Bachelor Thesis

Safe lane changing

A study into the practical implementation of the Lane Change Assistant

M.T.A. Roelofsen
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Preface

This study is a Bachelor Thesis for my study in Civil Engineering at the University of Twente, and is carried out at the Jilin University in China. The research is part of the cooperative research project between the Jilin University and the University of Twente in the Netherlands on the lane changing safety assistance. The assignment focuses on the question how the Lane Change Assistant can be implemented in practice.

My four-month stay in China gave me not only the opportunity to finish my Bachelor studies, it also gave me a unique view at Chinese culture and student life. Living in China is completely different from my usual life in the Netherlands, which made my stay a fantastic and unforgettable experience.

I would like to thank several people for their contribution to this result. I would like to thank Professor Bart van Arem for giving me the opportunity to go to Jilin University and Jing Bie for his extensive support and advice during the complete project. I thank Lisheng Jin for guiding me during my stay at Jilin University, and for setting me up in China together with his students. I would also like to thank Ellen van Oosterzee for her support before, during and after my stay in China.

Mark Roelofsen

Abstract

This research presents a design for the Lane Change Assistant (LCA). This Intelligent Transport System advises the driver whether it is safe to change lanes on a highway under current traffic conditions. This research focuses on how the LCA can give a reliable advice in practice, by considering several practical issues. The practical issues that are taken into account consist of changing circumstances, measurement uncertainties and model assumptions. A sensitivity study into these issues is performed, showing that a scenario where an emergency brake occurs under rainy weather conditions results in the most uncertain advice to the driver. These results are used to create a design for the LCA which is robust to common practical issues. The system compensates for the practical uncertainties by using certain extra safety distance. The communication to the driver consists of a spectrum of five LED lights, each guaranteeing a certain degree of safety, by applying a certain safety distance.

In order to obtain these research results a micro simulation model is developed. This model is based on a lane change algorithm from the available literature and a vehicle following model. This powerful model relies on only a few negligible assumptions and has a probabilistic character to mimic the practice situation accurately.

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1. Introduction

As a result of the enormous growth in transport the last decades, our road networks are getting busier and busier. To prevent dangerous situations, the driver needs to pay more attention to his vehicular maneuver under heavy congestion. Under these circumstances, special attention is needed for the most difficult driving tasks. Lane changing is considered one of the most difficult tasks of driving. In 2008, 1.7% of the registered highway accidents (100km/h & 120km/h) in the Netherlands were caused by wrong lane changing (SWOV, 2009). Though this number may not seem shocking, these accidents are responsible for 10% of the total delay caused by accidents (Jin, Fang, Zhang, Yang & Hou, 2009).

Intelligent Transport Systems (ITS) applications in and around the vehicle help, or even take over, certain driving tasks from the driver and can therefore improve a driver's safety and traffic efficiency. Nowadays, more and more ITS applications become available on the market and more are still under development. One of these promising new techniques is the Lane Change Assistant (LCA). This assistant gives an advice to the driver on whether a lane change can be made safely, with regard to the current traffic situation. To be able to give this advice, the vehicle must be equipped with vehicle detection hardware. The implementation of an in-car system that supports the driver during lane changes contributes to less accidents and a higher safety level on the roads, and consequently leads to a reduction in the traffic delay.

Recently, several researches have been carried out which introduce a theoretical algorithm to calculate whether it is safe or not to change lane. This prediction can be made by using certain input variables that describe the environment continuously. However, when the LCA will be used in real life, it has to deal with some practical issues that current studies have not taken into account. This study covers this problem in the development of the LCA, and therefore, the focus of this research lies on the question how a lane change advice can be practically made. To generate a reliable advice in practice, the assistant must deal with several practical issues. This research will analyze to what extent these issues are present, and gives advice on how to prevent them from affecting the reliability of the advice.

1.1. Goal & Approach

The goal in this research is to find out how a lane change advice can be made practically, regarding the practical issues. This goal will be reached by assessing the performance and robustness of the LCA with respect to different conditions. The result of this study is a mathematical model that is considerate to common practical issues.

Research questions

Main research question:
How can a lane change advice be *practically* made?

Sub research questions:

1. Are the current models detailed enough to be a good approach from the real world?
2. How reliable is the advice from the lane change assistant in practice?
    a. How does the lane change assistant react to changing circumstances?
    b. What are the consequences of measurement uncertainty?
    c. What are the consequences of assumptions made in the model?
3. What safety distances must be considered?

1. Are the current models detailed enough to be a good approach from the real world?
It is necessary to know how detailed the current mathematical models are. The more input variables are taken into account by the algorithm, the more the algorithm approaches the real world, and a smaller safety distance is needed. In order to get an answer to this question a literature study is performed by checking which input variables are taken into account.

2a. How does the lane change assistant react to changing circumstances?
The LCA has to make a prediction for the traffic situation during the next few seconds. Since traffic can be very dynamic, predicting a traffic situation a few seconds ahead gives a certain degree of uncertainty in practice. The LCA has to consider possibly changing circumstances. The influence of an unexpected event to the LCA is determined by simulating this scenario, using the model developed for this research.

2b. What are the consequences of measurement uncertainty?
Since most input variables need to be detected by the on-board detection hardware, the LCA has to deal with measurement uncertainties in the input. The error caused by these input variables can be determined by classifying the degree of measurement uncertainty, the influence on the output, and the sensitivity of each variable. A simulation is used once more to get this information. By randomizing input variables in the model, their effect on the output can be determined.

2c. What are the consequences of assumptions made in the model?
Algorithms are based on several model assumptions to simplify reality. However, too much or rigorous assumptions can lead to an unreliable advice. This research identified the consequences of model assumptions.

3. What safety distances must be considered?
All the practical issues mentioned in sub research question 2 and the model limitations mentioned in sub research question 1 have a negative impact on the reliability of the output. In practice, a wrong advice from the LCA is unacceptable as it could directly lead to unsafe situations. In order to prevent this situation, the LCA needs to take certain safety distance into account. This is an extra distance to the surrounding vehicles, above the regular minimal longitudinal distance, to compensate to the uncertainties. To keep the driver in the loop, the LCA calculates an advice with five different safety margins. The simulation model was used to determine which safety distances are needed for which situations.

Approach
This research is performed by composing a simulation model in order to assess the consequences of common practical issues to the performance of the LCA. To obtain this model, firstly a literature review is required to find out how current mathematical lane change models work, and on what differences they rely. This research proposes key performance indicators in order to quantify the consequences of the practical issues. Once these connections are demonstrated, a solution can be worked out about how the reliability of the LCA can be maximized in practice by applying extra safety distances.

1.2. Report structure

The structure of this report is equal to the order of the research questions. This first chapter introduces the subject and reveals the framework in which this research is performed. The second chapter gives an overview of lane changing algorithms that are available in the literature. Then the third chapter introduces the Matlab model, which has been developed and applied in this research. The fourth chapter shows the effects of the practical issues to the reliability of the output. With this information, the required safety distances are calculated in chapter five. The overall conclusions and the appendix can be found in the last chapters.

1.3. Framework

This paragraph defines the scenario and the architecture of the LCA exactly. This limits the scope of the research and makes the research more clearly.

1.3.1. The scenario

Figure 1 shows the scenario used in this research.

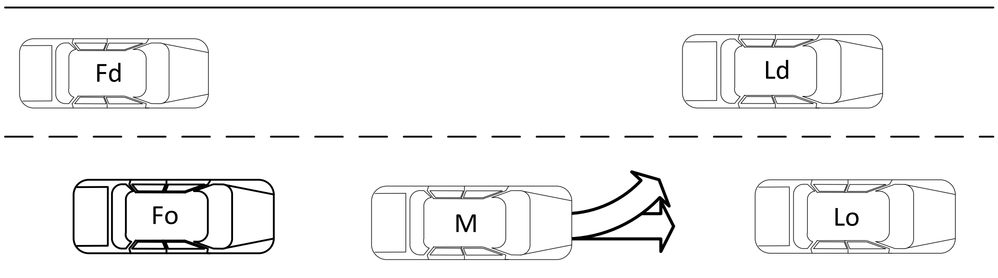

Figure 1. Scenario: Initial vehicle configuration

In this scenario, the LCA pays only attention to a maximum of four surrounding vehicles. Those vehicles are closest to the merging vehicle. The LCA does not consider other vehicles. The merging vehicle M is equipped with the LCA. The four surrounding vehicles are defined as follows:

- L_o is the leading vehicle in the original lane.
- L_d is the leading vehicle in the destination lane.
- F_o is the following vehicle in the original lane.
- F_d is the following vehicle in the destination lane.

The scenario consists of a two-lane highway system, where drivers move to the left lane to overtake the preceding vehicle L_o.

1.3.2. The architecture

Figure 2 depicts the general architecture of a lateral driver support system (Tideman, van der Voort, van Arem & Tillema, 2007). This research focuses on the *safety assessment algorithm*, within the sub-function *think*. In this step, the LCA generates an advice by using certain algorithm. The sensors in sub-function *sense* give the input. The Human Machine Interface (HMI) in sub-function *act* forwards the output to the driver.

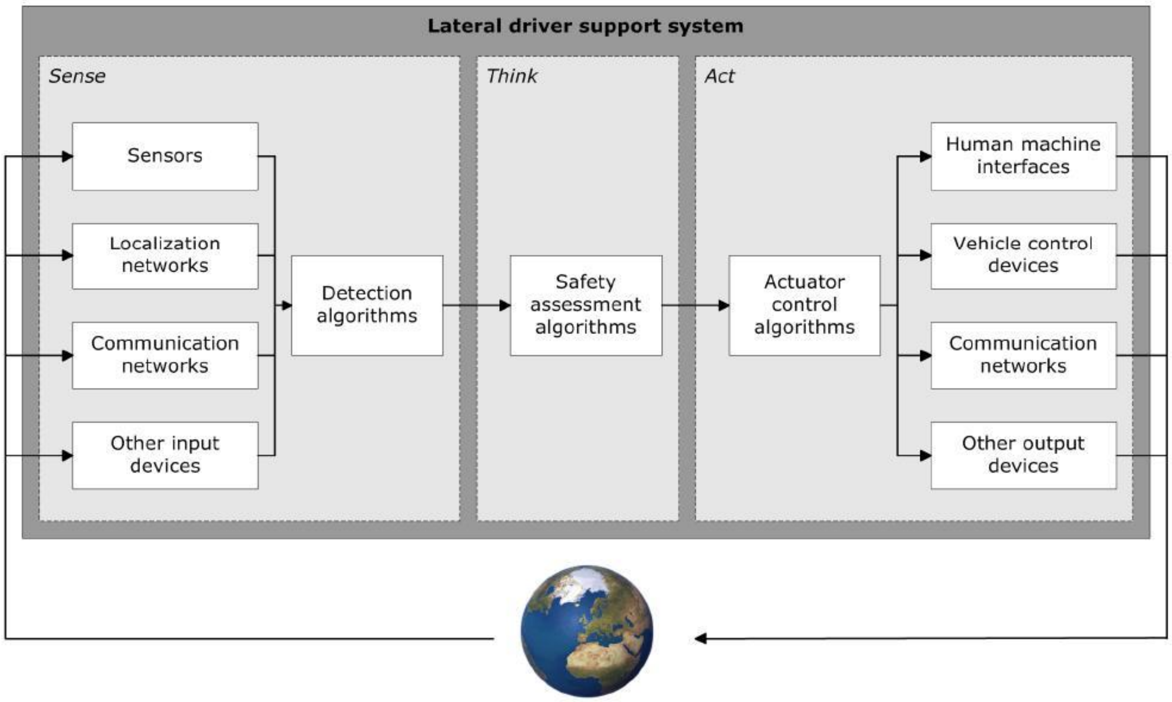

Figure 2. Architecture of a lateral driver support system

Tideman (2008) states that a different design of the LCA changes the way it is working. The design of the LCA within this research has to be clear from the beginning.

- The LCA advices in a positive way. This means it informs the driver when it predicts a safe lane change situation. In contrast to a negative type, which informs the driver when it is not safe to change lane.
- The LCA will only give advice for lane changes with the left lane as destination lane, as described in the scenario. It does not detect vehicles on the right side of the vehicle.
- The LCA operates in a free lane-changing scenario, thus not during merging from a ramp or an emergency lane change. A survey among drivers concludes that 94% of the drivers think an assistant in this situation can be useful (van Dijck & van der Heijden, 2005).
- The LCA assists the driver by only informing him. It does not help the driver or intervene automatically. In this way, the driver will stay in the loop, and responsible for controlling the vehicle.
- The HMI consists of LED-lights to inform the driver about the safety level. The HMI uses a spectrum of five lights to communicate to the driver. In this way, the LCA can generate a series of advices at different safety levels, without guaranteeing a 100% safe situation. Once more, the driver remains in the loop and responsible.
- There is no vehicle-to-vehicle or vehicle-to-infrastructure communication.

2. Literature review

At this moment, researchers develop the lane change assistant. This means that researchers have already done several studies in this research field. Some of these researches focused on developing a mathematical model for the assistant, in order to give a positive or negative advice. Besides, some car manufacturers have already created some simple implementations (Tideman, 2008). The state of the art of lane change systems and the recent researches on this topic will be discussed in this chapter, answering research question 1.

2.1. State of the art

At this moment, several car manufacturers have already implemented some simple systems in this field. These implementations give somehow an advice to the driver whether changing lane is safe under current circumstances.

An example of such a system is the BLind spot Information System (BLIS), developed by car manufacturer Volvo. Small sensors attached to the side mirrors detect vehicles in the blind spot. If a vehicle is detected, the driver gets a warning from the system not to change lane. The LCA becomes more advanced compared to this BLIS system. It does not only detect cars in the blind spot, but in the complete surrounding of the subject vehicle. Besides, the LCA gives an advice to the driver by using a mathematical model.

Figure 3. Volvo blind spot detector

The integrated PReVENT project is a European automotive industry activity to contribute to road safety by developing preventive safety applications. One of the subprojects of PReVENT, called, *Lateral Safe*, develops and introduces safety applications that contribute to the prevention of lateral/rear related accidents. In cooperation with the subproject *MAPS&ADAS*, an interface is developed which uses map data to warn the driver for upcoming dangerous situations. (PReVENT)

2.2. Literature

Recently, several studies have been performed which develop a lane change algorithm. This research analyzed these studies to compare their level of detail. The input variables, which are used to distinct safe from unsafe lane change situations, do express the level of detail.

Besides these mathematical models, this research also analyzed a research in the field of driver behaviour during lane changing. In this way, the mathematical models cannot only be compared with each other, but also with the operations a driver undertakes before deciding to change lane.

After introducing the researches, this paragraph will show the results of the literature review. The appendix gives a complete overview of which research uses which input variables.

2.2.1. Introduction of the researches

Jula, Kosmatopoulos & Ioannou (2000) developed an algorithm that calculates the minimum required initial longitudinal spacing to the surrounding vehicles to be able to change lane safely. This mathematical model analyzes the kinematics of the vehicles involved in a lane change to calculate the safety spacing. The research of Jula et al. (2000) focused on describing an algorithm for a lane change assistant. The research is partly based on an earlier research done by Kanaris, Kosmatopoulos & Ioannou (1997). In this study, Kanaris et al. (1997) use a research of Bascunana (1995) to calculate spacing requirements for lane changing in Automated Highway Systems (AHS) for different scenarios. Bascunana (1995) determines the conditions for safe and unsafe lane changing by working out four different cases.

Bascunana obtains the conditions for two vehicles involved in the lane-changing maneuver, including one of them as the merging vehicle. The study also focuses on the error of the variables and the reaction time of the driver.

Jin et al. (2009) developed a lane change model for the LCA, based on the Lane Departure Warning System. Jin et al. (2009) consider two vehicles in a highway scenario, a merging vehicle and a following vehicle in the target lane. They calculate the minimum required longitudinal space by collecting the kinematics of both vehicles. Besides, the model also applies extra safety spacing.

Hidas (2002) uses a flowchart as an overall structure of the lane-changing model. This flowchart imitates the driver's assessment to decide whether to change lane. Hidas developed this lane changing and merging algorithm for the Simulation of Intelligent TRAnsport Systems (SITRAS). The flowchart refers to the flowchart summarizing the driver's decision process, established by Gipps (1986). Gipps approaches lane changing from the driver's behavioural perspective by preparing a decision structure. This research covers the urban driving situation.

Wei (2001) describes the advantages of using an Artificial Neural Networks (ANN) model instead of a conventional model. The advantages mainly lie in the learning capability, by training the model. This reveals practical feasibility for intelligent personalized in-vehicle equipment. Besides, the ANN model mimics traffic characteristics more accurate.

2.2.2. Results

Four of the researches mentioned in paragraph 2.2.1 develop a lane change model. These researches are, together with Gipps' driver's decision structure, scanned on the input variables they use. Because of the scope of this research, this literature review distinguishes input variables which have to be measured every time-instant Δt, and variables which are constant over time (a pre-defined statistic). Besides, the literature study scanned these researches on assumptions and other simplifications in the model. The most important simplifications are:

- The model does not consider acceleration of the surrounding vehicles.
- The model does not consider all the surrounding vehicles.
- The model does not consider lateral movement.
- The model does not define safe and unsafe areas.
- The model does not consider jerk (i.e. the time-derivative of the lateral acceleration).
- The model does not consider safety margins.
- The model does not consider the preferred speed of the subject vehicle.

We define model efficiency as the ratio between the total number of input variables and the number of model assumptions. Table 1 gives an overview on these ratios. More details can be found in the appendix.

Research	Measure	Statistic	Assumptions	Ratio
Jin et al. (2009) Research on safety lane change model of driver assistant system on highway	6	7	5	0.15
Jula et al. (2000) Collision avoidance analysis for lane changing and merging	12	3	4	0.20
Kanaris et al. (1997) Strategies and spacing requirements for lane changing and merging in Automated Highway Systems (AHS)	13	9	3	0.18
Bascunana (1995) Analysis of lane change crash avoidance	9	4	5	0.15
Gipps (1986) A model for the structure of lane changing decisions	12	2	0	0.50

Table 1. Overview of literature review

From table 1, it is clear that using more input variables generally leads to a reduction of assumptions. Of course, Gipps (1986) scores best because this research is not based on a mathematical model.

This research uses the model of Jin et al. (2009). This model is, in contrast to the others, transparent instead of a black box. This makes it easier to implement and expand the algorithm to reduce the number of assumptions. Besides, it has a relatively low amount of measured variables and many static variables, which benefits model reliability. This report presents the model in chapter 3.

Jin et al. (2009) compare their research with Jula et al. (2000). From this comparison, they draw the conclusion that the former research scores better than the latter one. For instance, by fulfilling a lane change it accepts a shorter gap. Besides, its vehicle velocity responses more quick, without losing sight of passenger comfort.

3. Model setup and usage

A lane change model is required in order to perform a study to the practical implementation of the LCA. As proposed in chapter 2, this research used the lane change model set up by Jin et al. (2009) as a basis. In order to create a complete traffic model, this lane change model is together with a vehicle following model implemented in one complete model. Many input variables are adjustable in this model in order to create certain traffic situation, as required in this research. The output can be displayed as a top view on the highway on which the vehicles are moving. Simulation software Matlab has been used to run the model.

3.1. Model scope

When drivers perform lane changes, several situations can occur. Figure 4 depicts these situations chronologically. The model is based on handling all these situations.

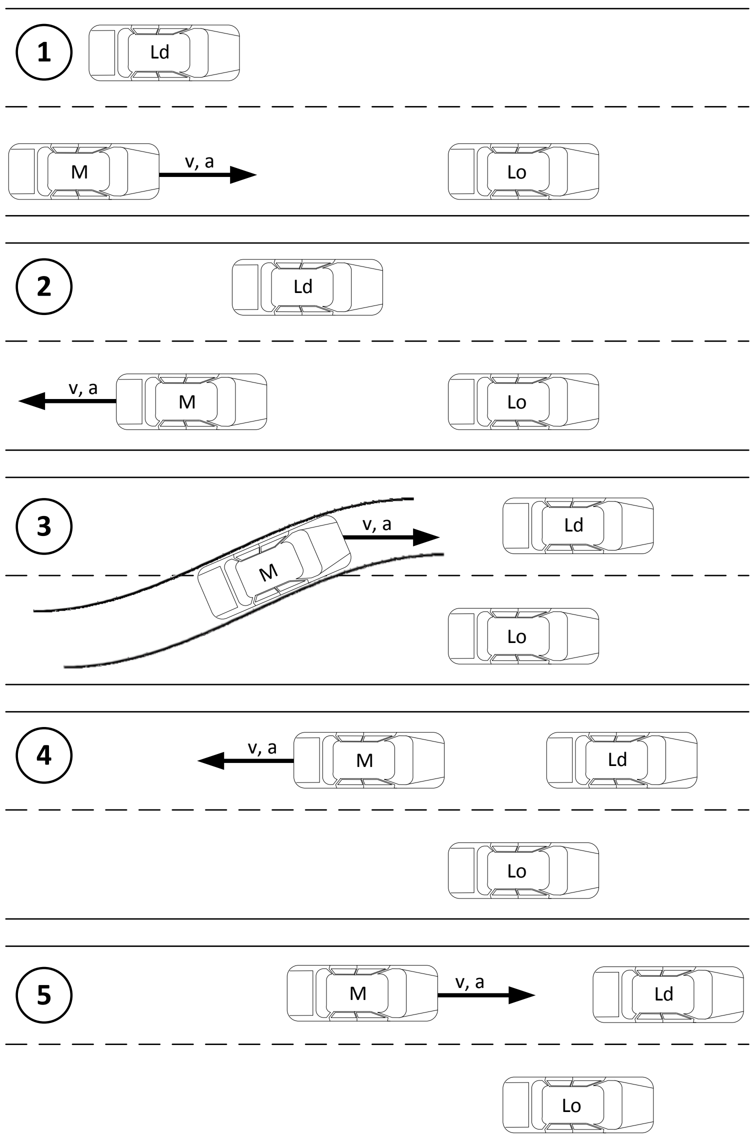

Figure 4 Overview of situations with: 1. M accelerates in original lane 2. M brakes in original lane 3. M accelerates during lane change 4. M brakes in destination lane 5. M accelerates in destination lane

Figure 4 shows five different cases. When vehicle M changes lane, it can encounter these situations chronologically. First, M is cruising unhindered in the right lane at preferred speed. When it is approaching the preceding vehicle L_o it needs to decelerate in order to maintain a safe gap. While M does not reach the preferred speed anymore, it wants to change lane. During the lane change maneuver, it accelerates to the preferred speed. While cruising in the left lane, it has to decelerate when preceding vehicle L_d is approaching. When M has a safe gap to L_d, it will start accelerating, attempting to reach the preferred speed. When mirrored, these situations also apply for vehicle M and following vehicles F_o and F_d.

This analysis states that the merging vehicle M must be able to accelerate and decelerate longitudinal in the original and destination lane. Besides, vehicle M must be able to accelerate both longitudinal and lateral during lane changing to the destination lane.

The model has all these procedures implemented. To realize this, the model needs to make three decisions every time step. Does M need to initialize an acceleration procedure? Does M need to initialize a braking procedure? Does M need to initialize a lane change procedure? Besides, the model consists of a part that executes the decisions by calculating both the longitudinal and lateral positions and generating (visual) output every time step.

3.2. Hierarchy in the model

The model handles certain hierarchy to be sure it takes safety measures if needed. Important decisions can overrule less important decisions. In order to prevent dangerous situations, the most important task is that the vehicle can decelerate any time if needed. For this reason, the brake model goes above the acceleration and lane change model. One situation is excluded: during a lane change vehicle M will not decelerate for L_o, but accelerate to adapt to the higher speed in the destination lane.

In case the model does not need to initiate a braking procedure, M desires to cruise at the pre-defined desired speed v_{ref}. If the current speed is below v_{ref}, M will try to initiate an acceleration maneuver with $a=a_{comf}$, the maximum comfortable acceleration.

At last, when M wants to accelerate in the original lane, but the appearance of L_o does not allow M to do so, it will find out whether it can perform a lane change by consulting the LCA.

3.3. Micro simulation model

This paragraph explains in detail the way the Matlab model works. An overview of the input variables is given and the basic mathematical formulas are presented. The scenario used in this research is presented in paragraph 1.3.1.

3.3.1. Adjustable input variables

All input variables that the model uses can be adjusted in order to create different situations. Table 2 displays an overview of these adjustable input variables.

Distance [m]	
Starting position M	$x0_M$
Starting position Lo	$x0_{Lo}$
Starting position Ld	$x0_{Ld}$
Starting position Fo	$x0_{Fo}$
Starting position Fd	$x0_{Fd}$
Length vehicle M	L_M
Length vehicle Lo	L_{Lo}
Length vehicle Ld	L_{Ld}
Length vehicle Fo	L_{Fo}
Length vehicle Fd	L_{Fd}
Width vehicle M	W_M
Width vehicle Lo	W_{Lo}
Width vehicle Ld	W_{Ld}
Width vehicle Fo	W_{Fo}
Width vehicle Fd	W_{Fd}
Width of each lane	H
Safe parking space	D_0
Time [s]	
Simulation time	T_{sim}
Time steps (Δt)	dt
Time to complete lane change	T
Acc. time during lane change	t_{lat}
Head time distance	C_1

Acceleration [m/s^2]	
Initial acceleration M	a_M
Initial acceleration Lo	a_{Lo}
Initial acceleration Ld	a_{Ld}
Initial acceleration Fo	a_{Fo}
Initial acceleration Fd	a_{Fd}
Max. comfortable acceleration	a_{comf}
Max. emergency deceleration	$-a_{em}$
Velocity [m/s]	
Initial velocity M	v_M
Initial velocity Lo	v_{Lo}
Initial velocity Ld	v_{Ld}
Initial velocity Fo	v_{Fo}
Initial velocity Fd	v_{Fd}
Desired speed M	v_{ref}

Table 2. Overview of input variables

3.3.2. Acceleration Model

If the current velocity of vehicle M is less than the desired speed, the vehicle will decide to accelerate. A margin of 1 m/s is applied. Acceleration follows the construction

$$\text{If } v_{ref} > v_M(t) + 1 \qquad \text{then} \qquad a_M(t) = a_{comf} \quad \text{until} \qquad t = t + \frac{v_{ref} - v_M(t)}{a_{comf}}$$

This action can be performed by vehicle M in as well the original lane as the destination lane. The surrounding vehicles do not use the acceleration model because it gives no benefit to this research.

3.3.3. Lane Change Model

If vehicle M is in the original lane and has to brake for leading vehicle L_o, Matlab uses the lane change model to determine whether M can safely perform a lane change to the left lane. The model of Jin et al. (2009) only takes vehicle F_d into account. However, a dangerous situation can still occur when no attention is paid to vehicle L_d. For this reason, the model is expanded to also regard L_d before deciding to change lane, using a similar technique as for vehicle F_d.

Gipps (1986) states that a relative advantage of 1 m/s between both lanes is sufficient to decide moving to the left lane. Jin et al. (2009) state that for safety reasons M will only change lane if $v_{ref} \geq v_{Fd}$.

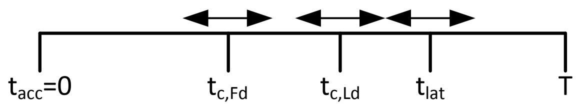

Figure 5. Timeline for lane changing

If M meets these restrictions, the LCA calculates an advice using the algorithm. Figure 5 shows the time segmentation used in this algorithm. At t_{acc}=0, the merging vehicle decides to change lane and starts accelerating. Time t_c stands for the collision point with one of the other vehicles in the destination lane. The collision point is the instant that the longitudinal distance to another vehicle is minimal. Time t_{lat} means M stops accelerating and reaches the desired speed. At T, vehicle M completes its lateral displacement.

Desired acceleration of merging vehicle M

$$a = \frac{v_{ref} - v_M(t)}{t_{lat}} \quad \text{, if} \quad a > a_{comf} \quad \text{then} \quad a = a_{comf} \quad \text{and} \quad t_{lat} = \frac{v_{ref} - v_M(t)}{a_{comf}}$$

From here, the minimum safety spacing to Fd and Ld are calculated separately:

Regarding Ld	*Regarding Fd (formed by Jin et al., 2009)*
Calculate the time instant when vehicle M arrives at collision point	
$t_c = \frac{v_M(t) - v_{Ld}(t)}{a}$, with $t_c \geq 0$	$t_c = \frac{v_{Fd}(t) - v_M(t)}{a}$, with $t_c \geq 0$
Calculate the minimum required distance at t_{acc}=0	
$Sr(0)_{\min} = \frac{v_M(t) - v_{Ld}(t)}{t_c} - 0.5 \cdot a \cdot t_c^{\ 2} + L_{Ld}$	$Sr(0)_{\min} = \frac{v_{Fd}(t) - v_M(t)}{t_c} - 0.5 \cdot a \cdot t_c^{\ 2} + L_M$
Calculate the safe following space	
$D_{cr} = c_1 \cdot v_M + D_0$	$D_{cr} = c_1 \cdot v_{Fd} + D_0$
Calculate the Minimum Safety Space (MSS)	
$MSS = Sr(0)_{\min} + D_{cr}$	$MSS = Sr(0)_{\min} + D_{cr}$

If the current gaps between M-L_d and M-F_d are larger than their MSS, the advice to the driver will be positive. Figure 6 depicts this situation. The LCA needs to calculate five different MSS in order to be able to give the driver an advice with an increasing safety margin (chapter 5). In order to achieve this, we can vary the safe following space parameters c_1 and D_0. Parameter t_{lat}, influencing the longitudinal acceleration during lane changing, is the only other variable that is not pre-defined in the lane change algorithm.

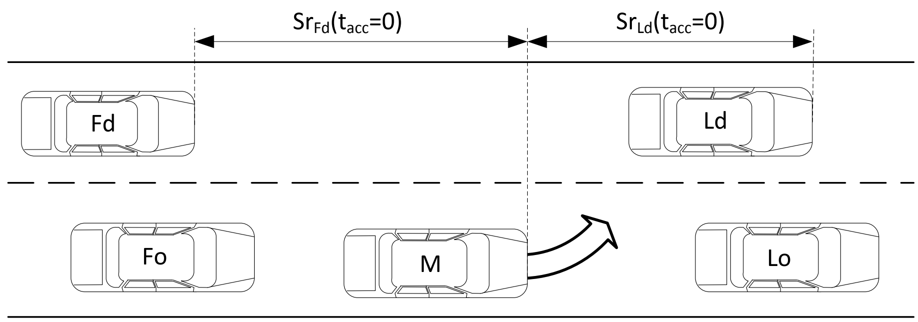

Figure 6. Initial distance to vehicles F_d and L_d

3.3.4. Brake Model

Vehicles must keep a distance of at least 2 seconds from each other to guarantee safety (Dutch Ministry of Transport, Public Works and Water Management, 2000). If a vehicle is approaching its predecessor, it has to start its brake procedure on time, in order to maintain a minimum gap of at least 2 seconds continuously. The brake algorithm can be applied by vehicle M to brake for L_d or L_o, or it can be applied by following vehicles F_d or F_o to brake for M. Other situations are not taken into account, because it gives no benefit to this research.

Time needed to perform braking maneuver

$$t = \frac{\Delta v + \Delta a \cdot t}{a_{comf}}$$

Available time left

$$t = \frac{Sr(t) - L_{predecessor} - 2 \cdot v_{following}(t)}{0.5 \cdot (\Delta v + \Delta a \cdot t)}$$

, where the denominator stands for average approaching speed

The following vehicle must start its braking maneuver if ‘time needed’ ≥ ‘time available’

$$\frac{\Delta v + \Delta a \cdot t}{a_{comf}} \geq \frac{Sr(t) - L_{predecessor} - 2 \cdot v_{following}(t)}{0.5 \cdot (\Delta v + \Delta a \cdot t)}$$

Or simplified

$$Sr(t) \geq \left(\frac{\Delta v + \Delta a \cdot t}{a_{comf}} \right)^2 + 2 \cdot v_{following}(t) + L_{predecessor}$$

If this inequality is violated, the following vehicle starts braking at $a=a_{comf}$ for $T = \frac{\Delta v}{a_{comf}}$. In addition, every vehicle can perform an emergency brake maneuver if needed (chapter 4).

3.3.5. Positioning

After having developed the acceleration-, lane change- and brake model, the positions of all the cars can be determined for the next time step. For the merging vehicle, the model does calculate the longitudinal and lateral positions separately.

For every vertex of the vehicles, the model calculates the longitudinal position by using the recursive function every time step

$$x_{long}(t) = x_{long}(t-1) + v \cdot \Delta t + 0.5 \cdot a \cdot \Delta t^2$$

For the merging vehicle, the model corrects the longitudinal position during lane changing, while the vehicle is positioned at an angle α, as displayed in figure 7. The model realizes this by using sin(α) and cos(α) functions.

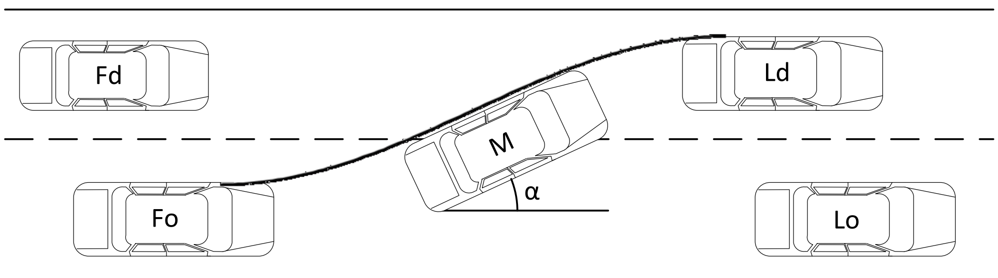

Figure 7. Lateral displacement merging vehicle M

For the non-merging vehicles, the lateral position is constant and calculated with a simple formula to make sure the vehicle drives in the middle of the lane continuously. This position only depends on the lane width H, the vehicle width W, and the lane the vehicle is driving in.

For the merging vehicle, during lane changing the model calculates the lateral velocity with a simple sinus function for every time step t_{lc}. Although the lateral displacement is easily assumed sinusoidal, empirical data collected by photographing lane changes on multilane highways shows that this lateral displacement pattern seems to be appropriate. Because of the sinusoidal function, also the time-derivatives velocity, acceleration and jerk function are smooth which guarantees passenger comfort (Worall & Bullen, 1970).

Lateral velocity vehicle M

$$v_{lat}(t_{lc}) = -\frac{H}{T} \cdot \cos\left(\frac{2 \cdot \pi}{T} \cdot t_{lc}\right) + \frac{H}{T}$$, where $-\frac{H}{T}$ defines the minimum and $+\frac{H}{T}$ defines the maximum value of $v_{lat}(t_{lc})$

With this information, angle α in figure 7 can be determined

$$\alpha = \frac{v_{lat}(t_{lc})}{v_M(t_{lc})}$$

From the lateral velocity function, we can obtain the function for lateral displacement by integrating

$$x_{lat}(t_{lc}) = 0.5 \cdot (H - W) + W - \frac{H \cdot \sin\left(\frac{2 \cdot \pi \cdot t_{lc}}{T}\right)}{2 \cdot \pi} + \frac{H \cdot t_{lc}}{T}$$

Again, the model corrects the lateral position by using angle α.

3.4. Generating output

The described model is still deterministic. Since this research focuses on the practical situation, we have to deal with uncertainties. For this reason, the model must behave probabilistic. To achieve this, certain variables are randomized. By simulating many runs with a randomized configuration of variables, all situations within the pre-defined scenario will be analyzed. The variables are distributed uniform within certain range. These ranges are set in a conservative way, to provoke interesting lane changes. On the other hand, the selected ranges are reasonable and cannot directly result in dangerous traffic situations. The variables that are uniformly distributed concern the starting positions, the initial speeds, the car lengths, the width of the vehicles and the initial acceleration of vehicles L_o and L_d (only negative values). Figure 8 depicts the initial vehicle positions and dimensions of a random run.

In practice, the LCA creates another source of uncertainty. The LCA can measure the input variables with certain error. To simulate this, the input variables of the LCA will take two values. One real value, used to calculate the positions of the vehicles every time step, and one perception value, used by the LCA. This perception value is normally distributed, with the real value as mean and certain standard deviation.

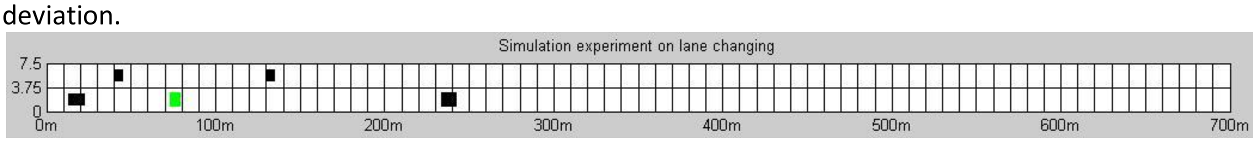

Figure 8. Random initial vehicle positions and dimensions

Every run simulates for 20 seconds. The time that M needs to complete a lateral displacement during lane changing is set to 5 seconds.

As mentioned, this probabilistic model should run many times, to get reliable results. Simulating 1000 runs is sufficient, since two different samples show negligible differences.

When time step Δt is set to 0.1 second, the model simulates the real world with acceptable accuracy.

To show the performance of the probabilistic model, some output is created. It is interesting to know the crash ratio and the ratio of runs where vehicle M decides to change lane. The result is:

- Crash ratio: 0.001
- Lane change ratio 0.426

These output ratios are appropriate, indicating acceptable distribution ranges and standard deviations.

Matlab can also show the output as visualization. Figure 9 depicts an example of the visual output where M performs a safe lane change. The vehicles can have different colors. If vehicle M is green, and the others vehicles black, the current situation is safe. Vehicle M is in a dangerous situation when a vehicle turns to yellow. When vehicles turn red, a collision with vehicle M has occurred.

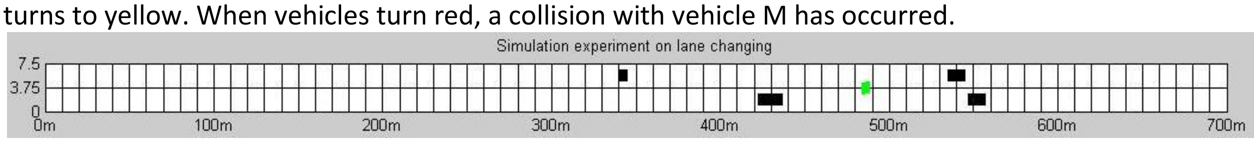

Figure 9. Visual model output

Key performance indicator

Lee, Olsen & Wierwille (2004) advise to use the Time To Collision (TTC) as the key performance indicator for the safety level, as it takes both distance and relative velocity into account. However, in order to avoid complex output, this research uses the ratio critical situations as performance indicator. Where a critical situation is defined as a gap between M and one of the surrounding vehicles of less than 0.5 second. This measure also takes both distance and relative velocity into account and is for that reason appropriate for this research. From this perspective, the safety level is in this research is defined as the percentage of runs that no critical situation occurs.

3.5. Assumptions and simplifications

By expanding the lane-changing model with a vehicle-following model, one of the goals was to decrease the number of assumptions. Chapter 2 and the appendix list the initial assumptions of the model of Jin et al. (2009). After developing the new model, we revise these assumptions once more.

Initially, Jin et al. assumed that the surrounding vehicles have no acceleration. During the development of this model, this issue has been taken into account. Now, all the vehicles show acceleration and deceleration.

The merging vehicle and the following vehicle in the destination lane were the only vehicles taken into account. The new model considers four surrounding vehicles, which is sufficient.

Jin et al. did not consider lateral movement. As described in paragraph 3.3.5, the merging vehicle will displace lateral with a sinusoidal lateral-velocity function.

Jin et al. did not define safe/unsafe regions initially. Using the model, safe and unsafe regions are prepared in chapter 5.

Jin et al. did not consider jerk. As described in 3.3.5, this model considers lateral jerk. The model does still not take longitudinal into account.

The influence of lateral acceleration to the longitudinal speed is assumed zero. In addition, the model neglects the limited friction proposed by Gillespie (1992). This theory states that braking during combined longitudinal and lateral motion significantly degrades the braking capabilities of the vehicle.

The lane change algorithm of Jula et al. (2000) considers that the merging vehicle initially accelerates/decelerates with constant longitudinal acceleration, in order to create sufficient spacing with the surrounding four vehicles. This algorithm does not cover certain gap adjustment; it is up to the driver to do this. Thus, this is not an assumption, but a restriction.

4. Sources of uncertainty

When implemented in practice, the LCA has to deal with several practical issues. Since these issues can have a negative impact on the LCA, it must be clear what their influences are. The issues that will be raised in this chapter are the consequences of changing circumstances, measurement uncertainty and model assumptions. This chapter answers research question 2.

4.1. Changing circumstances

One of the issues the LCA has to deal with in practice is changing circumstances. Because traffic conditions may be very dynamic, predicting the traffic situation for the next few seconds brings along certain degree of uncertainty. This paragraph concentrates on an event that can have a major impact on the predicted advice. If a preceding vehicle suddenly initiates an emergency brake, the traffic situation changes very fast. The LCA must be designed robust enough to withstand this situation. Research is done to two important aspects of an emergency brake: road condition and reaction time. Other unexpected changing circumstances as curves are assumed to have less impact than an emergency brake scenario.

4.1.1. Definition of an emergency brake

We assume an emergency brake as the maximum deceleration under current circumstances. Bian, Li, Jin and Lian (2005) define the maximum deceleration as:

$$a_{em}(t) = a_{\max}(t) = -\mu_{xp}(t) \cdot g$$

Where g is the gravity acceleration and μ_{xp} the peak value of road friction, which Bian et al. define as:

$$\mu_{xp}(t) = 0.92 \cdot 0.1304^{\sigma} + 0.002 \cdot e^{\sigma} \cdot (64 - v(t))$$

Where v is the vehicle velocity at time t. Parameter σ describes the road conditions, as displayed in table 3.

Road condition	Asphalt (dry)	Asphalt (wet)	Earth (wet)	Snow (fresh)	Snow (compact)	Ice (dry)	rainy
σ	0	0.134	0.253	0.60	0.75	1.0	1.2

Table 3. Parameter for road condition

This empirical formula is a simplified version from the one proposed by Bian (2003), and accurate enough for application in this research.

4.1.2. Model usage

The function for emergency braking is implemented in the Matlab model. Within the first 8 seconds of each run one of the vehicles M, L_o or L_d suddenly starts performing an emergency brake. The following vehicles have a pre-defined reaction time of 0.5-2 seconds. If needed, the following vehicles will then start an emergency brake too. The model considers that a following vehicle needs to start an emergency brake if it has less than 2 seconds distance to the preceding vehicle in the same lane, which is already performing an emergency brake. Every vehicle has its own maximum deceleration, depending on its speed and the road condition. Vehicle M will not start a lane change maneuver when it is the initiator of the emergency brake scenario.

4.1.3. Results

The model is applied to simulate the emergency brake scenario in order to measure the consequences of two aspects: road condition, which also takes the current weather condition into account, and reaction time, defined as the time it takes for the following vehicle to respond to an emergency brake.

As performance indicator, the ratio of runs where a critical situation occurs is used. As a reference, a basic safety spacing is applied with parameters c_1=1.5s and D_0=10m (Jin et al., 2009).

Road condition

Figure 10 shows the results.

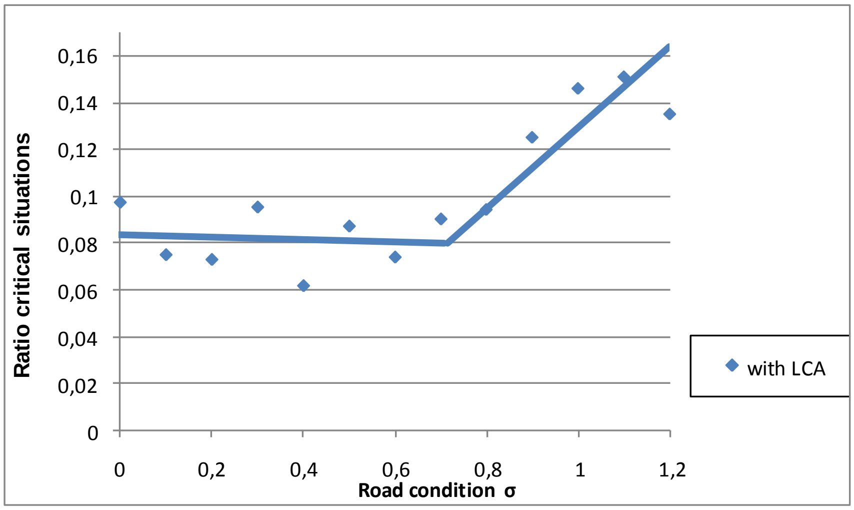

Figure 10. Sensitivity of the road condition

The relationship in figure 10 is assumed to be linear. The graph shows clearly that for low values, the road condition shows low influence on the safety, which is assumed zero. This means the applied safety spacing is adequate for this range. When road conditions start to get worse, the number of critical situations increases. A larger safety distance will reduce this effect. The sensitivity, defined as the derivative of the graph, for of the graph is 0.17.

Reaction time

Figure 11 shows the results.

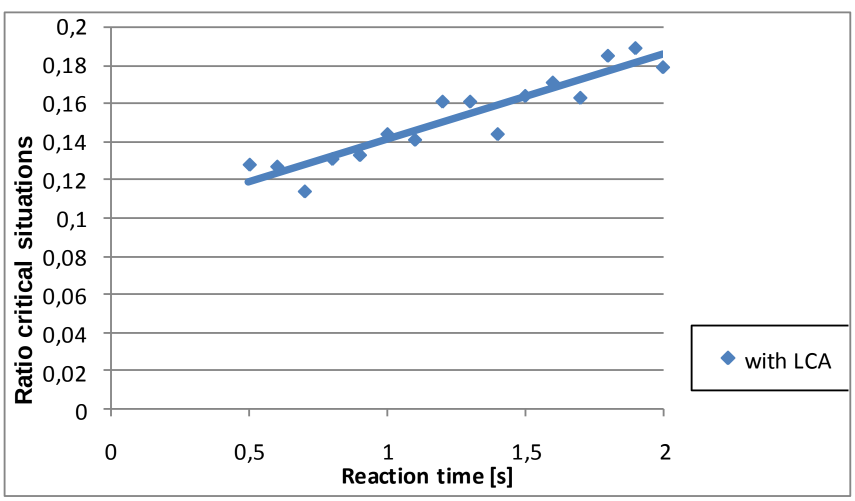

Figure 11. Sensitivity of the reaction time

The relationship in figure 11 behaves linear. For the complete range, the safety level is sensitive to the reaction time. The current applied safety measures are insufficient to create an insensitive relationship. However, sensitivity is low with $0.04s^{-1}$.

4.2. Measurement uncertainty

The LCA requires certain input in order to generate an advice to the driver. The LCA uses detection hardware on the vehicle to obtain the necessary information. In practice, it is possible that some input contains an error or is incomplete for some reason. This paragraph indicates what the consequences are of uncertainty in the input variables.

4.2.1. Inventory of input variables

Table 4 gives an overview of the input variables used by the LCA in order to generate an advice. For several of the listed variables, their values need to be collected every time step by measuring. For several other variables, the information needs to be collected otherwise. This research focuses on the first group, which is also displayed in table 4.

Description	Variable	Input variables used by LCA	Measurement Input variables
Velocity vehicle M	$v_M(t)$	●	●
Velocity vehicle F_d	$v_{Fd}(t)$	●	●
Velocity vehicle L_d	$v_{Ld}(t)$	●	●
Desired speed vehicle M	v_{ref}	●	
Acceleration time	t_{lat}	●	
Comfortable acceleration	a_{comf}	●	
Length vehicle M	L_M	●	
Length vehicle L_d	L_{Ld}	●	●
Safe parking space	D_0	●	
Head time distance	c_1	●	
Position vehicle M	$x_M(t)$	●	●
Position vehicle F_d	$x_{FD}(t)$	●	●
Position vehicle L_d	$x_{LD}(t)$	●	●

Table 4. Overview of input variables used by the LCA

In theory, the LCA also needs to measure L_M, but it we assume that this value can be determined very precisely and does not change.

The position variables depend on the current position, velocity and acceleration values. Besides, the velocity input variables depend on their acceleration values. Thus, actually the LCA should also consider accelerations. However, no research will be done to these input variables, it is assumed that the uncertainty caused by these input variables is covered by both the velocity and position variables.

4.2.2. Model usage

As described in chapter 3, the model simulates the practical environment by adding perception input values that the LCA uses to give an advice. To determine the influence of each of the seven input variables mentioned in table 4, the model will run for different standard deviations. Each time we vary the standard deviation of one variable within certain range, while keeping to others constant.

Chapter 3 concludes that 1000 runs are enough to get reliable research results. A check shows that this amount of runs also results in an acceptable normally distributed sample of perception values.

4.2.3. Results

Like paragraph 4.1, the ratio of runs where a critical situation occurs is used as performance indicator. Besides, equal basic safety spacing is applied, with parameters c_1=1.5s and D_0=10m. The variables are subdivided to position, velocity and vehicle length. The figures 12-14 show the results.

Vehicle position

Table 4 makes clear that the positions of vehicle M, F_d and L_d must be considered. Figure 12 shows the results.

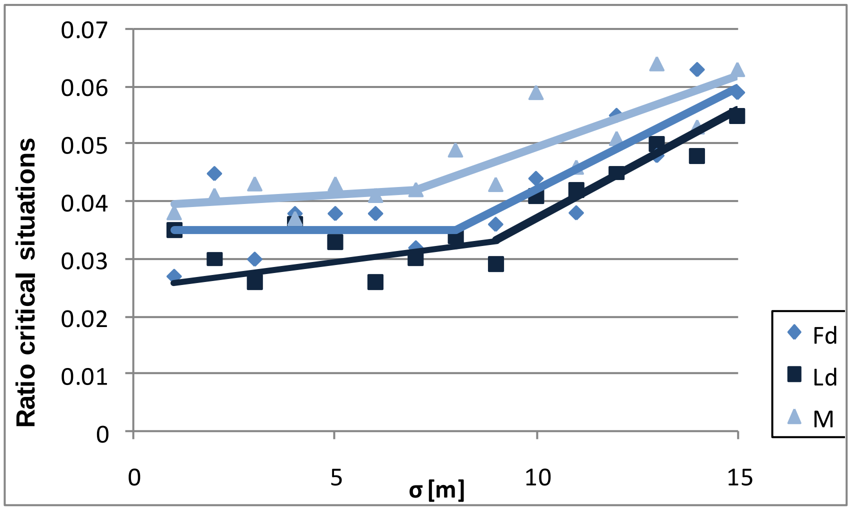

Figure 12. Sensitivity of vehicle position

The relationships in figure 12 are assumed to be linear. The influence on the safety level is assumed zero for all vehicles as it shows to be minimal for small standard deviations,. This means the applied safety spacing is adequate for this range. For large standard deviations, all the vehicles show a clear decrease in the safety level. Vehicles F_d, L_d and M have a sensitivity of respectively 0.004m^{-1}, 0.004m^{-1} and 0.003m^{-1}, where we define sensitivity as the derivative of the functions. Of course, applying a different safety distance will change these results.

Vehicle speed

According to table 4, the velocities of vehicles M, F_d and L_d need to be considered. Figure 13 shows the results.

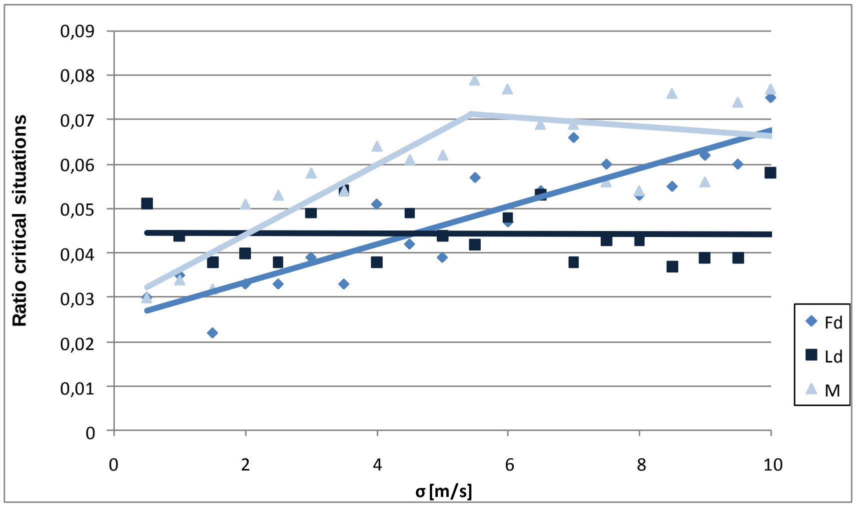

Figure 13. Sensitivity of vehicle speed

The relationship of vehicle F_d shows clearly to be linear. The standard deviation has an influence on the ratio of ciritcal situations. The current safety measures are insufficient to prevent F_d from showing a sensitivity of 0.004s/m.

The relationship of L_d is clearly linear, with an almost horizontal trendline. With the current safety measures, the influence on the safety ratio is assumed zero.

The relationship of M is assumed to be linear. For small standard deviations the safety ratio shows to be sensitive with a coefficient of 0.008s/m. For larger values, the standard deviation has a very small effect on the safety ratio, which is assumed zero. For this input variable, the applied safety distance is insufficient.

Vehicle length

Table 4 makes clear that only the vehicle length of L_d is of importance. Figure 14 shows the results.

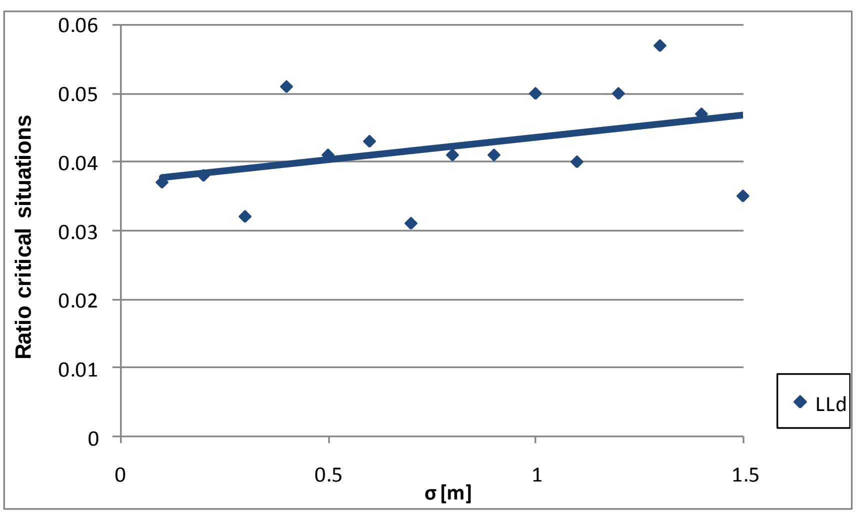

Figure 14. Sensitivity of vehicle length

The relationship in figure 14 shows linearity. For the complete range, the standard deviation has certain influence on the safety ratio. However, this influence is very small with a sensitivity of only $0.007m^{-1}$. Compared to the other input variables, the vehicle length is rather insensitive to the safety level.

4.3. Assumptions in the model

Paragraph 3.5 lists the remaining model assumptions and simplifications after expanding the simulation model. Whereas the original model relies on many assumptions, as listed in paragraph 2.2, this mathematical model uses only a few assumptions.

Firstly, the model does still not consider jerk. However, Bian et al. (2005) state that it will only take 0.2 second to reach maximum deceleration. Regarding the time step in the model of 0.1 second, the effect of this simplification is assumed negligible.

The influence of the lateral displacement to the longitudinal positions is assumed zero. Jin et al. (2009) state that we can neglect the influence of lateral acceleration to the longitudinal speed, because of the high speed and small longitudinal angle,. For the same reason, also the influence of the limited friction (Gillespie, 1992) is neglected.

Concluding, the few remaining assumptions in this model will have negligible consequences on the output. This answers research question 2c. No research has been done to the exact consequences.

5. Safety distances

This study has focused on several aspects that the LCA has to deal with in practice. Once an inventory is made of the impact of all these practical issues on the safety level, the next step is to determine which safety distances need to be taken into account, to compensate to these sources of uncertainty.

5.1. Approach

This chapter covers the process of generating reliable output to the driver by using the research results of this study (chapter 4). Figure 15 depicts this process. As proposed in the framework (paragraph 1.3), the HMI consists of five LED lights, thus an advice will be given on a spectrum of five safety levels. When it is clear which safety distances lead to which safety levels, it is possible to define safe and unsafe regions.

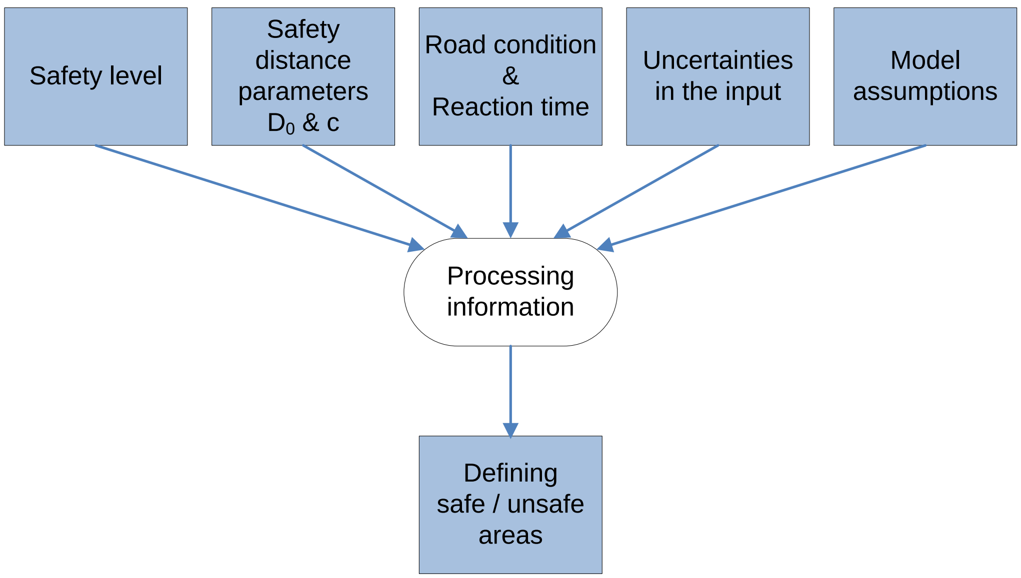

Figure 15. Research results are used to define safety spacing

Chapter 4 discussed several topics, which are displayed at the top of figure 15. This chapter applies all these topics in the design of the LCA. This paragraph discusses what role these topics play in this chapter.

Safety level

Throughout this research, we expressed the safety level as the percentage of runs that no critical situation occurs, as specified in paragraph 3.4. This chapter will also use the safety level as the performance indicator.

Safety distance parameters D_0 & c

As described in paragraph 3.3.3, the minimum safety distance will be calculated as $D_{cr}=c_1 \cdot v+D_0$. In order to give an advice to the driver in a range of five safety levels, the parameters in this formula must take different values. To prevent a complex situation, this research only varies parameter c_1 will. This parameter is preferred above D_o because together with the speed variable it has more influence that results in a tailor-made advice.

Road condition & reaction time
As made clear in paragraph 4.1, these variables show to have huge consequences to the safety level. To be able to give a reliable advice, the LCA considers these issues, thus special attention will be given to them in this chapter.

Uncertainties in the input
Paragraph 4.2 describes the consequences of the uncertainties in the input. Compared to the road condition and the reaction time, the consequences of this issue are low. Besides, the graphs show a rather low sensitivity. Moreover, state of the art detection hardware use sophisticated models which results in low uncertainties (standard deviations) in practice. Although the impact of uncertainties in the input to the safety level might be small, we will still consider these variables to get a LCA design that adapts best to the practical environment.

Model assumptions
Paragraph 4.3 concludes that the remaining model assumptions have very small consequences, and can therefore be assumed negligible. Thus, no attention is paid to the assumptions in the model while designing the HMI.

Paragraph 5.2 discusses how developers can generally design and specify safety levels. As a result, paragraph 5.3 shows what safety distances the LCA should apply in certain scenario, in order to compensate to the practical issues.

5.2. Design safety levels

The design of the safety levels of the LCA is dependent on the requirements of the developer. Chapter 4 concluded there are nine variables that have an influence on the reliability of the advice of the LCA, and thus the safety level. Two variables deal with an emergency brake scenario (chapter 4.1) and seven variables deal with the measurement uncertainties (chapter 4.2).

Figures 16-24 all depict the influences of certain variable and the safety parameter c_1 to the safety level. Every diagram is plotted three times, representing different values of the variable. This gives an indication of the sensitivity of the concerning variable to the safety level. Figure 16 shows that bad weather condition have a clear negative impact on the safety level while figure 17 depicts the influence of reaction time to the safety level. Figures 18-24 present the influence of different standard deviations in the measurement variables to the safety level.

In order to set safety levels, which is done in the next paragraph, the developer has to decide what scenario the LCA should be able to withstand, by selecting a value for every variable. He can use figures 16-24 to get an indication of the consequences from picking certain value.

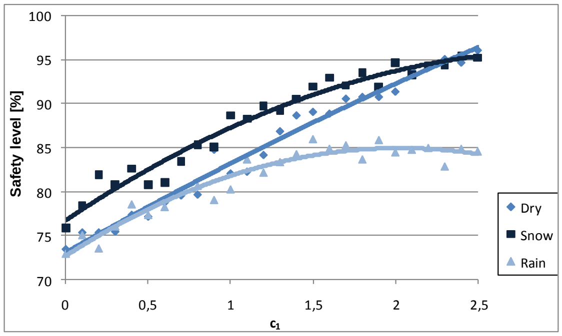

Figure 16. Safety level road condition

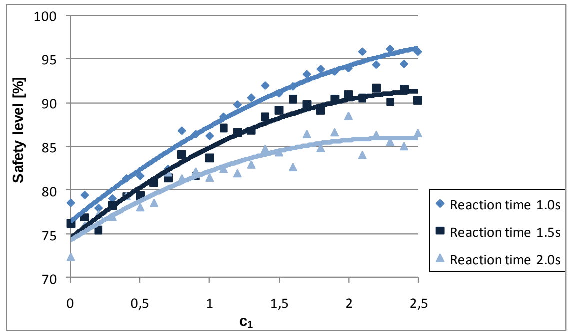

Figure 17. Safety level reaction time

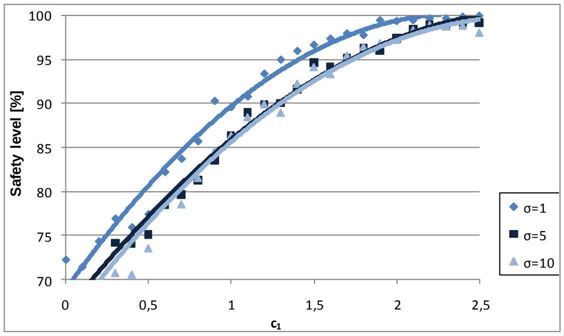

Figure 18. Safety level velocity vehicle M

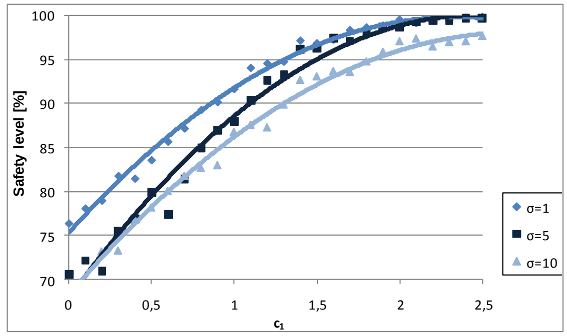

Figure 19. Safety level velocity vehicle F_d

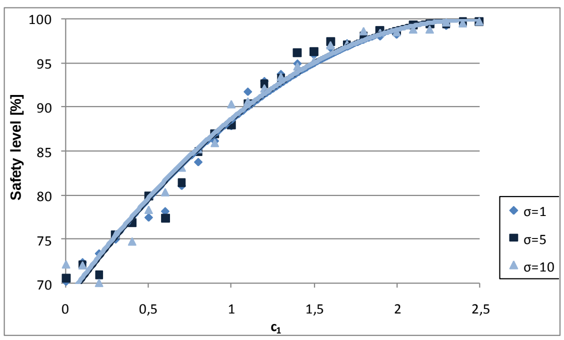

Figure 20. Safety level velocity vehicle L_d

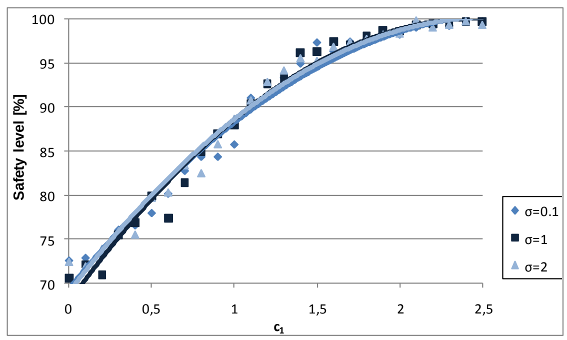

Figure 21. Safety level length vehicle L_d

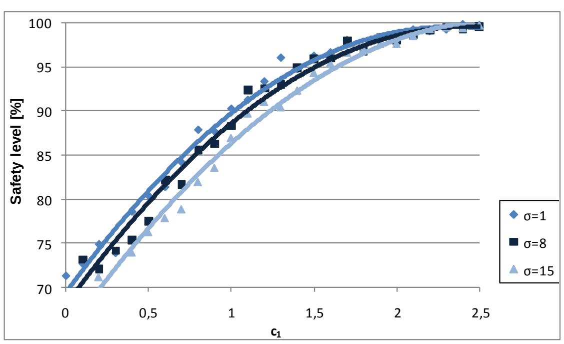

Figure 22. Safety level position vehicle M

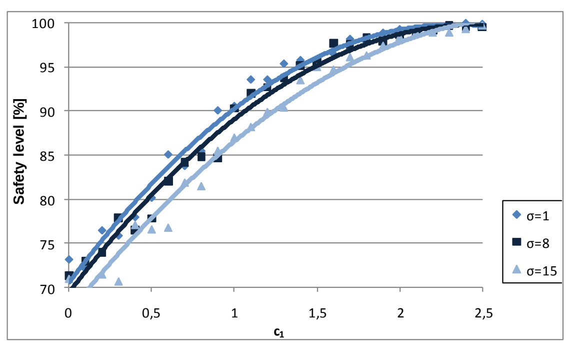

Figure 23. Safety level position vehicle F_d

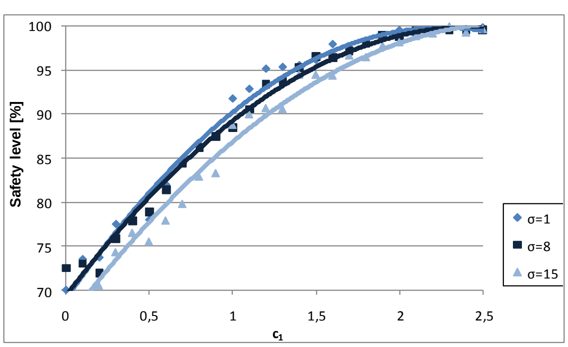

Figure 24. Safety level position vehicle L_d

5.3. Results: Collision region

This paragraph shows how to apply certain selected scenario, as described in previous paragraph. The goal is to propose collision regions. To be able to give an advice on a spectrum of five safety levels, we should specify these levels first by using different values for safety parameter c_1. For certain scenario, we define these corresponding values for c_1 in this paragraph.

Scenario

As example, we choose a scenario that should be able to withstand an emergency brake under rainy weather conditions. Using figures 16-24 the nine variables are set as displayed in table 5.

Variable	Value
Road condition	σ = 1.2 (rain)
Reaction time	t = 1.5s
Velocity vehicle M	σ = 5m/s
Velocity vehicle F_d	σ = 5m/s
Velocity vehicle L_d	σ = 5m/s
Length vehicle L_d	σ = 1m
Position vehicle M	σ = 8m
Position vehicle F_d	σ = 8m
Position vehicle L_d	σ = 8m

Table 5. Selected scenario

Figure 25 shows the relationship between the safety distance and the safety level, within the chosen scenario.

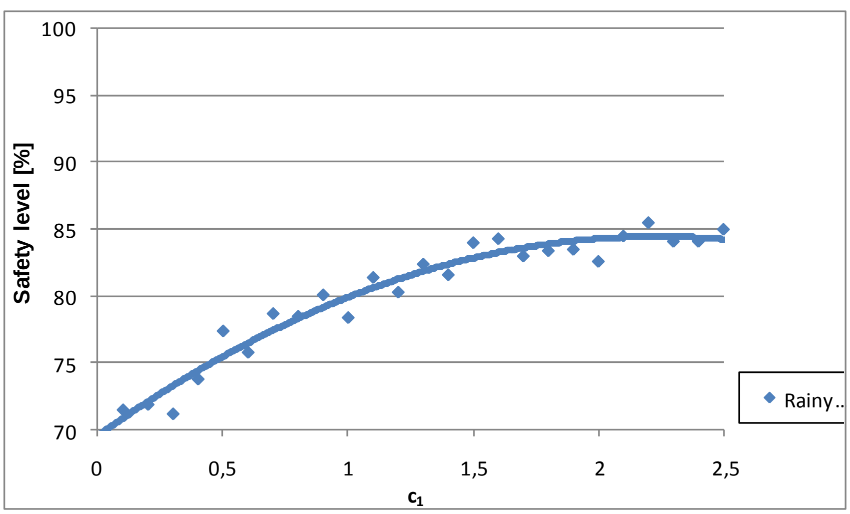

Figure 25. Safety level emergency scenario

Safety levels

Safety levels can be set using figure 25. We assume that a safety level below 70% is unacceptable, thus the lowest safety level is set at 70%. The highest safety level is the maximum value of the trendline: 84.4%. For these safety levels, the corresponding values for c_1 are respectively 0.03 s and 2.23 s. Although the graph is definitely not linear, the safety levels are set with equal steps of 0.55 s for c_1, in favour of the driver perception. Table 6 gives an overview of these safety values.

The different values for the safety parameter c_1 are set within an emergency scenario. The corresponding safety levels do only apply in the concerning emergency brake scenario with rainy weather. However, it makes more sense to show the corresponding safety levels of a normal scenario. Table 6 also shows these statistics.

HMI [Number of LEDs burning]	1	2	3	4	5
Safety parameter c_1 [s]	0.03	0.58	1.13	1.68	2.23
Safety level emergency brake scenario [%]	70.0	76.3	80.8	83.5	84.4
Safety level normal scenario [%]	67.3	80.7	90.6	97.0	99.8

Table 6. Overview of different safety levels in the LCA design

By using the information in table 6, it is possible to define the collision regions. As explained in chapter 3, the LCA takes vehicles L_d and F_d into account when generating an advice. For both vehicles, the model is used to define the safe and unsafe regions.
To be able to produce clear safe and unsafe margins, we need to apply some simplifications to the model.

- All vehicles have no initial acceleration
- The longitudinal acceleration during lane changing is not dependent on variables v_{ref} and t_{lat}, but always equal to a_{comf}.
- All the vehicle lengths are set to a fixed value.
- The probabilistic model is customized to behave deterministic.

We plot the five different safety levels of the LCA by setting out the relative velocity against the minimal required gap. Figures 25 and 26 show the results for respectively vehicles F_d and L_d.

Results
Figure 25 and 26 depict the safe and unsafe regions for the scenario described in table 5. For both the vehicles F_d and L_d, these figures make clear what safety distance with vehicle M the LCA should consider in order to guarantee certain safety level. As shown in the figures, these diagrams are linked with the HMI.

The differences between figure 25 and 26 demonstrate that vehicle M requires more safety spacing with L_d than F_d for positive values of the relative longitudinal velocity.

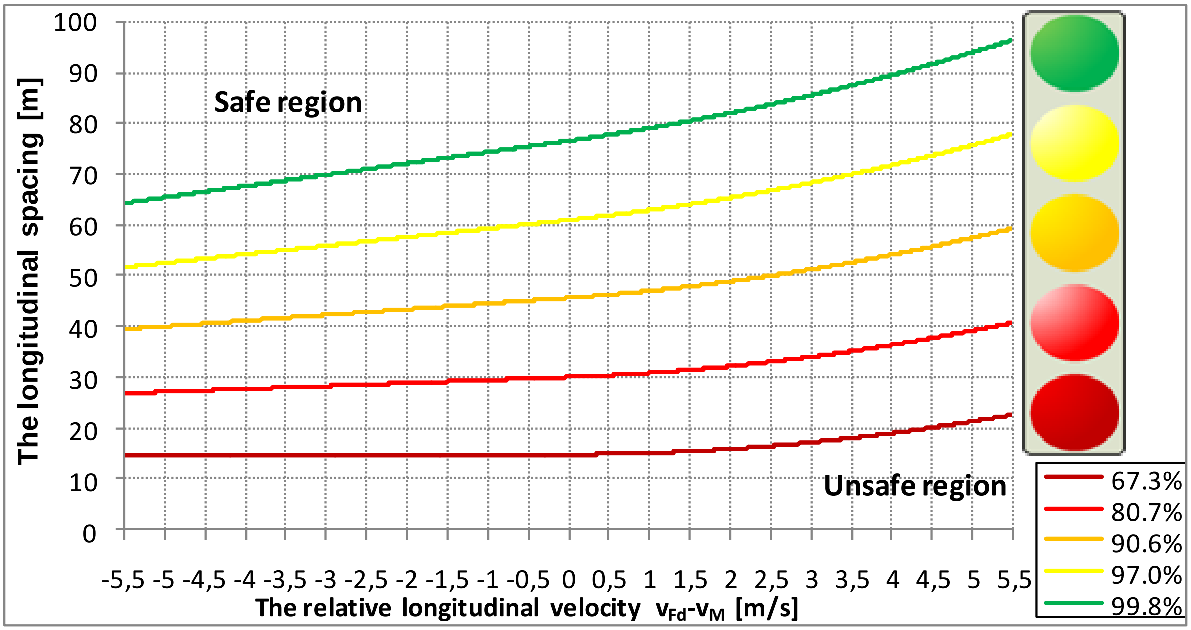

Figure 25. The collision region between M and F_d

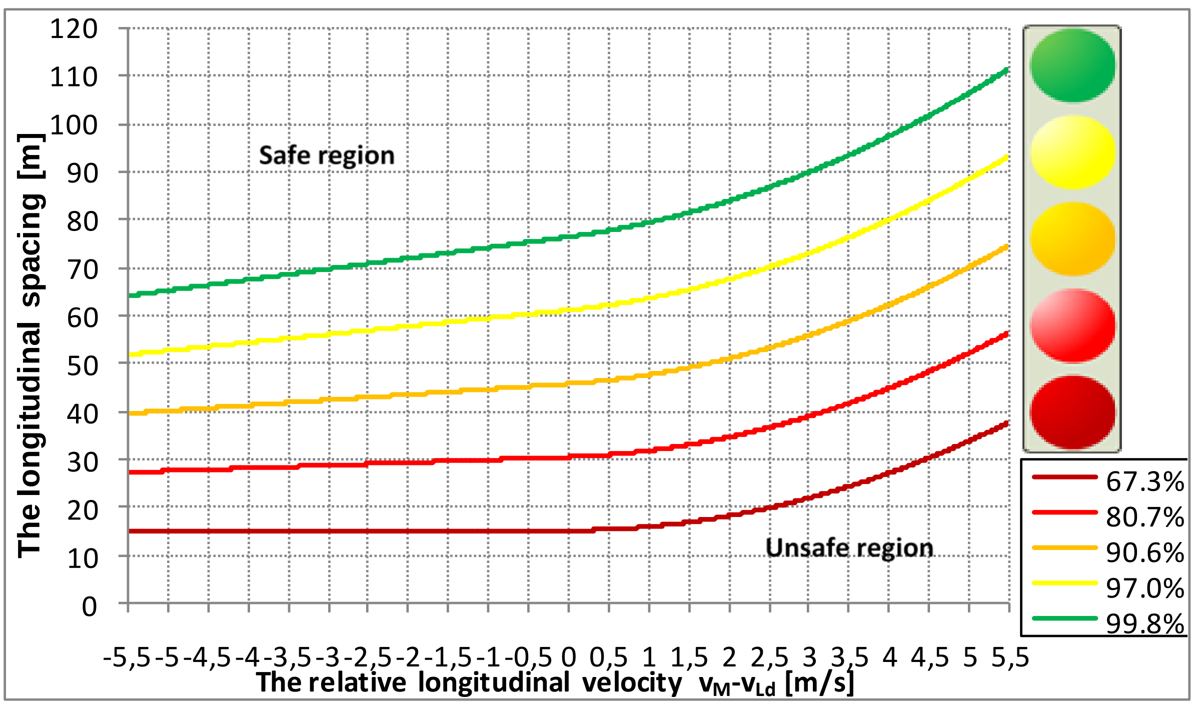

Figure 26. The collision region between M and L_d

6. Discussion

Lane changing is a complex traffic process, which makes it complicated to capture in a mathematical model. Many scenarios and tactics to create sufficient spacing to the surrounding vehicles are conceivable. Developing a simulation model that considers all these aspects goes beyond the scope of this research. To simplify, the model developed in this research only gives an advice about the current traffic situation. It is up to the driver to use a tactic to move from the unsafe to the safe region, as visualized in figures 25 and 26.

The model simplifies the lane change algorithm by calculating the lateral position and its time derivatives separately from the longitudinal ones. In practice, both movement directions exert influence on each other. The consequences of this simplification are assumed zero.

The model pays relatively much attention to safety precautions and less to driver comfort. Although we consider safety indeed as far more important, we may not omit driver comfort. The balance between the opposites safety and comfort measures can be a point of discussion.

We can design the LCA in a way that even in the worst scenario the LCA can generate a rather reliable advice. On the other hand, in a regular scenario, the safety precautions do not lead to unreasonable large safety distances. From the author's point of view, this balance maximizes the usefulness of the assistant.

This study assumed that the LCA is not linked with other ITS. In theory, however, it is possible to connect the LCA with for instance a rain detector. The advantage is that in this way, the rain detector can inform the LCA about the current weather conditions and thus which scenario should be used. Similar cooperative advantages are imaginable when the LCA is linked with other ITS.

7. Conclusions

This research focuses on how the Lane Change Assistant can be implemented in practice, regarding the practical issues. The practical issues that are considered concern changing circumstances, measurement uncertainties and model assumptions.

This study introduces a new micro simulation model that gives support in answering the research question. This simulation model consists of a lane change model and a vehicle following model implemented in a highway scenario with one merging vehicle and four surrounding vehicles.

This research compares different lane change models from the literature with each other, in order to reveal which input variables are used and which assumptions the model makes. The LCA design uses a lane change algorithm that relies on only a few negligible assumptions. The system uses detection hardware to collect the input variables from the surrounding vehicles in the destination lane and the infrastructure. Together with the input variables from its own vehicle, the LCA can create an advice about the safety level to change lane under current traffic conditions.

This study also performs a sensitivity analysis to the input variables, showing that the reliability of the advice is much more sensitive for changing circumstances, than to the consequences of measurement uncertainties or model assumptions. The unexpected changing circumstance in this research concerns an emergency brake scenario.

The practical implementation of the LCA can be established by applying certain safety distance above the minimum required initial longitudinal spacing to compensate to the practical issues. The LCA continuously calculates this safety distance for five different safety parameters, all guaranteeing certain safety level. The configuration of these safety levels depends on the scenario that the LCA is supposed to withstand. A developer of the LCA can set this configuration with nine variables that describe to what extent the three practical issues exist.

The HMI of the LCA consists of five LED lights. When the LCA gives a positive advice at the lowest safety level, only one LED will burn. A positive advice at the maximum safety level makes all the five LEDs burn. Thus, a positive advice for the selected scenario guarantees certain minimum and maximum safety level. Finally, the driver decides to change lane or not, using the system's advice.

7.1. Further research

This study proposes a design for the LCA that is robust to deal with practical circumstances. The scope of this research focuses on a LCA without cooperation with other systems. However, this assistant offers some opportunities to cooperate with other ITS and in-car systems. Further research can indicate to what extent cooperation with other ITS is possible. As described in chapter 6, the LCA can give a more accurate advice when it gets information about the current weather condition.

This study focused on a 2-lane highway scenario. Further research can make clear how the LCA can be widely implemented, for instance in other highway scenarios, or even a rural road or urban environment. Besides, the LCA might also be developed for merging scenarios, instead of only for free lane changing.

Tideman et al. (2007) described the general architecture of a lateral driver support system, as depicted in figure 2. This study focused on the sub-function *think*. Researchers can use this research to create a link to the other sub-functions *sense* and *act*.

Lee et al. (2004) performed a study to the driver behaviour during natural lane changes, focusing on sub-function *act*. Researchers can use the results from this research to find out what the best way is to inform the driver about the current possibilities to change lane. What is the best design of the HMI and what is its location in the vehicle?

Sub-function *sense* concerns the detection hardware, such as cameras. Additional research can be done to the accuracy of state of the art detection hardware, and the exact influences to the reliability of the advice. Other interesting topics are what to do if in practice for some reason certain input information is missing. Besides, it is interesting to know to what extent the reliability increases when not only current the traffic situation is considered while generating the advice, but for instance also the traffic situation at t-1.

Wei (2001) uses Artificial Neural Networks that have learning capabilities in his design of the LCA. By training the model, the LCA can personalize the system to the driver's behaviour. Further research to the feasibility of using ANN in practice can be interesting.

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9. Appendix – Literature review

First, this appendix gives an overview of input variables and assumptions of every research in the literature. In this overview, measured and static input variables are listed separately. At last, this information is presented in a brief overview.

Jin et al. (2009): Research on safety lane change model of driver assistant system on highway

Measured input

Initial distance between M and F_d	Sr(0)
Space between two vehicles in current state	$D_{survey}(t)$
Velocity of vehicle M, L_d, F_d	$V_j,\ j \in \{M, L_d, F_d\}$
Current time	t

Static input

Length vehicle M	L_v
Safe parking distance	D_o (10m)
Desired speed of vehicle M	v_{ref}
Time vehicle M accelerates during lane change	t_{lat}
Head-time distance	c_1 (1-2s)
Constant	k_1 (0.3)
Constant	k_2 (1.5)

Assumptions

1. It is assumed that the other vehicles have no acceleration
2. The merging vehicle and the following vehicle in the destination lane are the only vehicles
3. Lateral movement is not taken into account
4. Safe/unsafe areas are not defined
5. Jerk is not taken into account

Jula et al. (2000): Collision avoidance analysis for lane changing and merging

Measured input

Initial lateral distance between upper side vehicle M and lower side vehicle L_d / F_d	S
Initial speed and acceleration of vehicle M, L_d, L_o, F_d, F_o	$\left.\begin{matrix} V_j(0) \\ a_j(t) \end{matrix}\right\} j \in \{M, L_d, L_o, F_d, F_o\}$
Current time	t

Static input

Time after t=0 to adjust longitudinal position and velocity of vehicle M before merging	t_{adj}
Time, after t_{adj}, vehicle M needs for longitudinal acceleration, until velocity is equal to destination lane	t_{long}
Time, after t_{adj}, needed to complete the lane change	t_{lat}

Assumptions

1. It is assumed that the other vehicles have no acceleration
5. Jerk is not taken into account

6. No extra safety margin is defined, only theoretical circumstances are taken into account
7. The subject vehicle has no preferred speed; it only adapts its speed to the target lane

Kanaris et al. (1997): Strategies and spacing requirements for lane changing and merging in Automated Highway Systems (AHS)

Measured input

Minimum lateral distance between two vehicles k and h	L_{lat}^{kh}
Intended lane change distance	d_l
Velocity original lane	v_o
Velocity destination lane	v_d
Maximum available acceleration and jerk	$\left.\begin{matrix} a_{j\max} \\ J_{j\max} \end{matrix}\right\\} j \in \{l_1, l_2, f_1, f_2\}$
Current time	t

Static input

Appropriate chosen maximum acceleration/deceleration to maintain safety and comfort	a_{comf}
Maximum available acceleration merging vehicle M	$a_{M\ max}$
Maximum available jerk merging vehicle M	$J_{M\ max}$
Time instant at which the merging vehicle switches from decelerating to accelerating	t_{ch}
Time vehicle M needs to adjust its longitudinal position and velocity	t_{long}
Time vehicle M needs to adjust the lateral movement	t_{lat}
Total time to complete the lane change	t_{LC}
Reaction time to detect an emergency braking situation	t_d
Constant for 'limited friction angle' vehicle M	F_c

Assumptions

1. It is assumed that the other vehicles have no acceleration
4. Safe/unsafe areas are not defined
7. The subject vehicle has no preferred speed; it only adapts its speed to the target lane

Bascunana (1995): Analysis of lane change crash avoidance

Measured input

Initial longitudinal distance between the front bumpers of two vehicles	L_o
Length vehicle 2	l_2
The longitudinal closing velocity ($V_2 - V_1$)	V_c
Longitudinal deceleration (from any surrounding vehicle)	d
Current time	t

Static input

Length of vehicle 1 (M)	l_1
Longitudinal deceleration merging vehicle	d'
Time between initiation of the lane change and moment front vehicle 1 (M) reaches interception point	t_p

Time between initiation of the lane change and moment
rear vehicle 1 (M) reaches interception point t_p'
Time taken by vehicle 1 (M) to execute the lane change t_L

Assumptions
1. It is assumed that the other vehicles have no acceleration
2. Only two vehicles are taken into account: the merging vehicle and one other vehicle (vehicle 2, on different positions)
3. Lateral movement is not taken into account
5. Jerk is not taken into account
6. No extra safety margin is defined, only theoretical circumstances are taken into account

Gipps (1986): A model for the structure of lane-changing decisions
Measured input
Present lane l_n
Preferred lane (adjacent to present lane) l_p
Target lane l_t In this research given by scenario
Available lanes N
Location of the front of vehicle n $X_n(t)$
Effective length of vehicle n-1 s_{n-1}
Estimation of the most severe braking driver of vehicle
n-1 is prepared to undertake $\hat{b}$
Current time t
Relative advantages both lanes, regarding:
Comfort (Speed difference between lanes of more than 1m/s is desirable)
Safety level (gap acceptance depends on degree of urgency)

Static input
Desired speed of the driver V_n
Most severe braking the driver is prepared to undertake b_n^*

Assumptions
Urban environment instead of highway

Overview
The reviewed researches have several input variables in common. The table on the next page gives a brief overview of these overlapping variables. Besides, an overview is made of the assumptions of the researches. The variables are defined on the following pages.

Gipps' research is hardly to compare with the other researches, since this research is about the driver behaviour. The driver performs many operations, and therefore we can consider it as input. For this reason, in practice, not only the listed input variables are taken into account, but indirectly the driver can use every input variable he wants. Actually, the assumptions in other researches can be seen as aspects that are disregarded compared to this research. Thus, in the overview table every cell is at least marked with an empty bullet for this research.

Overview

	Variable	Research number					Total:
		1.	2.	3.	4.	5.	
	Sr(0)	●			●	o	2
	S		●	●		o	2
MEASURE	$D_{survey}(t)$	●				●	2
	d_l			●		o	1
	l_2				●	●	2
	$V_M(t)$	●				●	2
	$V_{Ld}(t)$	●				●	2
	$V_{Lo}(t)$					●	1
	$V_{Fd}(t)$	●				●	2
	$V_{Fo}(t)$					●	1
MEASURE	$V_M(0)$		●			o	1
	$V_{Ld}(0)$		●			o	1
	$V_{Lo}(0)$		●			o	1
	$V_{Fd}(0)$		●			o	1
	$V_{Fo}(0)$		●			o	1
	V_0			●	●	o	2
	V_d			●	●	o	2
	$a_M(t)$		●			o	1
	$a_{Ld}(t)$		●			o	1
MEASURE	$a_{Lo}(t)$		●			o	1
	$a_{Fd}(t)$		●			o	1
	$a_{Fo}(t)$		●			o	1
	$a_{Ld\ max}$			●	●	●	3
	$a_{Lo\ max}$			●	●	●	3
	$a_{Fd\ max}$			●	●	●	3
	$a_{Fo\ max}$			●	●	●	3
	$J_{Ld\ max}$			●		o	1
MEASURE	$J_{Lo\ max}$			●		o	1
	$J_{Fd\ max}$			●		o	1
	$J_{Fo\ max}$			●		o	1
	t	●	●	●	●	●	5
	Total:	6	12	13	9	12	

	Variable	Research number					Total:
		1.	2.	3.	4.	5.	
	L_v	●			●	o	2
	D_o	●				o	1
	V_{ref}	●				●	2
STATISTIC	a_{comf}			●		●	2
	$a_{M\ max}$			●	●	o	2
	$J_{M\ max}$			●		o	1
	t_{adj}		●	●		o	2
	t_{long}		●	●		o	2
	t_{lat}	●	●	●	●	o	4
	t_{LC}			●	●	o	2
	t_d	●		●		o	2
STATISTIC	F_c			●		o	1
	K_1	●				o	1
	K_2	●				o	1
	Total:	7	3	9	4	2	

Not taken into account:	Research number					Total:
	1.	2.	3.	4.	5.	
1.Acceleration other vehicles	●	●	●	●		4
2.Other vehicles	●			●		2
3.Lateral movement	●			●		2
4.Safe/unsafe areas	●		●			2
5.Jerk	●	●		●		3
6.Safety margin		●		●		2
7.Preferred speed		●	●			2
Total:	5	4	3	5	0	

Research numbers

1. Research on safety lane change model of driver assistant system on highway
2. Collision avoidance analysis for lane changing and merging
3. Strategies and spacing requirements for lane changing and merging in Automated Highway Systems (AHS)
4. Analysis of lane change crash avoidance
5. A model for the structure of lane changing decisions

Measure

Distance	
Sr(0)	Initial longitudinal distance between M and another vehicle
S	Initial lateral distance between vehicle M and L_d / F_d
$D_{survey}(t)$	Longitudinal space between two vehicles in current state
d_l	Intended lane change distance
l_2	Length surrounding vehicle
Velocity	
$V_M(t)$	Velocity vehicle M at time t
$V_{Ld}(t)$	Velocity leading vehicle destination lane at time t
$V_{Lo}(t)$	Velocity leading vehicle original lane at time t
$V_{Fd}(t)$	Velocity following vehicle destination lane at time t
$V_{Fo}(t)$	Velocity following vehicle original lane at time t
$V_M(0)$	Initial velocity vehicle M
$V_{Ld}(0)$	Initial velocity leading vehicle destination lane
$V_{Lo}(0)$	Initial velocity leading vehicle original lane
$V_{Fd}(0)$	Initial velocity following vehicle destination lane
$V_{Fo}(0)$	Initial velocity following vehicle original lane
V_o	Velocity original lane
V_d	Velocity destination lane
Acceleration	
$a_M(t)$	Acceleration vehicle M at time t
$a_{Ld}(t)$	Acceleration leading vehicle destination lane at time t
$a_{Lo}(t)$	Acceleration leading vehicle original lane at time t
$a_{Fd}(t)$	Acceleration following vehicle destination lane at time t
$a_{Fo}(t)$	Acceleration following vehicle original lane at time t
$a_{Ld\ max}$	Maximum available acceleration leading vehicle destination lane
$a_{Lo\ max}$	Maximum available acceleration leading vehicle original lane
$a_{Fd\ max}$	Maximum available acceleration following vehicle destination lane
$a_{Fo\ max}$	Maximum available acceleration following vehicle original lane
Jerk	
$J_{Ld\ max}$	Maximum available jerk leading vehicle destination lane
$J_{Lo\ max}$	Maximum available jerk leading vehicle original lane
$J_{Fd\ max}$	Maximum available jerk following vehicle destination lane
$J_{Fo\ max}$	Maximum available jerk following vehicle original lane
Time	
t	Current time

Statistic

Distance

L_v	Length vehicle M
D_0	Safe parking distance

Velocity

V_{ref}	Desired speed of vehicle M

Acceleration

a_{comf}	Maximum acceleration/deceleration to maintain safety and comfort
$a_{M\ max}$	Maximum available acceleration vehicle M

Jerk

$J_{M\ max}$	Maximum available jerk vehicle M

Time

t_{adj}	Time after t=0 to adjust longitudinal position and velocity of vehicle M
t_{long}	Time vehicle M accelerates to equal velocity in destination lane
t_{lat}	Time vehicle M runs into target lane
t_{LC}	Time needed to complete the lane change
t_d	Reaction time to detect an emergency braking situation

Other

F_c	Constant for limited fraction angle vehicle M
K_1	Constant 1
K_2	Constant 2