System (IPAS) which parks your car completely automatically. All these systems try to optimize the traffic flow, safety or comfort by implementing smart technology into individual cars.

The ADA Systems can be divided in three sub-classes; intervening, warning, and informative (Spyropoulou, et al., 2010). An intervening system will perform the required actions, like braking and accelerating, automatically. A risk of such a system is that the reaction time will increase due to the fact that drivers do not have to drive actively (van Arem, et al., 2010; Brookhuis, et al., 2001; Spyropoulou, et al., 2010). An advantage is that these systems have the largest positive impact on traffic flow compared to warning and informative systems (Knoop, et al., 2010).

A warning system can give a warning by use of sound, light or counterforces to the steering wheel or gas pedal. Users of a warning system can choose to neglect this warning. A weakness of this system is that drivers on which the system has the highest impact have a tendency to neglect the system earlier (van Arem, et al., 2010).

An informative system does not influence the car directly, but gives warnings and advices to the driver. Research shows that current informative systems have no significant effect on driver behavior and thus on safety or traffic flow (Dutch Road Authority, 2007). The main advantage of informative systems however, in contrast to the intervening systems, is that the driver remains active. Another advantage is that these systems are more easily accepted by users and can be more easily implemented in existing cars since they can be installed like a normal navigation system.

All three system types are used in the ADA Systems as described in the next sections.

2.2. Adaptive Cruise Control (ACC)

ACC is an intervening system which automatically maintains a safe time gap between a car and its predecessor. The goal of ACC is an increased comfort level for the driver. However, it has an influence on the traffic flow as well. An ACC system can control the speed of a vehicle and the distance to a predecessor better than a driver can. This means less high decelerations and less unintentional speed changes when using ACC, which reduces congestion (van Driel & van Arem, 2010).

A safe headway distance is considered to be two seconds, although headways are mostly below one second (Taieb-Maimon & Shinar, 2001). Since ACC has a much smaller response time than humans, the safe headway time can decrease significantly. A smaller headway means less needed space per vehicle and thus a higher capacity of the road.

Minderhoud (1999) studied the effects of ACC and found an increase of road capacity of up to 4 % when the ACC headway was set to a value of 0.8s and the penetration was set to 10%. A higher penetration rate of ACC means a higher capacity gain, up to 25% with a penetration rate of 100%.
For the research of Minderhoud (1999) the following methodology was used. First the experimental setup was made followed with a general description of microscopic models. After that the requirements for the model application were defined. Once the requirements were clear, the evaluation of existing models was done, to find a suitable model. Since no existing model met the requirements it was decided to build a new model (Simone). All assumptions of the Simone model are listed as well as the ACC specific assumptions. Once the experimental setup and the used model with its parameters were known the simulation study was performed and the results were analyzed.

The effect on safety of ACC is discussed in a literature study done by Christoph (2010). It was concluded that ACC can have a positive effect on safety when there is no congestion; the number of accidents in one study decreased with 12.9%. In congested traffic the use of ACC can have a negative influence on safety.

### 2.3. Intelligent speed adaption (ISA)

ISA compares the actual speed with the maximum allowed speed (van Arem, et al., 2010). If the speed is too high the system will automatically reduce the speed or give a warning to the driver. The system is also known as External Cruise Control (ECC) (Aikim, et al., 2000). ISA is developed to increase the safety on the roads.

The following methodology for the modeling of Intelligent Speed Adaptation (ISA) was used by Spyropoulou et al. (2010):

1. Decide between macro and micro simulation
2. Select a traffic model and select a traffic simulation tool
3. Identify the relevant model parameters
4. Define and implement parameter values, by use of a simulator study.
5. Thorough examination of the traffic simulation tool code to determine which sections should be adapted for the implementation of ISA.

Using this approach a significant influence of ISA on travel time was found, due to lower speed variations and thus lower accelerations and decelerations. However this was only true for the intervening ISA system; the informative and warning system only had an influence during free flow conditions. For the intervening system the travel time reduced from 127.38 s to 65.38 s, a decrease of 48.7 %. This result was found during medium flow of 1000 veh/h measured per lane over a length of 1.5 km with a penetration rate of 100 %. During heavy flow, 1600 veh/h measured per lane, the travel time increased from 94.5 s to 108.9 s or 15.3 % due to ISA.

Aikim et al. (2000) describes the modeling of the effects of Co-operative Following (CF) and ISA on a lane drop location with the help of the first version of the ITS modeler: MIXIC. As a start a single lane network to identify the system performance in a simple environment was used. Once the network was extended to the real situation, i.e. three lanes and a lane drop at the left hand side after four km, the system did not work as expected. In this case it probably happened due to the problems in the functional design of CF. In other cases this could also be due to bugs in the translation into a model. The useful results of the study showed a decrease of 7% of the maximally observed traffic volume.

Yannis, et al. (2002) investigated the use of microscopic simulation models to assess the safety of two ADA Systems: ACC and ISA. They used three different traffic models to be sure the measured differences were a result of ACC or ISA and not a result of the models’ reaction to that. However, in the end it was still not clear if certain behavior, in this case for instance increased lane change behavior, would happen
in reality or was a result of incorrect calibration of the model for the new situation. Conclusion from this paper is that all behavioral changes as visible in a simulation with a newly developed ADA system have to be tested in a simulator or in reality.

The effect on safety of ISA is discussed as well by Christoph (2010). Several studies found safety increases. These safety increases varied: a reduction of 10% to 36% for accidents with personal injury was found, and a reduction of 18% to 59% was found for fatal accidents, depending on penetration rate and ISA type.

2.4. Lane keeping Assistant (LKA)
This safety oriented system has a warning and an intervening version (Wilschut, et al., 2011). In the first case a warning will be given if the car is going to switch lanes without using its indicators. In the second case the car will steer back automatically. There are several systems which are basically all doing the same. These are summarized under the name “lane departure warning systems” (Visvikis, et al., 2008). An extension to the lane departure systems is the lane change assistant or blind spot monitor. It detects vehicles in or approaching the blind spot. If there are vehicles in that area and the car is going to switch lanes, a warning or a counter steering will be given (Visvikis, et al., 2008). These systems have no impact on traffic flow, but can possibly be used in combination with CCC. No extensive safety studies are done so far for these systems.

2.5. Congestion Assistant
This intervening system is developed to increase traffic efficiency and safety. It works with two components: an active gas pedal which gives a counterforce when a driver is approaching a congested area with a too high speed and a Stop&Go system which performs the accelerating and decelerating in the congested area.

Van Driel & van Arem (2010) performed a study on this congestion assistant. Four requirements for the used modeling approach were made:
- It should be possible to simulate a driver and a vehicle, the interactions between vehicles, and between driver and vehicle.
- It should be possible to simulate differences in driving behavior due to the congestion assistant.
- It should be possible to simulate highways and the relevant bottlenecks thereof.
- It should be possible to realistically represent traffic flow dynamics including congested flow and the flows during the switch from free flow to congestion.

The ITS Modeler as developed by TNO, was found to meet all the criteria and was used for the study. ITS Modeler is a specially developed java written plugin for the simulation package Paramics. This plugin makes it possible to implement ADA Systems.

A lane drop from four to three lanes which causes congestion was chosen as a location to simulate the effects of the congestion assistant on traffic flow. The Stop&Go system was set to have a headway time of 0.8 s. In that situation a reduction of delay of 30% was found with a penetration rate of 10%. With a penetration rate of 50% a delay reduction of 60% was found. Both reductions were mainly caused by the Stop&Go system, where the active gas pedal didn’t have much influence.

The system can increase safety as well as it decreases the amount of hard breakings and Time to Collisions (TTC) (van Driel, 2007).
2.6. Connected Cruise Control (CCC)

The system of which the research results are presented in this report, Connected Cruise Control (CCC), is an informative system which gives drivers information how to drive in, or on the brink of, congested conditions. In these situations the traffic flow is currently less than optimal. CCC focuses on traffic flow improvement in order to reduce travel time by giving advices to drivers in such a way that congestion will be prevented or decreased and thus traffic flow optimized. These advices are based on the predicted future traffic situation up to three km ahead. They will cover the speed, lane to drive on, and the headway time.

Central in the CCC system is the back-office. Based on the detector data and the data it receives from CCC vehicles, it predicts the future traffic situation. Based on the difference between the predicted and desired future traffic situation it determines a general advice for a certain lane in a certain area. This generic advice is than translated into a vehicle specific advice. The advices are sent to the CCC in-car-unit which checks if the advice is still valid based on the legal and traffic situation the vehicle is in. In order to get these validations the in-car-unit has a camera and a built in map with maximum speeds. After that the Human Machine Interface (HMI) transmits the advice, together with a motivation why the advice is given, to the driver.

See for a schematic overview of the system figure 2.

The development of CCC is performed by a consortium led by Delft University of Technology. Other partners in the project are automotive industrial partners (NXP, NAVTEQ), knowledge institutes (Delft University of Technology, University of Twente, Eindhoven University of Technology, TNO and SWOV), Clifford, Technolution, and the national road operator Rijkswaterstaat.

The project started in 2010, and is currently concentrated on the system design of the technical components, the mathematical models for traffic prediction and advice determination, and the Human Machine Interface (HMI).

This study focuses on advice determination, more specifically on the advice selection and the effects of the advices.

CCC will give advices during all possible traffic situations, as defined by Kerner (2004): free flowing, synchronized flow, and wide moving jams. In the free flowing phase, there is a different speed for each
lane and the traffic can choose its own speed to a certain degree. In synchronized flow, the speed is lower and is almost the same on all lanes. The flow in this phase is on its maximum. However, small disturbances can lead to a complete stand still of the traffic, which is the third phase. This is also referred to as stop-and-go or shock waves. A standstill often happens near an on-ramp, off-ramp, or other merging section (Knoop, et al., 2010). The origin from these stand stills are often merges into gaps which are too small. CCC will not prevent merges into too small gaps directly, but aims to prevent these situations by giving special advices which decrease the need for merges into small gaps.

2.7. Methodology conclusions
From the different methodologies as presented in this chapter several things can be learned. It is wise to make a list of model requirements based on the desired outcomes. This list can then be used to define which type of model will be used and which model meets the requirements best. A good understanding of the chosen model will help to identify the areas of the model which needs editing or extension in order to implement CCC. It is wise to give a good overview of the assumptions as used during implementation, as learned from Yannis, et al. (2002). It is wise to do the model implementation and editing in small steps on a simple network as can be learned from Alkim et al. (2000). During this implementation the visualization of the model can be used to check how realistic the behavior is.

2.8. Possible outcomes
For different ADA Systems, different outcomes were found. The main difference between the CCC system and the systems described is that CCC is an informative system. It is likely therefore that the results will be less positive than for intervening systems. Since both ISA and the congestion assistant result in a decrease of travel time of around 50% with 100 and 50% penetration this is the upper limit which can be expected of the CCC system with a 100% penetration. However, since it is an informative system, the travel time reduction is more likely to be between 10% and 25%. The capacity gain is likely to be much less than the capacity gain of 25% as found by Minderhoud (1999), since that capacity gain is due to a decrease of headway time by use of an intervening system and the possible increase as result of CCC advices will be due to a better use of the road by use of an informative system. For ISA and the congestion assistant an increase of safety was found, as well as for ACC in non-congested situations (Christoph, 2010). Marchesini & Weijermans (2010) indicate that it is not clear if a reduction of congestion, and thus an increase of speed, will cause a decrease or increase of safety. Based on these studies, the possible influences of the CCC system on safety are unclear.
3. Methodology
This chapter describes the used methodology. First an overview of the used methodology is given. In the following sections some decisions on the first steps of the methodology are presented. These include the used simulation environment, the used traffic model, the modeled location and time, and the calibration parameters. The CCC implementation and the experimental design are described in separate chapters forming the actual work of this study.

3.1. Used methodology
The methodology as described in Spyropoulou et al. (2010) was used as a basis for the methodology used in the current study, since it is a good framework for modeling ADA Systems.

Based on the methodology as used by Spyropoulou et al. and the methodology conclusions as listed in the previous chapter, the used methodology was made as given below:

1. Identify model requirements
2. Decide between macro and micro simulation
3. Select a traffic model and select a traffic simulation tool
4. Identify the relevant model parameters which need to be edited
5. Define and implement parameter values, and test model
6. Determine which sections should be adapted or added for the implementation of CCC
7. Adapt or add sections to implement CCC, test the model after each change
8. Validate model
9. Run experiments

The used assumptions in step 7 are listed at the end of the relevant sections.

3.2. Model requirements and model choice
The focus of this study is on the effects of the advices to be given to the HMI in case of a lane drop. But as the design of HMI is still not finished and the reaction of drivers to that system is not yet known, the advices are implemented as given directly to the driver. This means that possible problems in understanding the message or other human errors were not taken into account in this study.

Since the advices are given to individual drivers, the model to be used must be able to simulate individual vehicles and their drivers. Besides that it should be possible to simulate the interactions between vehicles. As the study focusses on advices in case of (nearly) congested situations at a lane drop, as described in section 3.5, the model must be able to simulate a congested lane drop situation as well.

A micro simulation, which can simulate individual cars, is a good choice based on these requirements. According to Oketch & Carrick (2005) a micro-simulation is the only available method that allows examination of complex traffic problems such as intelligent transportation systems and congested networks.

There are several micro traffic simulation packages available, but all lack the possibility to define and implement ADA systems. The specially developed java written plugin ITS modeler, as developed by TNO, and as used by Van Driel & van Arem (2010), does have the possibility to implement ADA Systems. Therefore it was used for this research. Since the ITS modeler only works with the Paramics simulation software, the choice for Paramics was made as well.
Other common simulation packages are VISSIM and CORSIM. Several studies have tried to compare these packages. CORSIM is found not to be very good at all modeling aspects, but there is still discussion whether VISSIM or Paramics is better (LU, et al., 2010; Choa, et al., 2002). Which package is best depends on what the specific tasks are to be carried out. In this case Paramics is a good choice because of its good performing ability in case of congested networks (Ratrou & Rahman, 2008).

3.3. LMRS and ITS modeler combination

Although the ITS modeler is useful for implementation of ADA systems, it has its shortcomings as well. The main shortcoming is the lack of relaxation in the model. Relaxation is defined as the relaxation of headway time after a lane change. During lane changes drivers accept smaller headways. It is assumed that, after the lane change is performed, drivers slowly increase their headway time to the normal time. To overcome this problem the Lane Change Model with Relaxation and Synchronization (LMRS) (Schakel, et al., 2011), which includes relaxation, is implemented into the ITS modeler. The LMRS model has been specifically developed for the CCC project. The use of the LMRS code means that the lane change, free driving and car following parts of the ITS modeler are replaced with the relevant LMRS code. It was chosen to implement LMRS into the ITS modeler and not use the standalone version of LMRS, as the ITS modeler can easily be extended with other models, has several well defined output possibilities and is used at TNO where this study was done.

3.4. Model specification

The ITS Modeler is a plugin which fully replace the driver models of Paramics. Only the creation of vehicles, the update of the location of vehicles, and the design of the network were done with Paramics. The drivers, their characteristics and the characteristics of these vehicles are created by the ITS Modeler. Paramics for instance creates trucks and cars. ITS Modeler than gives a truck a truck driver and a car either a CCC-car driver or a driver without CCC.

The type and amount of output data of the simulation is as well set in the ITS Modeler in which all desired outputs can be defined. The driver behavior per driver type, limited by the vehicle constrains, is determined by the LMRS model. Based on this behavior the vehicle states are determined and sent to Paramics to update the vehicles on the network. This behavior is repeated for every time step. See for a schematic overview figure 3.

Below an overview of LMRS is presented. First the longitudinal behavior is described based on the description as given in “Effects of Cooperative Adaptive Cruise Control on Traffic Flow Stability” (Schakel, et al., 2010), second the lateral behavior is described based on the description as given in “LMRS: An integrated Lane Change Model with Relaxation and Synchronisation” (Schakel, et al., 2011).
In LMRS an adapted version of the IDM model (Helbing, et al., 2000), IDM+, is used to model the longitudinal driving task. The main feature of the model is the non-linear response to speed differences, included in $s^*$, the dynamic desired headway. How the acceleration is determined is visible in equation 1.

$$\frac{dv}{dt} = a \cdot \min \left( 1 - \left( \frac{v}{v_0} \right)^4, 1 - \left( \frac{s^*(v, \Delta v)}{s} \right)^2 \right)$$

$$s^*(v, \Delta v) = s_0 + vT + \frac{v\Delta v}{2\sqrt{ab}}$$

Equation 1: Acceleration calculation in the LMRS model (Schakel, et al., 2010)

In this formula $a$ is the comfortable acceleration, $v$ is the current speed, $v_0$ is the desired speed, $s_0$ is the minimum headway (at standstill), $T$ is the desired time headway, $\Delta v$ is the speed difference with the leader, $s$ is the current distance headway and $b$ is the comfortable deceleration.

The desired time headway is given by the following formula:

$$T(t) = T(t - \Delta t) + \left( T_{max} - T(t - \Delta t) \right) \frac{\tau}{\Delta t}$$

Equation 2: Desired time headway (Schakel, et al., 2011)

$T(t)$ is the desired time headway time at time $t$, $T_{max}$ is maximum desired headway, $\Delta t$ is the time step and $\tau$ is the relaxation factor.

The first part as given by $1 - \left( \frac{v}{v_0} \right)^4$ determines the behavior in free driving, when no predecessor limits the speed. The last part determines the acceleration possible when a predecessor limits the speed. The possible acceleration is calculated based on the speed difference between the driver and its limiting predecessor and the headway in meters a driver wants to have. The resulting acceleration can never be smaller than a certain fixed threshold $a_{\text{min}}$.

Three desires together determine the total desire to change to the left- or right-lane. These three desires are the desire to follow a route ($d_r$), to gain speed ($d_s$) and to keep right ($d_k$).

The route desire depends on a mandatory lane change, due to a lane drop or route specific exits. The closer by, in distance or in time, the lane change point is, the higher the desire to change lanes.

The desire based on speeds is based on the anticipated speed of the current lane, the left-lane and the right-lane. The higher the possible speed gain, the higher the desire to change lanes. A possible speed gain on the right-lane is only taken into consideration in case of congestion, when it is allowed to overtake on the right.

The desire to change lanes due to the keep right-rule is set to the $d_{\text{free}}$ value, when a driver can reach his desired speed on the lane to the right. The formula for the total desire holds: $d = d_r + \theta_v (d_s + d_k)$. $\theta_v$ is a factor which determines if voluntary lane change desires are included together with mandatory lane change desires or not.
Positive desires are split up based on three thresholds: $d_{\text{free}}$, $d_{\text{sync}}$ and $d_{\text{coop}}$. The type of lane change depending on these thresholds is as follows: Free Lane Changes (FLC), Synchronized Lane Changes (SLC) and Cooperative Lane Changes (CLC).

For little desire, no lane change will be performed. For a somewhat larger desire, FLC is performed requiring no preparation whatsoever. In SLC and CLC a potential lane changer is willing to synchronize speed with the target lane. This is achieved by following a vehicle in that lane. Concurrently this will align the vehicle with a gap (if there is a gap); this is thus a simple gap-searching model. In CLC, the potential follower will additionally start to create a gap by using the indicator. The lane change with the highest desire will be performed if possible and desired ($d \geq d_{\text{free}}$). If the lane change is not possible, lane change preparation (SLC and CLC) may be performed.

At relatively high speeds, the remaining time per required lane change determines the desire. At relatively low speeds, the remaining distance becomes dominant in determining the desire.

The above presented behavior is summarized in figure 4.

![Figure 4: Overview of LMRS lane change behavior](image)

A gap is accepted or rejected based on the resulting deceleration that follows from the car following model (IDM+) (Schakel, et al., 2010). Gaps that result in a too large deceleration are rejected as they are unsafe, uncomfortable or impolite. The gap is accepted if both the lane changer and the new follower will have an acceleration that is larger than some safe deceleration threshold.

The total model procedure consists of 12 steps, of which 11 are only valid for cars that are currently not changing lanes, and one is only valid for cars that are changing lanes. A lane change takes three seconds. The model steps, which are listed below, are performed each time step. A time step of 0.5 s is used as a balance between short running times and modeling precision.

**Not changing lanes:**
1. Relax headway from current headway to minimum headway (if current headway is smaller)
2. Calculate route desire
3. Calculate anticipated speeds
4. Calculate speed desire
5. Calculate keep-right desire
6. Combine desires
7. Check gap-acceptance based on required decelerations
8. Make lane change decision
9. Follow leader
10. If applicable, synchronize
11. If applicable, create gap
Changing lanes:
1 Follow leader

3.5. Location specification
From Knoop, et al. (2010) it became clear that congestion mainly takes place at merging sections. However, due to the limited time frame of this study, only one such situation was researched. Since on- and off-ramps differ too much in size, location and other characteristics, the research focusses on a special merging section: a lane drop location.
A real lane drop location was simulated to test the model including the implemented parameter values. This location is located on the A20 between Rotterdam and Gouda. Nearby Nieuwerkerk aan den IJssel, the number of lanes drops from three to two which sometimes causes congestion. This location is therefore a good choice for the current research. Traffic in the direction of Gouda is the only traffic modeled, which means that possible congestion due to looking at the traffic situation at the road in the opposite direction is neglected in this study.
Traffic is put randomly on the lanes at the start of the network. Slow vehicles can possibly be placed on the left-lane and fast vehicles on the right-lane. Around two km is needed before the traffic situation is realistic. Since drivers with CCC receive advices up to three km before the lane drop, a total length of around five km is modeled before the lane drop. To be able to measure all the influences of the lane drop, a length of 1.4 km after the lane drop is modeled as well. The modeled area is therefore between hectometer sign 37.8 and 44.4 and has a total length of 6.6 km. In figure 5 a detailed location scheme is given including distances in meters between points of interest.

3.6. Situation specification
In the simulated area, 21 detector locations are available. Each location has one detector per lane and data is available per minute. For validation data of the 8th of June 2009 between 5:50 AM and 8 AM is used. On this day there were no holidays, roadworks or other special situations.

All congestion occurs within the used timeframe, at the start and at the end some free flow is included as a reference. The congestion takes place between 6.10 and 7.30 AM; see figure 6. The speed in this figure is measured close before the lane drop location where the congestion is occurs most heavily.
3.7. Model parameter values

Since the LMRS is calibrated on the same location and time as the location in this research, the calibrated values of the LMRS were used as parameters. No calibrating, which means determining the correct values for parameters in order to reflect local conditions correctly, was needed.

To verify and validate the model, the real situation was modeled; the results of this verification and validation are presented in chapter 6.

The trucks and the off- and on-ramp to Nieuwerkerk aan den Ijssel (off- and on-ramp nr. 17) were excluded once the model was tested to be valid in order to keep the initial situation as simple as possible and exclude possible influences of the on- and off-ramp, as learned from Alkim et al. (2000). To match reality as close as possible, the total number of vehicles at the lane drop location and the traffic distribution over the simulated time are kept the same. This means that the remaining OD matrix is multiplied with a factor 1.23. Although the number of vehicles is kept the same, the amount of Personal Car Units (PCU) is not the same. The used space per truck compared to the used space per car decreases when the speed increases. This effect is caused by the increase of headway distance when the speed increases. The headway time of 1.2 s, which causes the increase in headway distance, is equal for both vehicle types. The PCU per truck will thus decrease when the speed increases, making it difficult to compensate for the non-existence of trucks. No compensation was included in the performed simulation study which resulted in a smaller congested period.

All the values which are described in this section can be found in table 1 which is based on Schakel, et al. (2011). The values are calibrated values for this specific location which means that they cannot be used as a general standard. The values are elaborated on below.

The maximum comfortable acceleration (a) is the maximum possible acceleration in the model since it is assumed that drivers do not want to accelerate faster.

The maximum comfortable deceleration (b) is the deceleration drivers want to have at most. However, sometimes they are forced to decelerate with a higher value; the highest deceleration possible in the simulation is given as \( a_{\text{Min}} \).

The standard headway time of all vehicles is given by \( T_{\text{max}} \), but it is assumed that during lane changes they accept much smaller headway times, of which the absolute minimum is \( T_{\text{min}} \). After a lane change drivers slowly “relax” to their original headway of \( T_{\text{max}} \). The duration is dependent on the relaxation time (\( \tau \)). See for the formula’s in which they are used equation 1 and equation 2.
The desired speed \( (v_{\text{des}}) \) is independent of the current traffic situation, it only depends on maximum allowed speed (in this case 120 km/h) and the vehicle type. Since not all drivers have the same desired speed a standard deviation \( (\sigma) \) is given as well. Drivers try to reach their desired speed as close as possible.

To calculate the available space, the lengths \( (l) \) of the vehicles are set to a specific value depending on vehicle type.

As described in section 3.4, there are three types of behavior based on the lane change desire: free lane change, synchronization and cooperative lane change.

It is assumed that the desire to change lanes due to a lane drop or routing decision (a mandatory lane change) is either based on time \( (t_0) \) or on distance \( (x_0) \). Drivers feel a need to change lane as soon as they are within 43 s or 295 meters of a mandatory lane change point.

The relevant thresholds for the desire to switch lanes are listed as \( d_{\text{free}}, d_{\text{sync}} \) and \( d_{\text{coop}} \). Since in the Netherlands overtaking on the right is prohibited as long as there is no congestion, drivers ignore a possible speed gain on the right if their speed is above a speed threshold, \( v_{\text{crit}} \).

<table>
<thead>
<tr>
<th>Parameter name</th>
<th>Symbol</th>
<th>Truck</th>
<th>Car</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum comfortable acceleration</td>
<td>a</td>
<td>0.4</td>
<td>1.25</td>
<td>m/s²</td>
</tr>
<tr>
<td>Maximum comfortable deceleration</td>
<td>b</td>
<td>2.09</td>
<td>2.09</td>
<td>m/s²</td>
</tr>
<tr>
<td>Maximum deceleration</td>
<td>( a_{\text{Min}} )</td>
<td>-6</td>
<td>-6</td>
<td>m/s²</td>
</tr>
<tr>
<td>Normal minimum headway time</td>
<td>( T_{\text{max}} )</td>
<td>1.2</td>
<td>1.2</td>
<td>s</td>
</tr>
<tr>
<td>Minimum headway time possible</td>
<td>( T_{\text{min}} )</td>
<td>0.56</td>
<td>0.56</td>
<td>s</td>
</tr>
<tr>
<td>Relaxation time</td>
<td>( \tau )</td>
<td>25</td>
<td>25</td>
<td>s</td>
</tr>
<tr>
<td>Desired speed</td>
<td>( v_{\text{des}} )</td>
<td>85</td>
<td>123.7</td>
<td>km/h</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>( \sigma )</td>
<td>2.5</td>
<td>12</td>
<td>km/h</td>
</tr>
<tr>
<td>Length</td>
<td>l</td>
<td>15</td>
<td>4</td>
<td>m</td>
</tr>
<tr>
<td>Anticipation distance</td>
<td>( x_0 )</td>
<td>295</td>
<td>295</td>
<td>m</td>
</tr>
<tr>
<td>Remaining time for lane change</td>
<td>( t_0 )</td>
<td>43</td>
<td>43</td>
<td>s</td>
</tr>
<tr>
<td>Lane-change threshold</td>
<td>( d_{\text{free}} )</td>
<td>0.365</td>
<td>0.365</td>
<td>m</td>
</tr>
<tr>
<td>Synchronized Lane-change threshold</td>
<td>( d_{\text{sync}} )</td>
<td>0.577</td>
<td>0.577</td>
<td>m</td>
</tr>
<tr>
<td>Cooperative Lane-change threshold</td>
<td>( d_{\text{coop}} )</td>
<td>0.788</td>
<td>0.788</td>
<td>m</td>
</tr>
<tr>
<td>Anticipated speed at right threshold</td>
<td>( v_{\text{crit}} )</td>
<td>60</td>
<td>60</td>
<td>km/h</td>
</tr>
</tbody>
</table>

Table 1: Used parameter and values (Schakel, et al., 2011)

3.8. Conclusion

In this chapter the used methodology for the performed research was presented and elaborated. The CCC implementation and experimental design is discussed in the next chapters. The micro simulation package Paramics is chosen as simulation model, combined with the ITS modeler plugin which makes it possible to implement CCC into the simulation. This ITS modeler plugin is optimized by implementing the LMRS model, which is described in this section as well, into it. Since this LMRS model is calibrated and validated for the same location and time as used in this research, the A20 between Rotterdam and Gouda during the morning peak of the 8th of June 2009, the relevant model parameters were already implemented and tested. The used model was verified and validated by modeling the real situation, although the on- and off-ramp to Nieuwerkerk aan den IJssel and the presence of trucks were excluded from the simulation in order to purely measure the lane drop effects. The results of the verification and validation are presented in chapter 6.
4. CCC implementation
This chapter describes the CCC system as implemented in this research. First the area in which the CCC system works is described. The next section describes when the system is turned on or off. After that the three possible advices which can be given are described. On which lanes these advices are tested is described in the next chapter, during the description of the experimental design. 100% compliance is assumed for all advices.

4.1. Implementation area
The goal of the CCC advices at a lane drop location is that the traffic situation at the lane drop will be as optimal as possible, leading to a minimum amount of congestion. In the initial situation the congestion occurs mostly on the middle- and left-lane, while the right-lane has less vehicles and a higher speed. A better situation would consist of more vehicles on the right-lane and enough space for vehicles on the left-lane to switch to the middle-lane. In such a situation no drivers have to switch lanes at the last moment before the lane drop which can be negative for the traffic flow. An example of such a desired situation is given in figure 7, the top figure gives a possible situation in case of non-equal spread, the bottom figure an example of a better spread of vehicles over the lanes.

Drivers receive an advice 3km before the lane drop to create that situation on time. Once the lane drop is passed, advices are no longer needed and the advice is turned off. The area where drivers get an advice is referred to as the advice area.
A traffic prediction model for CCC is not yet available. The limited time available did not allow building that model. Therefore the prediction of future traffic situations, which is also part of the CCC system, is not modeled. Instead of a prediction, the actual situation in the area up to 1 km before the lane drop is used to determine if the system should turn on or off. This area is referred to as the trigger area.
Four detectors are located in the trigger area, which have an in between distance of 200 to 300 meters. Based on the flow and speed measured by the detectors, the situation in the trigger area is determined. This is done every minute.
As visible in figure 8, vehicles on on- or off-ramps did not get an advice. The advice area, plus an area of 749 meters after the lane drop, is used to measure the effects of the advices; this is referred to as the measure area.
4.2. Trigger specification

The CCC system only gives advices when there is congestion, or the chance for congestion is very high. But there is no data available what exactly the trigger should be to turn the system on and off. However, three triggers and their thresholds are proposed by Klunder & Jonkers (2011): total flow, flow on middle- or left-lane, and speed on middle- or left-lane. These triggers were used in the simulation to turn the CCC system on and off. The values of these triggers are updated every minute. The implementation method and values for these triggers are listed below.

The total flow over all lanes is set equal to the highest flow measured by a detector in the trigger area during one minute. The trigger threshold is set to 67 or more vehicles per minute (4020 veh/h).

The flow on the middle or left-lane is set equal to the highest lane flow measured by a detector in the trigger area during one minute. The trigger threshold is set to 34 or more vehicles a minute (2040 veh/h each lane).

The speed on the middle- or left-lane is set to the lowest lane speed measured by a detector within the trigger area. The speeds measured by a detector were averaged per minute as default. The trigger threshold is set to 80 km/h or less.

To decide if the system should be turned off, the same triggers are measured as well, but different thresholds are used. These trigger-off thresholds are 58 or less vehicles per minute (3480 veh/h) for the total flow, 30 vehicles or less per minute (1800 veh/h each lane) for the flow on the middle and left-lane, and 90 km/h or more for the speed on middle and left-lane.

Initially one reached on-threshold was enough to turn the CCC system on. This caused the CCC system to turn on and off several times before the main period of congestion sets in. Most of the time, the system was turned on because the threshold of one trigger was reached for only one minute. To prevent the system for flickering too much due to this, it was chosen that at least two trigger thresholds must be reached before the system is turned on. The implementation of this condition resulted in a reduction of the CCC-on periods. It is expected that by further editing of the trigger values the number of periods can be decreased even more.
To turn the system off, all off-thresholds must be reached. It was shown that the system did not turn off too early, indicating that these off triggers are working well. All above indicated thresholds are visible in figure 9 and summarized in table 2.

![Speed vs. Intensity](image1)

![Speed](image2)

**Figure 9: Fundamental diagram of real situation and triggers of total (top) and left- and middle-lane (bottom) intensities**

<table>
<thead>
<tr>
<th>Trigger</th>
<th>On value</th>
<th>Off value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total flow (veh/min)</td>
<td>67</td>
<td>58</td>
</tr>
<tr>
<td>Flow on middle-lane (veh/min)</td>
<td>34</td>
<td>30</td>
</tr>
<tr>
<td>Flow on left-lane (veh/min)</td>
<td>34</td>
<td>30</td>
</tr>
<tr>
<td>Speed on middle-lane (km/h)</td>
<td>80</td>
<td>90</td>
</tr>
<tr>
<td>Speed on left-lane (km/h)</td>
<td>80</td>
<td>90</td>
</tr>
</tbody>
</table>

**Table 2: initial trigger values**
4.3. Speed advice
This section describes why a speed advice is given, how it is implemented and which assumptions were made.

4.3.1. Reasons for a speed advice
There are no large speed differences between lanes during periods of synchronized flow and congestion. In situations where there is a high flow but there is no synchronized flow yet, it may be profitable to decrease the speed differences between lanes by giving speed advices. The smaller these speed differences, the higher flow can be reached, since it is easier to switch lanes with small speed differences, which leads to a better spread of vehicles over the road.

4.3.2. Speed advice implementation
When a CCC driver is on a lane with a speed advice, the driver’s maximum speed is set to the speed of its right-predecessor. If a speed advice is given to drivers on the right-lane, the maximum speed is set to the speed of the left-predecessor. The new maximum speed is never higher than the infrastructure maximum speed of 120 km/h.
If the drivers’ speed is above the advised speed, the speed is decreased as given by the following formula based on the formula given in equation 1 in the previous chapter:

\[
\frac{dv}{dt} = a \cdot \max \left( 1 - \left( \frac{v}{v_0} \right)^4, m \right)
\]

Equation 3: acceleration behavior

The acceleration factor \(a\) is calibrated to a value of 1.25 in the used LMRS model, \(v\) is the speed of the driver, \(v_0\) is the advised speed, and \(m\) is the assumed maximum deceleration drivers perform after getting the advice, which value is set to -1 m/s\(^2\). In case of a speed advice this acceleration will be negative which means a deceleration.

If a driver is no longer in the advice area, or the CCC trigger is off, or the advised speed increased to a value above the allowed speed of the infrastructure, the speed advice is turned off. When the driver changed lanes to a lane without a speed advice the advice is turned off as well consequently. Another advice is given in that situation if needed. See figure 10 for an overview of the reasons to turn off the speed advice.

![Figure 10: Reasons to turn off speed advice](image)
4.3.3. Used assumptions for speed advice
The speed advice is implemented using two assumptions:
- Drivers will decelerate with $1\text{m/s}^2$ at most after an advice is given.
- Drivers always follow the given advice.

4.4. Lane change advice
This section describes why a lane change advice was given, how it is implemented and which assumptions were made.

4.4.1. Reasons for a lane change advice
Studies show that the right-lane is under-utilized during non-congested traffic conditions (Knoop, et al., 2010). To increase the utilization rate of this lane, the advice to change lanes from the middle-lane to the right-lane can be given. Since there is a lane drop to two lanes it can be necessary, in busy traffic conditions, to advice drivers to go to the right-lane until half the amount of the vehicles is on the right-lane.

To create a better spread of locations where drivers switch from the left- to the middle-lane, a lane change advice can be given to drivers on the left-lane. Drivers will then change lanes up to two km before the lane drop instead of close to the lane drop.

The lane change advices were only given when the drivers’ speed is above 100 km/h which indicates free flow, since lane changes in the congested area can increase the congestion.

4.4.2. Lane change advice implementation
To indicate if a lane change advice is needed, the amount of traffic in the trigger area needs to be known. To measure this amount of traffic, the density was taken rather than the flow. This was done because density incorporates speed, where a low flow can be caused by a low speed or a small amount of vehicles. To calculate the density the average speed in a certain area, the harmonic speed, is needed. This harmonic speed could not be determined from the detector data. Therefore the average speed over time was used to calculate the density. It was assumed that this would lead to a good estimate of the needed vehicles on the right-lane, since the calculation error is roughly the same for the total density and the density on the right-lane.

A lane change advice from the middle-lane to the right-lane was given if the density on the right-lane was less than 50% of the total density on one or more of the four detectors in the trigger area. New lane change advices were not given if the density on the right-lane was 60% or more of the total density on one or more of the four detectors.

Initial runs showed that out of 100% lane change advices, only 60% resulted in an actual lane change. This result was most likely caused by the lane change advice cancelation when the speed dropped below 100 km/h. To receive 50% of the drivers on the right-lane, 83% of the drivers minus the percentage drivers already on the right-lane, need to receive a lane change advice, since 0.83 times 0.6 results in 0.5.

The number of drivers on the middle-lane needed to receive a lane change advice was therefore given by 0.83 times the average density in the trigger area, minus the average density of the right-lane. This amount was then extrapolated to the whole advice area, which means multiplying it with a factor three.
Starting with the driver with the lowest speed, all CCC drivers on the middle-lane received a lane change advice until the required number of lane change advices was given. CCC drivers only received a lane change advice if they met the criteria as defined in figure 11. Drivers which entered the advice area during the minute and met all criteria, received a lane change advice if there were still vehicles needed on the right-lane. If there was a lane change advice given to the left-lane, all CCC drivers on that lane who met the criteria as defined in figure 11 received a lane change advice, independent of the needed vehicles on the right-lane. All drivers with CCC in the whole advice area got the advice not to change lanes to the left to avoid unnecessary lane changes.

Drivers who have a lane change advice tried to find a possible gap to merge in during 30 seconds. This was simulated by adding an extra desire, besides the already existing desires to follow a route (d_r), to gain speed (d_s) and to keep right (d_k). This lane change desire (d_c) is set to the value of d_free during the first 30 seconds. If there is no gap available after 30 seconds the d_c value is set to the d_sync value. Drivers will synchronize their speed with the target lane during 15 seconds and will accept smaller gaps to merge in than before. If still no success, the advice desire is set equal to the d_coop value. This results in the use of the indicator, to force a gap to merge in, and the minimum desired gap is even smaller.

For this behavior a time difference rather than a distance difference was assumed since the travelled distance is highly dependable on speed, where it was assumed that drivers feel more urgency to follow up the advice if the advice is older.

If a driver is no longer in the advice area or his speed is below 100 km/h or the CCC trigger is turned off, the lane change advice is turned off. If a driver changed lanes, the lane change advice is no longer valid, and other advices (if any) are given, see figure 12.

---

**Figure 11: Lane change behavior**

- Last lc advice > 1 minute ago?
- No predecessor or follower with lc advice?
- Speed > 100 km/h?
- On left-lane?
- On Middle-lane and still lc advices needed?
- Lane change advice
- Find gap
- Synchronize with target lane
- Use indicator

**Figure 12: Reasons to turn off the lane change advice**

- CCC trigger off
- No longer in advice area
- No lane changes to the left
- Speed < 100 km/h
- Check for other advices
- Changed lanes
- Lane change advice off
4.4.3. Used assumptions for lane change advice
The lane change advice is implemented using seven assumptions:
- Urgency to change lanes depends on time.
- Drivers start synchronizing their speed to the target lane after 30 seconds.
- Drivers use their indicator after 45 seconds.
- The situation in the trigger area is a good prediction for the future: the density ratios will not change too much in the coming 2 minutes.
- Half the amount of traffic should be on the right-lane at the lane drop location in order to optimize traffic flow.
- The error in the calculated needed lane change advices due to the use of the average speed instead of the harmonic speed in the density calculation is acceptable.
- Drivers always follow the given advice.

4.5. Headway advice
This section describes why a headway advice is given, how it is implemented and which assumptions were made.

4.5.1. Reasons for a headway advice
By increasing the headway on a lane it was made easier for drivers to merge into that lane since there were more possible and bigger gaps to merge in. Goal was fewer drivers which have to change to the middle-lane right before the lane drop, and more drivers which merge to the right-lane.

4.5.2. Headway advice implementation
When all the relevant criteria for a headway advice were met, the desired maximum headway, as used to calculate $s^*$ in equation 1, of the driver was increased from the standard 1.2s to 3s. It is assumed that drivers have a time dependent reaction to the headway advice: they want to have the advised headway within one minute. It was therefore assumed that the increase to 3s is done within one minute in a linear way according to the following formula:

$$\Delta T = \frac{T_{\text{max}} - T}{60}$$

Equation 4: Desired headway increase if headway advice

$T_{\text{max}}$ in this case is the advised headway of three seconds and $T$ is the actual headway. All values are in seconds. One minute was assumed since it is the minimum time the advice is valid and roughly the time it takes to drive 2 km with the maximum allowed speed of 120 km/h. Drivers will therefore have the advised headway at least one km before the lane drop.

It was assumed that a driver will not increase the headway again to three seconds when he receives a new predecessor, except for situations where its new headway is almost three seconds. Instead of increasing the headway again, the drivers desired maximum headway is set to its new headway with a minimum of the original value of 1.2 seconds. After one minute he can receive a new headway advice. See for an overview figure 13.
4.5.3. Used assumptions for headway advice

The headway advice is implemented using eight assumptions:

- Larger gaps on a lane are an incentive for drivers to switch lanes.
- Drivers are willing to increase their headway to three seconds.
- Drivers want to reach the advised headway within one minute.
- The increase to three seconds is linear in time.
- Drivers do not want to increase their headway again to three seconds after getting a new predecessor.
- Drivers will not decrease their headway after getting a new predecessor.
- Drivers are willing to increase their headway again to three seconds after one minute.
- Drivers always follow the given advice.

4.6. Truck implementation

To include the lane change advice correctly when there are trucks in the network, it was needed to calculate the desired amount of vehicles on the right-lane while taking the different amount of Personal Car Units (PCU) a truck counts for into account.

To calculate the desired amount of vehicles on the right-lane, the length of the vehicles, the average headway time per vehicle type, the percentage of trucks, the percentage of trucks on the right-lane, and the average speed per vehicle type was needed to know. The implementation which takes these factors into account is described below.

The used space by a vehicle, on which a PCU is based, is given by the absolute distance drivers want to have in every situation ($s_0$) plus the distance drivers want to have depending on their speed ($v$) and headway ($T$), plus the length of the vehicle ($L_{\text{truck}}$ or $L_{\text{car}}$). $s_0$ is 2 meter, $L_{\text{truck}}$ is 15 meter, and $L_{\text{car}}$ is 4 meter as explained in section 3.7. $T$ could differ between 0.56 and 1.2 seconds in the simulation, but it was not possible to measure the actual average headway per vehicle type by use of the detectors. The headway was therefore set to the average headway value of 1 second for both types.

The amount of PCU’s per truck (truckPCU) is given by dividing the used space of a truck by the used space of a car. One PCU is set to be the needed space of a car, where the PCU factor for trucks depends on. As the length of a truck is larger than the length of a car, the truckPCU will be larger than 1. See the equation below for the complete formula.
The relative amount of PCU’s (totalPCU) compared to the amount of vehicles, is calculated by use of the formula below. The percentage of trucks in the network (truck%) times the truckPCU gives the relative total PCU of all trucks together. Added to that is the percentage of cars in the network, as 1 car is 1 PCU. It is assumed that the relative amount of trucks compared to the amount of vehicles is constant over time. As the truckPCU is larger than 1, the totalPCU will always be larger than 100%, except for the experiments without trucks. The totalPCU in that case is the same as the amount of cars in the network which is 100%. That means that the calculations as described in this section will not have an influence.

\[
\text{totalPCU} = \text{truck}\% \times \text{truckPCU} + \text{car}\%
\]

Equation 6: Formula to calculate the total PCU in the network

It is assumed that all trucks drive on the right-lane. If 50% of the vehicles are on the right-lane, which is the goal of the lane change advice, the total PCU’s on the right-lane (PCU right-lane) will be more than 50% as can be calculated by use of the below listed formula, where the amount of car PCU’s is given by 50% of the vehicles minus the amount of trucks.

\[
\text{PCU right-lane} = \text{truck}\% \times \text{truckPCU} + 50 - \text{truck}\%
\]

Equation 7: PCU on the right-lane

By the dividing the previous two outcomes the percentage of PCU’s on the right-lane relative to the total amount of PCU’s (PCU%) is calculated as visible below.

\[
\text{PCU}\% = \frac{\text{PCU right-lane}}{\text{Total PCU}}
\]

Equation 8: Percentage of PCU on the right-lane

By using the previous formulas the PCU% is always above 50%, in case of 50% of the vehicles on the right-lane. The relative amount of PCU’s on the right-lane minus the desired amount of 50%, times the total amount of PCU’s in the network gives the unnecessary PCU’s on right-lane (uPCU):

\[
\text{uPCU} = \text{Total PCU} \times (\text{PCU}\% - 0.5)
\]

Equation 9: Too much PCU’s on the right-lane if 50% of the vehicles on that lane

The actual needed percentage of vehicles on the right-lane to receive 50% of the PCU’s on that lane is given by the desired number of PCU’s on that lane (PCU right-lane – uPCU) which is then converted back to the desired amount of vehicles by subtracting the total amount of trucks PCU’s and adding the number of trucks (-truck%*truckPCU + truck%).

\[
\text{Needed vehicles on right-lane} = \text{PCU right-lane} - \text{uPCU} - \text{truck}\% \times \text{truckPCU} + \text{truck}\%
\]

Equation 10: Actual needed percentage of vehicles on the right-lane

Using this approach, including the assumption that all trucks always drive on the right-lane and using the average headway time of 1 second, the percentage of vehicles needed on the right-lane per speed is given in table 3. These vehicle percentages are based on 11% trucks in the network.
Based on the above described calculations the actual number of lane change advices to be given was calculated as indicated in section 4.4.2 (Lane change advice implementation).

<table>
<thead>
<tr>
<th>v(km/h)</th>
<th>truckPCU</th>
<th>% of vehicles needed on right-lane</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>4.03</td>
<td>33.32</td>
</tr>
<tr>
<td>20</td>
<td>2.54</td>
<td>41.52</td>
</tr>
<tr>
<td>40</td>
<td>2.08</td>
<td>44.06</td>
</tr>
<tr>
<td>60</td>
<td>1.85</td>
<td>45.30</td>
</tr>
<tr>
<td>80</td>
<td>1.72</td>
<td>46.04</td>
</tr>
<tr>
<td>100</td>
<td>1.63</td>
<td>46.52</td>
</tr>
</tbody>
</table>

Table 3: % vehicles needed on right-lane

4.6.1. Used assumptions for truck implementation

Trucks are implemented using three assumptions:

- Trucks always drive on the most right-lane.
- The average headway time of 1s for both cars and trucks is sufficient.
- The percentage of trucks is constant over time.

4.7. Advice combination

Three advices can be given to improve traffic flow. To which lanes they can be given is visible in figure 14.

All lanes can receive two advices. To overcome problems an order was defined. The lane change (lc) advice is the most important one, it overrules the other advices. If a driver has the advice to change lanes, but has not changed yet, it will not receive a speed or headway advice. Once a driver is in a new lane, and the lane change advice is no longer valid, the driver can receive a speed and a headway advice. If a driver receives a headway advice and a speed advice at the same time, the used LMRS model will automatically take the highest deceleration.

![Figure 14: Advice vs. lane](image)

Figure 15 provides an overview of the possible advices and to which drivers they are given. All these possibilities are discussed in the previous sections. The speed advice is always given to all CCC drivers on the lane where the advice is valid for, except when a driver has a lane change advice. The lane change advice to drivers on the middle-lane who meet the criteria is only given if less than 50% of the vehicles are on the right-lane. If there is a lane change advice to drivers on the left-lane it is always given to all drivers which meet the criteria. The headway advice is given to drivers which meet the criteria who do not have a lane change advice.
The advice area in which CCC drivers can get advices was defined as up to three km before the lane drop location. Based on the situation as measured by four detectors in the area up to one km before the lane drop location it is decided if the CCC system will start to give advices. If the CCC system is turned on, drivers can get, if they meet all advice specific requirements, a lane change advice or a headway and/or a speed advice. A lane change advice overrules other given advices. If trucks are included in the network less than 50% of the vehicles need to be on the right-lane as trucks use more space than cars. The amount of needed vehicles is then calculated by use of the Personal Car Unit (PCU) of a truck.
5. Experimental design

This chapter describes how the model was verified and validated, how the previously described advices were combined with each other, which experiments were done with them, and how the results were measured. The results themselves are described in the next chapter.

5.1. Verification and validation

Verification was done to determine if the model represented the reality well enough using the visualization of Paramics. The plugin code (ITS modeler with LMRS implemented) was edited until the expected vehicle behavior of the model was visible. Expected vehicle behavior is in this case based on the behavior of the original LMRS model, which is based on reality.

Validation, the process of determining to which extend the model represents a real situation, was already done by the author of the LMRS model. To be sure there were no major differences between the LMRS model and the model used for this research, the method as described by Oketch & Carrick (2005) was used. If this method showed reasonable results the model was assumed to be valid. The method holds that a statistic was used that deals with relative and absolute differences between the simulated flow and the real flow. This statistic, GEH, gives an indication of the goodness of fit of the simulated flow. The GEH statistic is also used by the UK and Californian Government (Chu, et al., 2003; Dowling, et al., 2002). The name comes from the inventor of this method, Geoffrey E. Havers. This method is particularly useful since it compares the flows, and not the speeds which are a result of that flow. It was assumed that the relationship between flow and speed is well defined in the LMRS model since that is calibrated on the same location. The GEH statistic is a useful method since it is possible to make a set of requirement on the outcomes of this method on beforehand. This study uses the requirements for the outcomes as used in several other studies.

The formula of the statistic is visible below. In this formula is M the simulated flow and O the real flow.

\[
GEH = \sqrt{\frac{(M - O)^2}{0.5 \times (M + O)}}
\]

Equation 11: GEH statistic

If the value of GEH is below five, the simulated flow is assumed to be a good fit of the real flow. If the value is between five and ten the model should be adapted in order to reach a lower value, but if that is not possible within the budget boundaries, the outcome is assumed to be good enough to work with. If the GEH value is above ten the flows are not a good fit of the real flows. The GEH statistic can only be used over a timeframe of an hour as a minimum, since the previous named boundaries are defined based on hourly flows. The simulated flows were therefore compared on a relative large timeframe of one hour.

Based on Oketch & Carrick three requirements for the outcomes are defined:

1. GEH is on average five or less.
2. 80% of the GEH’s are below five.
3. No GEH is above ten.
The locations where a GEH was performed are detector locations. The first detector is located at the start of the network to check if the created flow is the same as in reality. Others are located directly after on- and off-ramps and the lane drop location, see table 4 for exact locations of the used detectors.

<table>
<thead>
<tr>
<th>Situation</th>
<th>GEH check location</th>
</tr>
</thead>
<tbody>
<tr>
<td>Start Network</td>
<td>37.8</td>
</tr>
<tr>
<td>On-ramp 16</td>
<td>38.6</td>
</tr>
<tr>
<td>Off-ramp gas station</td>
<td>39.9</td>
</tr>
<tr>
<td>On-ramp gas station</td>
<td>40.6</td>
</tr>
<tr>
<td>Off-ramp 17 and lane drop</td>
<td>42.951</td>
</tr>
<tr>
<td>On-ramp 17</td>
<td>43.32</td>
</tr>
</tbody>
</table>

Table 4: GEH check locations

Six runs were made as an input. Each run was performed with a different seed, but with the same OD matrix. A seed is a string of random numbers which has an influence on the model. The numbers of vehicles generated each minute, the desired speed of a vehicle, the destination of a vehicle and the type of a vehicle is dependent on the seed. The GEH statistic was therefore used to study the flow per hour averaged over all 6 seeds. Since the simulated time was from 5:50 AM to 8:00 AM, two periods could be analyzed. The first period is between 5:50 AM to 6:50 AM, the second period is between 6:50 to 8:00 AM. The average GEH value per location over the whole simulated period is given as well.

5.2. Experimental setup

After the model was proved to be valid, four different experiments were conducted to investigate the effects of the advices:

1. Lane-change advice from middle-lane to right-lane in combination with a speed advice on the left-lane and a headway advice on the middle-lane
2. Experiment one in combination with a lane change advice on the left-lane
3. Experiment one in combination with a speed advice on the right-lane
4. Experiment one in combination with headway advice on the right-lane

Experiment 1 is a combination of three advices, as was proposed by Klunder & Jonkers (2011). It was expected that all these three advices have a positive influence on the traffic situation. If the results of experiment one showed a positive influence, all individual advice results were assumed to be positive as well.

In experiment 2, 3 and 4, the added effect of the extra advice was measured in an attempt to optimize the traffic flow further, since it is not known how these advices interact with the advices in experiment one. See for an overview of the given advices per experiment the table below.

<table>
<thead>
<tr>
<th>Advice/Exp. nr.</th>
<th>Left-lane speed</th>
<th>Middle-lane headway</th>
<th>Middle-lane lane change</th>
<th>Left-lane lane change</th>
<th>Right-lane speed</th>
<th>Right-lane headway</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td>X</td>
</tr>
</tbody>
</table>

Table 5: Overview of performed runs to test advices
Based on the outcomes of these four experiments, the advices with a positive influence on the traffic flow were combined together into one advice combination. With this combination a sensitivity analysis on the effects of penetration increase and decrease is done consisting of five experiments:

5. Penetration rate of 2%
6. Penetration rate of 5%
7. Penetration rate of 10%
8. Penetration rate of 20%
9. Penetration rate of 40%

The difference in outcomes between the situation with a penetration rate of 2 and 5 indicate the sensitivity to a small increase of penetration when the penetration rate is small. The difference in outcome between the situation with 20 and 40% indicate the sensitivity for an increase of penetration rate when the penetration rate is already high.

Two experiments with different scenarios are done to indicate the sensitivity of the CCC system for other circumstances:

10. 11% trucks included.
11. On- and off-ramp 17 added to the network.

Experiment 10 consists of the same network as used for the other experiments but with trucks included. 11% of the vehicles were a truck in this experiment, as it was in reality. For this simulation the rules as defined in section 4.6 were needed. As the amount of PCU’s per truck is dependent on the speed and other factors the increase of road usage due to the implementation of trucks could not be determined. The total number of vehicles was therefore kept the same as in the other experiments; the original OD matrix times 1.23. This equal amount of vehicles means an increase of traffic in terms of PCU’s.

Experiment 11 used the network as used for validation including the busy off- and on-ramp to Nieuwerkerk aan den IJssel. No trucks were included in this experiment. Initial runs using the demand as used for validation showed no congestion at the lane drop, due to the absence of trucks. Therefore the original OD matrix was multiplied with 1.1 to compensate for this.

The number of runs needed was given by the formula as stated in equation 12 (Daamen, 2011). In this formula, the \( n \) stands for the number of runs, \( Z \) is the confidence level, assuming a normal distribution, \( d \) is the accuracy level; the maximum allowed plus or min shift from the old mean value to the new mean value when an extra run is done, and \( \sigma \) is the standard deviation.

\[
 n \geq \frac{Z^2}{d^2} \cdot \sigma^2
\]

Equation 12: number of runs needed given de confidence interval, accuracy and standard deviation (Daamen, 2011)

To indicate the number of needed runs, 30 initial runs of the basic situation were done. All congestion takes place between 6.15 AM and 6.45 AM in these runs. The desired reliability was set to 95% which gives a \( Z \) value of 1.96. The accuracy was set to 2.5 km/h, which gives a bandwidth of 5 km/h. The standard deviation over the average speeds during the congestion period of all 30 runs is 6.45. Based on these parameter values at least 26 runs were needed to limit the chance to 0.05 that an extra performed run would cause the average speed over all runs to be 2.5 km/h more or less than the current average value. 30 runs per experiment were done to ensure the confidence level of 95% was reached when CCC advices were implemented and the standard deviation could possibly increase.
All experiments, except experiment 5, 6, 8 and 9 which test the sensitivity to penetration rate, were done with a penetration rate of 10%. 10% is used since effects with a lower penetration rate can possibly not be measured or can be caused by other factors than the advices. A higher penetration rate seems unrealistic for the near future. See for an overview of the experiments, the number of runs and the used penetration rates, the table below.

<table>
<thead>
<tr>
<th>Exp. Nr.</th>
<th>Experiment description</th>
<th># Runs</th>
<th>Penetration rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Lc and headway advice middle-lane, speed advice left-lane</td>
<td>30</td>
<td>10</td>
</tr>
<tr>
<td>2</td>
<td>Experiment 1 plus lane change advice left-lane</td>
<td>30</td>
<td>10</td>
</tr>
<tr>
<td>3</td>
<td>Experiment 1 plus speed advice on right-lane</td>
<td>30</td>
<td>10</td>
</tr>
<tr>
<td>4</td>
<td>Experiment 1 plus headway advice right-lane</td>
<td>30</td>
<td>10</td>
</tr>
<tr>
<td>5</td>
<td>Penetration rate of 2%</td>
<td>30</td>
<td>2</td>
</tr>
<tr>
<td>6</td>
<td>Penetration rate of 5%</td>
<td>30</td>
<td>5</td>
</tr>
<tr>
<td>7</td>
<td>Penetration rate of 10%</td>
<td>30</td>
<td>10</td>
</tr>
<tr>
<td>8</td>
<td>Penetration rate of 20%</td>
<td>30</td>
<td>20</td>
</tr>
<tr>
<td>9</td>
<td>Penetration rate of 40%</td>
<td>30</td>
<td>40</td>
</tr>
<tr>
<td>10</td>
<td>11% Truck</td>
<td>30</td>
<td>10</td>
</tr>
<tr>
<td>11</td>
<td>On- and off-ramp 17</td>
<td>30</td>
<td>10</td>
</tr>
</tbody>
</table>

Table 6: Experiment overview

5.3. Used indicators

Several indicators were used to measure the effects of the advices on both the traffic situation and the safety. All indicator values were measured in the measure area between 6 AM and 7:30 AM unless otherwise stated. This period of time is referred to as the measure period.

5.3.1. Used traffic situation indicators

The main goal of the CCC project is to decrease travel time. To indicate this travel time for all vehicles, the total travel time was measured. The travel time was calculated by averaging the speed of all vehicles which were in the measure area, as defined in section 4.1, during the measure period. The length of the measure area, 3.8 km, was then divided by this average speed. The average travel time times the flow, gives the total travel time. The lower this value is, the higher the influence of the advices on the travel time.

The vehicle loss hours were calculated to indicate the decrease of lost time due to congestion. In a perfect situation without congestion the vehicle loss hours will be zero. The total travel time minus the total travel time in free flow conditions gives the vehicle loss hours. The total travel time in free flow conditions was calculated using the average speed in free flow conditions: 110 km/h. This free flow speed was measured between 6:45 AM and 8:00 AM, the period all runs have free flow. The smaller the amount of vehicle loss hours the better.

The average speed was measured to indicate to which extend the average free flow speed of 110 km/h is reached. The higher this speed is the better.

The local density, based on data of detector 42.7, the detector closest in front of the lane drop, was calculated for all lanes to indicate the amount of congestion. A small density indicates less congestion. The number of lane changes was also measured, since lane changes may increase congestion. A smaller amount of lane changes is therefore positive.

Those five indicators together give a good overview of the performance increase of the network in terms of speed and flow when CCC advices are given.
The relative differences between the indicator values of the basic or other reference scenario and the simulated scenario are calculated as stated in equation 13. The use of this formula means that an increase of an indicator value of the simulated scenario is counted as positive.

\[
\frac{\text{Simulated scenario} - \text{Reference scenario}}{\text{Reference scenario}} \times 100\%
\]

Equation 13: Calculating relative differences

To indicate how sensitive the CCC system is for the penetration rate, the standard deviations for speed, the vehicle loss hours, and the total travel time were calculated. The inputs for these calculations are the averaged indicator values per seed.

### 5.3.2. Safety indicators

It is not completely clear how safety should be measured in a microscopic simulation. Real life traffic is always more unpredictable than traffic in a model (Minderhoud, 1999). So the safety measured in a simulation will always be better than in real life.

To measure the safety as good as possible several indicators were used. An important one is the standard deviation of speed; both van Driel (2007) and Marchesini & Weijermans (2010) indicate that a greater difference in speed between vehicles will lead to a higher risk for accidents. This standard deviation in speed is calculated based on the speed differences between all individual vehicles in the measure area, and is measured every minute.

A higher average speed can mean a decrease of safety as well. The average speed is calculated by measuring the speed of every vehicle in the measure area every second.

Another indicator proposed by Van der Horst (1990) is the percentage of Time To Collision (TTC) smaller than four seconds in the network, this percentage should be limited. A TTC of 4 or less seconds means that if a driver will continue to drive on its current speed and the drivers’ predecessor will do the same, the vehicles will collapse within 4 seconds. This TTC is measured relative to the total amount of TTC’s.

This means that the relative amount will decrease if the total TTC’s increases but the amount of TTC’s smaller than 4 seconds stays the same.

Indicators proposed by Marchesini & Weijermans (2010) are speed differences between lanes and the differences between traffic densities. Both differences should be minimized. These values are measured by detector 42.7 and are averaged over the whole measure period.

Yannis, et al., (2002) give as additional indicator the number of lane changes. A smaller amount of lane changes gives a higher safety level. The number of lane changes is given by the number of lane changes performed in the measure area.

All these indicators were used to measure the safety. No absolute safety level is given since it is not known how the different indicators interact with each other in real traffic situations (Yannis, et al., 2002). Therefore the indicators are only used as a comparison between simulation experiment results.
An overview of the used indicators, where they were measured and for which purpose they were used is given in the table below.

<table>
<thead>
<tr>
<th>Indicator</th>
<th>Measure location</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total travel time (h)</td>
<td>Measurement area</td>
<td>Throughput/ Sensitivity</td>
</tr>
<tr>
<td>Vehicle loss hours (h)</td>
<td>Measurement area</td>
<td>Throughput / Sensitivity</td>
</tr>
<tr>
<td>Average speed (km/h)</td>
<td>Measurement area</td>
<td>Throughput / Safety / Sensitivity</td>
</tr>
<tr>
<td>Average lane density (veh/km)</td>
<td>Detector 42.7</td>
<td>Throughput</td>
</tr>
<tr>
<td>Number of lane changes</td>
<td>Measurement area</td>
<td>Throughput / Safety</td>
</tr>
<tr>
<td>Standard deviation in speed (km/h)</td>
<td>Measurement area</td>
<td>Safety</td>
</tr>
<tr>
<td>TTC &lt;4 seconds (%)</td>
<td>Measurement area</td>
<td>Safety</td>
</tr>
<tr>
<td>Speed difference between lanes (km/h)</td>
<td>Detector 42.7</td>
<td>Safety</td>
</tr>
<tr>
<td>Density differences between lanes (veh/km)</td>
<td>Detector 42.7</td>
<td>Safety</td>
</tr>
</tbody>
</table>

Table 7: Indicator overview

5.4. Conclusion

Verification and validation was done by using the visualization possibility of Paramics. Validation was done by means of the GEH statistics which compares the real and simulated flows per hour. As the LMRS model was already validated and calibrated on the same location, the used model was assumed both valid and well calibrated if the GEH statistic showed sufficient results.

11 experiments were done, of which the first four were performed to determine the advices with the most positive results and the last five were performed to determine the sensitivity of the chosen advices for penetration rate. Several indicators were defined to determine the effects of the advices on throughput and safety. An overview of the indicators is given in table 7. The results of the verification, validation and experiments are described in the next chapter.
6. Results
This chapter describes the results of the verification and validation of the model, as well as the outcomes of the experiments as defined in the previous chapter.

6.1. Verification
During verification several differences with the original LMRS model were found. The two most important differences are discussed in this section.

The difference with the greatest influence is the vehicle generation. Paramics generates vehicles based on the given OD matrix, but does not check if the actual number of released vehicles does match with the number of vehicles as defined in the OD matrix. So if there is a high value of to be released vehicles for a certain minute, there is a certain chance the amount of actual released vehicles will be high as well but it is not guaranteed. The total amount of created vehicles is roughly the same, but their spread over time is different. This behavior causes every seed to be a different scenario since the distribution of traffic is of high influence on the chance of congestion.

Another difference was found in the lane change behavior. Due to a bug in the Paramics software which could not be located or solved, the function which causes vehicles to change lanes immediately could not be used. Instead of that function another function was used which causes the vehicle to change lanes as soon as they are able to according to the rules of Paramics. Due to this extra check of Paramics the real lane change takes place up to three seconds later. In case of trucks this lane change is sometimes canceled completely. This means that the traffic situation was slightly different as in the original LMRS model.

6.2. Validation
See for the average GEH values of all six runs table 8. The GEH values are very close to zero; this indicates a very good fit. The high GEH value at on-ramp 17 was caused by the difference in vehicle generation as described before. It is therefore not possible to decrease the GEH value further.

The model is assumed to be both valid and well calibrated based on the GEH values. It is assumed that the model will stay valid for the situation without trucks and on- and off-ramp 17 as well.

<table>
<thead>
<tr>
<th>Situation</th>
<th>GEH location</th>
<th>GEH measure time 5:50-6:50</th>
<th>GEH measure time 6:51-8:00</th>
<th>GEH Total time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Start Network</td>
<td>37.8</td>
<td>0.27</td>
<td>0.36</td>
<td>0.19</td>
</tr>
<tr>
<td>On-ramp 16</td>
<td>38.6</td>
<td>0.71</td>
<td>0.57</td>
<td>0.80</td>
</tr>
<tr>
<td>Off-ramp gas station</td>
<td>39.9</td>
<td>0.50</td>
<td>0.83</td>
<td>0.69</td>
</tr>
<tr>
<td>On-ramp gas station</td>
<td>40.6</td>
<td>1.24</td>
<td>0.51</td>
<td>1.04</td>
</tr>
<tr>
<td>Off-ramp 17 and lane drop</td>
<td>42.951</td>
<td>0.81</td>
<td>1.81</td>
<td>0.98</td>
</tr>
<tr>
<td>On-ramp 17</td>
<td>43.32</td>
<td>5.40</td>
<td>5.98</td>
<td>7.49</td>
</tr>
</tbody>
</table>

Table 8: Average GEH values

6.3. Experimental results
This section describes the results of the experiments as defined in the previous chapter. First the results of experiment 1-4 are described. Out of that the best advice combination was chosen, which is described in a concluding section. With this advice combination the sensitivity analysis was done. Based on the outcomes of the sensitivity analysis a safety analysis was done. This analysis is described in the seventh and last section of this paragraph.
6.3.1. Results of a headway and lane change advice to middle-lane in combination with a speed advice on the left-lane

Figure 16 provides an overview of the speed in the basic situation and the speed in the situation with a lane change advice from the middle-lane to the right-lane in combination with a speed advice on the left-lane and a headway advice on the middle-lane (experiment 1). This combination of advices is called CCC P10 since it includes a penetration rate of 10%. Both speeds are averaged over 30 runs. It is clearly visible that the CCC speed during congestion was higher, where it was the same as the basic speed in free flow.

![Figure 16: Mean speed in situation without and with a lane change, headway and speed advice](image)

The positive effect of the advices is visible in table 9 as well. A decrease of an indicator value is positive since it indicates a decrease of congestion, except for the average speed which increases when the congestion decreases. The relative differences are therefore colored green when they have a negative value, colored orange when they are zero and colored red when they have a positive value. For the average speed this is the opposite.

<table>
<thead>
<tr>
<th>Indicator</th>
<th>Basic scenario</th>
<th>CCC P10</th>
<th>Increase compared to basic situation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total travel time (h)</td>
<td>203.70</td>
<td>198.67</td>
<td>-2.47%</td>
</tr>
<tr>
<td>Vehicle lost hours (h)</td>
<td>13.16</td>
<td>8.13</td>
<td>-38.20%</td>
</tr>
<tr>
<td>Average speed (km/h)</td>
<td>102.89</td>
<td>105.50</td>
<td>2.53%</td>
</tr>
<tr>
<td>Average density (veh/km)</td>
<td>18.24</td>
<td>15.61</td>
<td>-14.41%</td>
</tr>
<tr>
<td># lane changes</td>
<td>4052.47</td>
<td>3778.80</td>
<td>-6.75%</td>
</tr>
</tbody>
</table>

Table 9: Indicator values for a combination of a lane change, headway and speed advice

All indicators show a positive result. The vehicle loss hours decrease with 38.2%. The number of lane changes decreases as well, possibly due the fact that all CCC drivers received the advice not to change to the left. Without the advice drivers will change to the left when they want to pass a predecessor. After the passing they will go back if that is possible, which is often not the case in busy road situations. The advice no to change to the left causes more vehicles to be on the right-lane and a decrease of lane changes. The speed increase itself is most likely caused by a better usage of the right-lane as explained.
in section 4.1. This better usage is most likely caused by the combination of the three advices. The lane change advice causes more vehicles to be on the right-lane. This results in more space on the middle-lane. The headway advice results in larger gaps between cars on the middle-lane, which makes it easier to switch lanes for drivers on the left-lane. The speed advice on the left-lane causes the speed on the left-lane to be almost equal to the speed on the middle-lane. This makes it again easier to switch lanes for drivers on the left-lane. There is an incentive for drivers on the left-lane to go to the middle-lane as there is a lane drop nearby. As a result of the advices and this incentive more left-lane drivers merge to the middle-lane on time. Fewer vehicles are therefore in the “queue” before the lane drop which decreases the amount of congestion.

6.3.2. Result of lane change advice on the left-lane

Figure 17 provides an overview of the effect on speed of a combination of a speed- and lane change advice on the left-lane and a headway- and lane change advice on the middle-lane (experiment 2). The results show an increase in speed compared with the basic situation but a decrease compared with the situation without a lane change advice on the left-lane. This is possibly caused by the fact that the lane change advice overrules the speed advice on the left-lane. As a result of the lane change advice the driver on the left-lane tries to switch lanes during 30 s without changing his or her speed. As the speed advice is of influence on the speed immediately after the advice is given, it is more effective on the short term. A second reason for the smaller decrease can be that fewer vehicles are on the left-lane due to the lane change advice. The remaining drivers can increase their speed therefore which can increase the average speed on that lane, which in turn can decrease the lane change possibilities and increase the congestion. A higher speed makes it more difficult to switch lanes. A third explanation can be that a speed advice is of influence on non CCC drivers, and a lane change advice is not. When a CCC driver limits the speed, his follower possibly has to decrease his speed as well. So by giving a speed advice it is easier for CCC drivers as well as for non-CCC drivers to switch lanes.

Table 10 provides an overview of the indicator values. All indicators show a decrease of congestion compared to the basic situation. All indicators show an increase of congestion compared to the situation without a lane change advice on the left-lane.
### 6.3.3. Results of a speed advice on the right-lane

Figure 18 shows that a speed advice on the right-lane (experiment 3) increased the congestion drastically even compared with the basic situation. By giving the speed advice the average speed on the right-lane was decreased. It was assumed that the lower speed, which makes lane changes easier, would create a better spread of traffic over the lanes with a net decreased congestion period as result. This assumption is not valid. The negative effect of a lower speed on the right-lane does overpower the positive effect of a better spread of traffic over the lanes. A possible explanation can be that equal speeds on lanes make it easier to switch lanes, but at the same time less attractive, as there is no speed gain. In congested situations the keep-right rule does not hold. At the lane drop there is no off-ramp or exit as well, which means that there is no desire to switch lanes due to a route as well. For non-CCC drivers a speed gain is thus the only reason for a lane change. As there is an almost equal speed, there is no speed gain, which means the total desire to switch lanes is almost, or equal to zero. So the speed advice on the right-lane possibly does not increase the amount of lane changes to the right. Together with a lower speed on the right-lane, which decreases capacity, this can cause the increase in congestion as shown below.

<table>
<thead>
<tr>
<th>Indicator</th>
<th>Basic scenario</th>
<th>CCC P10</th>
<th>Left-lane lc advice</th>
<th>Increase compared to basic situation</th>
<th>Increase compared to CCC P10 situation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total travel time (h)</td>
<td>203.70</td>
<td>198.67</td>
<td>199.58</td>
<td>-2.02%</td>
<td>0.46%</td>
</tr>
<tr>
<td>Vehicle lost hours (h)</td>
<td>13.16</td>
<td>8.13</td>
<td>9.04</td>
<td>-31.29%</td>
<td>11.18%</td>
</tr>
<tr>
<td>Average speed (km/h)</td>
<td>102.89</td>
<td>105.50</td>
<td>105.02</td>
<td>2.06%</td>
<td>-0.46%</td>
</tr>
<tr>
<td>Average density (veh/km)</td>
<td>18.24</td>
<td>15.61</td>
<td>16.35</td>
<td>-10.39%</td>
<td>4.69%</td>
</tr>
<tr>
<td># lane changes</td>
<td>4052.47</td>
<td>3778.80</td>
<td>3945.30</td>
<td>-2.64%</td>
<td>4.41%</td>
</tr>
</tbody>
</table>

Table 10: Indicator values for a lane change advice from left-lane to middle-lane

![Figure 18: Results of CCC P10 in combination with a speed advice on the right-lane](image_url)
6.3.4. Headway advice on the right-lane

In figure 19 the result of a headway advice on the right-lane in combination with the advices given in experiment 1 (experiment 4) is visible. It was expected that larger gaps on the right-lane would cause more non-CCC drivers to go to the right-lane. From the results it can be concluded that this does not happen enough to have a more positive effect on the average speed compared to the CCC P10 situation. This can indicate that not enough gaps created by the headway advice are used. A larger headway is negative for the traffic flow as there is less space available for other vehicles. If all these headway would have been used by other drivers to merge to the lane with the headway advice, the spread of vehicles over the road would have been better and the negative effect of the headway advice would have been small, as the headway advice is not continued when a driver receives a new predecessor. If the gaps are not used by drivers to switch lanes, the drivers with the headway advice will have the headway advice until the lane drop is passed or the speed is below 100 km/h. This can increase the amount of congestion.

![Figure 19: Results of CCC P10 in combination with a headway advice on the right-lane](image)

Table 11 shows that all indicator values have a positive impact on the traffic situation compared to the basic situation, but a negative effect on the traffic situation compared to the situation without a headway advice on the right-lane, indicating the same result as figure 19. This can indicate that the negative effect of the headway advice on the right-lane is smaller than the positive effect of the CCC P10 advices.

<table>
<thead>
<tr>
<th>Indicator</th>
<th>Basic scenario</th>
<th>CCC P10</th>
<th>Right-lane headway advice</th>
<th>Increase compared to basic situation</th>
<th>Increase compared to CCC P10 situation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total travel time (h)</td>
<td>203.70</td>
<td>198.67</td>
<td>201.57</td>
<td>-1.05%</td>
<td>1.46%</td>
</tr>
<tr>
<td>Vehicle lost hours (h)</td>
<td>13.16</td>
<td>8.13</td>
<td>11.02</td>
<td>-16.23%</td>
<td>35.55%</td>
</tr>
<tr>
<td>Average speed (km/h)</td>
<td>102.89</td>
<td>105.50</td>
<td>103.98</td>
<td>1.06%</td>
<td>-1.43%</td>
</tr>
<tr>
<td>Average density (veh/km)</td>
<td>18.24</td>
<td>15.61</td>
<td>17.04</td>
<td>-6.57%</td>
<td>9.16%</td>
</tr>
<tr>
<td># lane changes</td>
<td>4052.47</td>
<td>3778.80</td>
<td>3978.77</td>
<td>-1.82%</td>
<td>5.29%</td>
</tr>
</tbody>
</table>

Table 11: Indicator values for headway advice to right-lane
6.3.5. Conclusion

The combination of a speed advice on the left-lane and a lane change and headway advice on the middle-lane showed a positive influence on the traffic situation. The other advices did not increase this effect. It is therefore not advised to implement a speed or headway advice on the right-lane nor a lane change advice on the left-lane. The sensitivity analysis was therefore done with the advice combination which showed the most positive results; CCC P10.

6.3.6. Sensitivity Analysis for penetration rate

The standard deviation of all three sensitivity indicators decreased when the penetration rate increased, as visible in figure 20. This is logical since congestion is more stochastic than free flow. As the amount of congestion reduces with a higher penetration rate, the standard deviation reduces as well. A smaller standard deviation means more reliable model outcomes with higher penetration rates.

Figure 20: Standard deviations per penetration rate of CCC drivers

Figure 21 provides an overview of the speed per penetration rate during the congested period. It is visible that even a small penetration of 2% has a positive influence on the speed. If the penetration rate increases, the average speed increases as well.

Figure 21: Mean speeds during the congested period for several penetration rates

A small penetration rate was not only positive for the traffic situation as a whole, but for the individual CCC driver as well. Table 12 shows that the average speed for CCC drivers was higher than the average speed of other drivers. CCC drivers drive relatively more on the right-lane due to the given lane change advice. The right-lane has a higher speed, so it is logical that on average the CCC drivers have a higher
speed as well. With increasing penetration rates the speed difference between the middle- and right-lane decreases, see figure 22. The speed difference between CCC drivers and non-CCC drivers decreases as well consequentially.

<table>
<thead>
<tr>
<th>Speed per driver type</th>
<th>P2</th>
<th>P5</th>
<th>P10</th>
<th>P20</th>
<th>P40</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average Speed CCC-drivers (km/h)</td>
<td>105.82</td>
<td>105.43</td>
<td>106.65</td>
<td>107.85</td>
<td>107.68</td>
</tr>
<tr>
<td>Average Speed other drivers (km/h)</td>
<td>103.11</td>
<td>103.80</td>
<td>105.37</td>
<td>106.84</td>
<td>107.52</td>
</tr>
<tr>
<td>Speed difference (km/h)</td>
<td>2.71</td>
<td>1.63</td>
<td>1.28</td>
<td>1.01</td>
<td>0.16</td>
</tr>
</tbody>
</table>

Table 12: Speed per driver type

Figure 22: Speed difference between middle- and right-lane (km/h)

Figure 23 shows how the separate indicators were influenced by the penetration rate. The relative increase compared to the basic situation is given.

The total travel time and the vehicle lost hours showed a decreasing decrease, and the average speed showed a decreasing increase, when the penetration rate increased. This relationship means that most congestion reduction is already obtained with a penetration rate of 20%; a further increase of penetration rate will only cause a relative small reduction of congestion. The maximum decrease of vehicle loss hours is 67.46%. However, this relative decrease is very sensitive for the used free flow speed. If as free flow speed the maximum speed of 120 km/h is used instead of the measured average speed of 110 km/h, the relative increase is halved to 35.2%.
The congestion reduction may be caused by a better use of the road resulting in a higher maximum flow. An increase of 4.06% compared to the basic situation was found with a penetration rate of 40%, see table 13. The flow was measured by aggregating the flows over five minutes at detector 42.7, close upstream the lane drop.

<table>
<thead>
<tr>
<th>Penetration rate (%)</th>
<th>Highest aggregated flow (veh/h)</th>
<th>Increase (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>5028</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>5028</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>5052</td>
<td>0.48</td>
</tr>
<tr>
<td>10</td>
<td>5112</td>
<td>1.67</td>
</tr>
<tr>
<td>20</td>
<td>5220</td>
<td>3.82</td>
</tr>
<tr>
<td>40</td>
<td>5232</td>
<td>4.06</td>
</tr>
</tbody>
</table>

Table 13: Flow increase per penetration rate

6.3.7. Sensitivity to presence of trucks

The previous mentioned experiments were performed without trucks. In reality trucks will be present on most highways. Therefore the sensitivity of the advices to the presence of trucks is tested. The outcomes of this experiment are described in this section.

In the performed simulation the actual length of cars and trucks was known, 4 and 15 meter, but the speed and headway per vehicle type and the actual percentage of trucks on the middle- and right-lane could not be determined from the detector data. Therefore it was assumed that the amount of trucks (11% of the vehicles) and the average headway of 1 second were constant over time, and that all trucks were always on the right-lane.

Given these limitations, the results were still found to be positive, see figure 24, but the effect compared to the situation without trucks decreased significantly.
Table 14 provides an overview of the indicator values for the basic situation with trucks and the P10 situation with trucks. There was a decrease of vehicle loss hours of 6.55%. However, in the situation without trucks this decrease was 38.2% with the same penetration rate. This indicates that the CCC advices as defined in this study are very sensitive for the presence of trucks. This sensitivity is possibly caused by the difficulties in the PCU prediction which leads to a wrong number of given lane change advices. Another factor which can be of influence is the maximum acceleration of trucks. Trucks have a maximum acceleration of 0.4 m/s\(^2\) and cars have a maximum acceleration of 1.25 m/s\(^2\). Due to this acceleration difference and the fact that most trucks drive on the right-lane, this lane can accelerate slower out of the congested area.

Table 14: Indicator values for the situation with trucks implemented

<table>
<thead>
<tr>
<th>Indicator</th>
<th>Basic scenario</th>
<th>P10</th>
<th>Increase compared to basic situation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total travel time (h)</td>
<td>203.86</td>
<td>201.70</td>
<td>-1.06%</td>
</tr>
<tr>
<td>Vehicle lost hours (h)</td>
<td>32.98</td>
<td>30.82</td>
<td>-6.55%</td>
</tr>
<tr>
<td>Average speed (km/h)</td>
<td>92.20</td>
<td>93.19</td>
<td>1.07%</td>
</tr>
<tr>
<td>Average density (veh/km)</td>
<td>19.86</td>
<td>19.14</td>
<td>-3.61%</td>
</tr>
<tr>
<td># lane changes</td>
<td>5618.50</td>
<td>5592.17</td>
<td>-0.47%</td>
</tr>
</tbody>
</table>

In the situation with trucks there was only a very small speed gain for CCC drivers, see table 15. This may be caused by the low maximum speed of trucks, which drive on the right-lane.

Table 15: Average speed difference between a CCC-driver and other drivers in a 10% penetration rate situation including trucks

<table>
<thead>
<tr>
<th>Speed per driver type</th>
<th>P10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average Speed CCC-drivers (km/h)</td>
<td>84.932</td>
</tr>
<tr>
<td>Average Speed other car drivers (km/h)</td>
<td>84.924</td>
</tr>
<tr>
<td>Speed difference (km/h)</td>
<td>0.008</td>
</tr>
</tbody>
</table>
6.3.8. Sensitivity to situation with on- and off-ramp 17

To test what the influence is of a complex situation, the network as used for validation was used. In the performed runs no trucks were included. Figure 25 provides an overview of the basic speed and the speed with a CCC penetration rate of 10% measured at detector 42.7, upstream the lane drop, and 43.32, downstream the lane drop and half way the on-ramp 17 from Nieuwerkerk aan den IJssel. The advices caused only a small positive effect at 42.7 were at 43.32 a negative effect is visible.

![Figure 25: Mean speed at 42.7 and 43.32 during congestion of the situation including on- and off-ramp 17](image)

Table 16 shows that the effect of the CCC advices as measured between 6 AM and 7:30 AM in the measure area is negative. Although the average density, as measured at 42.7, shows a slightly positive result, all other indicators show an increase of congestion. This may be caused by an increase of congestion downstream the lane drop caused by the merging vehicles from the on-ramp 17. At the lane drop 50% of the vehicles need to be on the right-lane to get an optimal traffic situation and make it easy for drivers on the left-lane, to go to the middle-lane. However, as the on-ramp 17 is on the right-side of the road, more than 50% of the vehicles need to be at the middle-lane in order to make room for merging vehicles from the on-ramp. See figure 26 for a visualization of the situation without CCC advices given. Because of this complex situation it is not possible to implement the advices as defined in the current study here.

<table>
<thead>
<tr>
<th>Indicator</th>
<th>Basic scenario</th>
<th>P10</th>
<th>Increase compared to basic situation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total travel time (h)</td>
<td>243.06</td>
<td>247.35</td>
<td>1.77%</td>
</tr>
<tr>
<td>Vehicle lost hours (h)</td>
<td>51.10</td>
<td>56.33</td>
<td>10.23%</td>
</tr>
<tr>
<td>Average speed (km/h)</td>
<td>86.87</td>
<td>84.95</td>
<td>-2.21%</td>
</tr>
<tr>
<td>Average density (veh/km)</td>
<td>14.43</td>
<td>14.34</td>
<td>-0.64%</td>
</tr>
<tr>
<td># lane changes</td>
<td>6469.67</td>
<td>6545.28</td>
<td>1.17%</td>
</tr>
</tbody>
</table>

Table 16: Indicator values of the situation including on- and off-ramp 17

![Figure 26: Basic traffic situation at the start of the congestion](image)
6.3.9. Safety analysis

The CCC advices had a positive influence on most safety indicators with a penetration rate of 10%, as visible in table 17. An increase in speed, which is a result of a decrease of congestion, can result in a decrease in safety. This possible decrease in safety is therefore a negative side effect of the decrease of congestion. The speed difference, compared to the basic situation, of the left-lane and the middle-lane increased due to the CCC advices. This can also imply negative consequences for safety. The decrease in standard deviation of speed, speed difference between the middle-lane and the right-lane, density difference between lanes, TTC’s smaller than 4 s and amount of lane changes are associated with an increase in safety. They are colored green therefore. The increase of speed difference was caused by a higher increase of the speed on the middle-lane compared to the speed increase on the left-lane. These effects are visible for other penetration rates as well.

<table>
<thead>
<tr>
<th>Indicator</th>
<th>Basic scenario</th>
<th>P10</th>
<th>Increase compared to basic situation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard deviation of speed</td>
<td>9.12</td>
<td>8.72</td>
<td>-4.34%</td>
</tr>
<tr>
<td>Speed difference middle- and left-lane (km/h)</td>
<td>6.63</td>
<td>7.16</td>
<td>7.92%</td>
</tr>
<tr>
<td>Speed difference right- and middle-lane (km/h)</td>
<td>5.72</td>
<td>4.55</td>
<td>-20.59%</td>
</tr>
<tr>
<td>Average speed (km/h)</td>
<td>102.89</td>
<td>105.50</td>
<td>2.53%</td>
</tr>
<tr>
<td>Density difference left- and middle-lane (veh/km)</td>
<td>11.89</td>
<td>7.86</td>
<td>-33.87%</td>
</tr>
<tr>
<td>Density difference middle- and right-lane (veh/km)</td>
<td>23.53</td>
<td>20.58</td>
<td>-12.55%</td>
</tr>
<tr>
<td>% TTC &lt; 4s</td>
<td>0.0130</td>
<td>0.0058</td>
<td>-55.30%</td>
</tr>
<tr>
<td># lane changes</td>
<td>4052.47</td>
<td>3778.80</td>
<td>-6.75%</td>
</tr>
<tr>
<td>Time headways (s)</td>
<td>2.46</td>
<td>2.45</td>
<td>-0.53%</td>
</tr>
</tbody>
</table>

Table 17: Safety indicator values for the basic scenario and 10% penetration rate

Figure 27 shows how the safety indicators were influenced by the penetration rate. Most indicators decrease when the penetration rate increases. The number of lane changes however, has its minimum at a penetration rate of 10%, and is almost equal to the basic situation with a penetration rate of 40%, it is not clear why.
Figure 27: Safety indicator values for several penetration rates

The amount of time to collisions smaller than 4 seconds decreased with up to 80%. This high decrease was possibly caused by the smaller speed difference between the middle- and right-lane. Another reason may be that drivers have more time or opportunity to perform a lane change, allowing more lane changes to be performed with smaller speed differences and less critical headways.

Most indicators show an increase in safety for all penetration rates. But as Yannis, et al. (2002) stated, no absolute safety indication can be given, since it is not known how the different safety aspects interact with each other.

6.4. Conclusion

A combination of a headway advice on the middle lane, a speed advice on the left-lane and a lane change advice to change lanes from the middle-lane to the right-lane, had a positive influence on travel time, as measured by all five indicators, namely total travel time, vehicle loss hours, average speed, average density, and total amount of lane changes. A higher penetration rate caused more decrease of congestion. The increase of congestion reduction was found to be decreasing as the penetration rate increases, which means that a relative small increase of penetration rate can cause a relative large decrease of congestion when the penetration rate is small. Most safety indicators showed an improvement implying an increased safety, except for the average speed and the speed difference between the left-lane and the middle-lane. The exact relationship and interactions between the various indicators are not known. No absolute conclusion on safety can be given therefore.
7. Discussion
This chapter discusses the choices made in this research as well as the outcomes of it.

Minderhoud (1999) found a capacity gain of up to 25%. The present study found an increase of maximum flow of 4.06% with a penetration rate of 40%. Although this is below the capacity increase as found by Minderhoud, it is still remarkable for a system which does not decrease the headway time.

A decrease of travel time of 10 to 25% was expected. However, this expectation could not be based on a study for an informative system since that does not exist. The found reduction of vehicle loss hours of 67.5% for a penetration rate of 40% was far more than expected. Although, this reduction is very sensitive to the used free flow speed, it is still comparable with other studies as mentioned in chapter 2 as these studies use a free flow speed of 110 km/m as well.

For the current study full compliance was assumed. In reality the given advices will not be followed up by all users. The found results are therefore more positive than they will be in reality.

The main reason for the decrease of congestion can be found in a better spread of vehicles on the road. As visible in figure 28, the density peak of the left-lane and right-lane decreased to almost the free-flow value when 40% of the drivers had CCC. The density on the middle-lane was still high. These densities indicate that more drivers were able to go from the left-lane to the middle-lane on time, which resulted in less congestion on the left-lane. But there is still improvement of the traffic situation possible as the density peak on the middle-lane indicates that not enough lane change advices were given to come to an equal spread of density over the middle- and right-lane. This may partially be caused by the calculation error of the density due to the use of the average speed instead of the harmonic speed.

Since every simulation is a simplification of reality, there can be behavior which is not implemented in the existing model. Although the model is valid for the existing situation, it may be not valid for the future CCC situation, due to the lack of the non-implemented behavior. The results as presented by this study are therefore not guaranteed to happen when the system is implemented in reality. This uncertainty can be minimized by use of simulator studies and real vehicle experiments which can identify such behavior.

In this study a value of 60% was used as a factor for lane change advices which are followed up. However, this value is not constant per penetration rate. See table 18 for the average values over 30 seeds per penetration rate. For small penetration rates this values was too high where for a penetration
rate higher than 40% the value was too small. Both cases can have had a negative influence on the research outcomes.

<table>
<thead>
<tr>
<th>Penetration rate (%)</th>
<th>Average followed up advices (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>79.04</td>
</tr>
<tr>
<td>5</td>
<td>75.76</td>
</tr>
<tr>
<td>10</td>
<td>71.48</td>
</tr>
<tr>
<td>20</td>
<td>65.02</td>
</tr>
<tr>
<td>40</td>
<td>57.80</td>
</tr>
<tr>
<td>100</td>
<td>38.87</td>
</tr>
</tbody>
</table>

Table 18: Percentage of followed up advices per penetration rate

The experiment which included trucks showed a negative influence of trucks on the CCC effectiveness, however, the effect is still positive.

The smaller congestion reduction is probably caused by three reasons:

- The assumption of all trucks on the right-lane is not always true.
- It is difficult to determine the actual percentage of trucks in the advice area.
- It is difficult to determine the actual average headway time and speed for cars and trucks, and thus difficult to accurately calculate the PCU per truck.

In reality it will be difficult to determine the actual average length of trucks and the actual average length of cars as well. It is expected that if all above mentioned parameters can be determined exactly for the advice area, the results as found by the experiments without trucks will be reached closely, only limited by the smaller acceleration factor of the trucks.

The results of the experiment with the on- and off-ramp to Nieuwerkerk aan den Ijssel showed that CCC advices have a net negative influence on the traffic situation. This indicates that the advices as proposed in the current study will not work here. For other complex lane drop situations the results may be similar. This may result in the need to investigate situation specific advices for such locations.

This study shows promising results for the CCC implementation. The results are even better than expected based on the results of other studies. With a more in depth study on the implementation for complex lane drop situation and the presence of trucks the CCC system’ performance may reach the level as found for the situation with only cars.
8. Conclusions and recommendations

This chapter summarizes the answers on the research questions as given in this report. Besides that several recommendations are listed.

8.1. Conclusions

The current research studied the effects of a lane change advice, a speed advice, and a headway advice on the traffic situation of a specific lane drop location; the A20 between Rotterdam and Gouda. This was done by means of a micro-simulation study which made it possible to model individual vehicles. 11 experiments were done. Each experiment was simulated 30 times, each time with a different random seed. The standard penetration rate used was 10%. See the table below for a description of all experiments.

<table>
<thead>
<tr>
<th>Exp. Nr.</th>
<th>Experiment description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Lc and headway advice middle-lane, speed advice left-lane</td>
</tr>
<tr>
<td>2</td>
<td>Experiment 1 plus lane change advice left-lane</td>
</tr>
<tr>
<td>3</td>
<td>Experiment 1 plus speed advice on right-lane</td>
</tr>
<tr>
<td>4</td>
<td>Experiment 1 plus headway advice right-lane</td>
</tr>
<tr>
<td>5</td>
<td>Penetration rate of 2%</td>
</tr>
<tr>
<td>6</td>
<td>Penetration rate of 5%</td>
</tr>
<tr>
<td>7</td>
<td>Penetration rate of 10%</td>
</tr>
<tr>
<td>8</td>
<td>Penetration rate of 20%</td>
</tr>
<tr>
<td>9</td>
<td>Penetration rate of 40%</td>
</tr>
<tr>
<td>10</td>
<td>11% Truck</td>
</tr>
<tr>
<td>11</td>
<td>On- and off-ramp 17</td>
</tr>
</tbody>
</table>

Table 19: Experiment number and description

Based on the outcomes of these experiments the research questions could be answered. The main question of this research was stated as:

*How can the traffic flow be improved at a lane drop location using CCC?*

From the answers to the sub-questions the answer to this question became clear. The first question was formulated as follows:

*What are good triggers for the CCC system?*

The trigger threshold values as defined before were found to be working fine. The trigger thresholds to turn on the system are:

- Flow on all lanes exceeds 4020 veh/h.
- Flow on middle- or left-lane exceeds 2040 veh/h.
- Speed on middle- or left-lane is below 80 km/h.

The trigger thresholds to turn off the system are:

- Flow on all lanes below 3480 veh/h.
- Flow on middle- and left-lane below 1800 veh/h.
- Speed above 90 km/h.

At least two on-trigger thresholds must be reached to turn the CCC system on and all off-trigger thresholds must be reached to turn the system off to prevent flickering. In most cases the total flow per
minute in the trigger area, together with the flow per minute on the middle-lane caused the CCC system to be turned on. Further optimization appears to be feasible by editing the thresholds of these triggers.

The second question holds:

Which lanes should receive which CCC advice?
A lane change advice for vehicles on the middle-lane to the right-lane will increase the flow at a lane drop. This lane change advice has to take into account the truck percentage on the right-lane, the average headway time, the current speed, the average lengths of the vehicles, and the percentage of lane change advices which result in an actual lane change, in order to be successful. Other advices which have a positive effect on the traffic flow are a speed advice on the left-lane equal to the speed of the right predecessor and a headway advice for vehicles on the middle-lane of three seconds. The advices will work if the parameters as listed for the lane change advice can be estimated. In complex lane drop situations, for instance a busy off-ramp and on-ramp in the neighborhood of the lane drop, these advices will show less positive results.

The third question was stated as follows:

How does the CCC penetration rate influence the traffic flow?
There is a positive influence of penetration rate on the effect of the advices. This effect is such that, for small penetration rates, a small increase of penetration rate will cause a relatively high reduction of congestion.

The answer to the main question is in short described below.
The traffic flow at a lane drop can be improved by giving a speed advice on the left-lane, and a headway and lane change advice on the middle-lane to CCC drivers during busy traffic conditions. The more CCC drivers there are, the higher the decrease of congestion. The advices have already an effect when there is a penetration rate of 2%. This effect is both positive for the traffic situation as a whole and the individual CCC driver. With a high penetration rate the vehicle loss hours will decrease up to 67% which is high compared to other studies.

Informative systems, of which CCC is one, can be implemented more easily in existing cars and will be accepted more easily by drivers. This easy implementation combined with the very positive results of the current study indicates that CCC has high potential. Further development of this system is therefore advised.

8.2. Recommendations
Several recommendations can be made; these are discussed here.

The most important recommendation is that all assumptions as listed in the report need to be tested. The observed results of the performed simulations depend on these assumptions. The most important assumption is the 100% compliance rate. The smaller this compliance value, the smaller the effects of CCC. Other important assumptions are done on the reaction of drivers to given advices. The drivers for instance may never use their indicator when they are advised to switch lanes. If that is the case, it may be needed to give the lane change advice earlier, as drivers need more time to find a possible gap. Another result of this can be that the lane change advice possibly can be valid even if the speed is below 100 km/h, as the use of the indicator, which causes other drivers to break, is the main reason for a negative effect on traffic flow during busy road situations.
There was only a lane change or headway advice given to drivers with a speed above 100 km/h. This resulted in the situation that, with low penetration rates, not enough CCC drivers were available to get a lane change advice to the right-lane. When the speed threshold is set to a lower value the results may be better therefore. Research on this tradeoff between minimum speed of the drivers with a lane change advice and the number of needed vehicles on the right-lane is advised.

For this research an advice area of three km was used. No research is done to indicate if this length is too short, long enough, or too long. If the advice area is extended, more drivers possibly have enough time to follow up the advices and a more positive result could be reached. If the area is shortened, possibly less drivers get an advice too early. This could improve the results as well. Further research is advised to investigate these effects.

Since the lane change advice on the left-lane and the headway advice on the right-lane show a positive effect compared to the basic scenario, they can possibly be implemented in a different way to create overall positive results. This can for instance be done for the lane change advice by giving a certain percentage of the traffic on the left-lane a lane change advice and the remaining drivers a speed advice. For the headway advice this can be done by only giving a headway advice when the speed difference between lanes is at most 10 km/h.

As described in the literature review several other ADA Systems are available or currently researched. One of these systems, the lane change assistant, can be of help for CCC. The effect of CCC is limited since it is not known what the elapsed time is between the advice given and the action performed. During that time the traffic situation can change, or the driver can perform the action too early or too late as indicated above. If CCC is combined with the lane change assistant, the advice to change lanes can be given on the moment it is safe to do so. By doing that, the actual time the action is performed can be set more specifically and the system performance will possibly increase.

For this study it was assumed that all drivers will follow up all advices. In reality this will not hold for an informative system like CCC. The amount of not followed up advices is most important for the lane change advice on the middle-lane. If x% of the drivers with this advice do not follow up the advice, more lane change advices have to be given to reach 50% of the vehicle on the right-lane. Other studies, which are already performed in the CCC project currently, have to show to which extend the given advices will be followed up.

A last important gap in the current knowledge is how to deal with trucks on the network. It is wise to research how to determine and predict the actual number of PCU’s on the right-lane at the lane drop.
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