Linköping studies in science and technology. Dissertations, No. 1248

Simulation of Surrounding Vehicles in Driving Simulators

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Norrköping 2009

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ISBN 978-91-7393-660-6   ISSN 0345-7524

Printed by LiU-tryck, Linköping 2009

Abstract

Driving simulators and microscopic traffic simulation are important tools for making evaluations of driving and traffic. A driving simulator is designed to imitate real driving and is used to conduct experiments on driver behavior. Traffic simulation is commonly used to evaluate the quality of service of different infrastructure designs. This thesis considers a different application of traffic simulation, namely the simulation of surrounding vehicles in driving simulators.

The surrounding traffic is one of several factors that influence a driver's mental load and ability to drive a vehicle. The representation of the surrounding vehicles in a driving simulator plays an important role in the striving to create an illusion of real driving. If the illusion of real driving is not good enough, there is an risk that drivers will behave differently than in real world driving, implying that the results and conclusions reached from simulations may not be transferable to real driving.

This thesis has two main objectives. The first objective is to develop a model for generating and simulating autonomous surrounding vehicles in a driving simulator. The approach used by the model developed is to only simulate the closest area of the driving simulator vehicle. This area is divided into one inner region and two outer regions. Vehicles in the inner region are simulated according to a microscopic model which includes sub-models for driving behavior, while vehicles in the outer regions are updated according to a less time-consuming mesoscopic model.

The second objective is to develop an algorithm for combining autonomous vehicles and controlled events. Driving simulators are often used to study situations that rarely occur in the real traffic system. In order to create the same situations for each subject, the behavior of the surrounding vehicles has traditionally been strictly controlled. This often leads to less realistic surrounding traffic. The algorithm developed makes it possible to use autonomous traffic between the predefined controlled situations, and thereby get both realistic traffic and controlled events. The model and the algorithm developed have been implemented and tested in the VTI driving simulator with promising results.

Populärvetenskaplig sammanfattning

Den här avhandlingen handlar om att kombinera mikroskopisk trafiksimulering och körsimulatorer. Mikroskopisk trafiksimulering är ett viktigt verktyg som framförallt används för att analysera olika förslag till förändringar i vägtrafiksystemet. Det kan handla om att jämföra olika korsnings- och vägutformningar eller trafiksignalsstrategier. I en mikroskopisk trafiksimuleringsmodell simuleras enskilda förar-fordonsenheter. Simuleringen bygger på delmodeller som beskriver hur förare accelererar, när de väljer att byta körfält, vilken hastighet de vill köra i, med mera.

En körsimulator är en modellkonstruktion som ska efterlikna verklig bilkörning. Föraren kör fordonet på samma sätt som ett riktigt fordon, medan den omgivande trafikmiljön simuleras. En körsimulator kan liknas vid ett avancerat datorbilspel. Körsimulatorer används bland annat för att studera förarbeteende. Den omgivande trafikmiljön spelar en viktig roll i arbetet med att skapa en illusion av verklig bilkörning. Om inte illusionen är tillräckligt bra finns en risk att testpersonerna kör annorlunda i körsimulatorn jämfört med hur de kör i verklig trafik.

I den här avhandlingen presenteras en modell för att generera och simulera omgivande trafik i en körsimulator. Modellen är baserad på mikroskopisk trafiksimulering. Körsimulatorer används ofta för att studera situationer eller händelser som sällan förekommer i det verkliga trafiksystemet, till exempel trafiksäkerhetskritiska händelser. För att säkerställa att alla försökspersoner kör under samma förutsättningar brukar de omgivande fordonens beteende strikt kontrolleras. Detta gör det möjligt att utsätta samtliga försökspersoner för samma situationer. Det medför dock ofta att de omgivande fordonen beter sig mindre likt verkliga bilförare. Genom att använda en mikroskopisk trafiksimuleringsmodell kan realismen ökas. Detta medför dock att förutsättningarna på detaljnivå kommer att skilja sig åt mellan försökspersonerna samt att det är svårare att utsätta förarna för förutbestämda situationer. För att lösa detta har en modell som kan växla mellan simulerad trafik och förutbestämda situationer utvecklats. De utvecklade modellerna har implementerats och testats i VTIs körsimulator med lovande resultat.

Acknowledgments

This thesis is the result of research carried out at the division of Communication and Transport Systems at Linköping University (LiU) and the Swedish National Road and Transport Research Institute (VTI). The research has been sponsored by the Swedish Road Administration through the Swedish Network of Excellence Transport Telematics Sweden.

First of all I would like to thank my supervisor Jan Lundgren for his encouragement, support and guidance. I'm also grateful to my additional supervisors Jonas Jansson, Mikael Adlers and Pontus Matstoms. Thanks also to Laban Källgren (VTI) for his priceless help with the integration with the VTI Driving Simulator III.

I would also like to show my appreciation to my colleagues at LiU and VTI, who make LiU and VTI stimulating places to work at. Special thanks to my friend and former roommate Andreas Tapani and to my other Ph. D. student colleagues for very interesting and useful discussions, to Arne Carlsson for sharing his knowledge of the traffic theory and simulation area, to Selina Mårdh and Anne Bolling for their help during the design and the realization of the driving simulator experiments conducted, and to the members of the VTI driving simulator group for sharing their massive experience within the driving simulator area.

I would also like to thank Stéphane Espié for our fruitful collaboration and for inviting me to come to Paris and work at his group at INRETS. Thanks also to Jenny Simonsson whom I started this work with during our master thesis and to Ingmar Andréasson who has kindly read and commented on the thesis draft.

Finally, I would like to express my gratitude to my family and friends for their encouragement and support. Last but not least, thank you Lin for all your love and support.

Norrköping, March 2009
Johan Olstam

Contents

1 Introduction

Microscopic traffic simulation, henceforth called micro or traffic simulation models, has become a powerful and cost-efficient tool for investigating traffic systems. Traffic simulation models incorporate sub-models for acceleration, speed adaptation, lane-changing, etc., to describe how vehicle–driver units move and interact with each other and with the infrastructure. The sub-models, henceforth called behavioral models, use the current road and traffic situation as input and generate individual driver decisions for example with regard to which acceleration rate to apply and which lane to travel in as output. Traffic simulation models offer the possibility to experiment with an existing or a future traffic system in a safe and non disturbing way. The traditional applications of traffic simulation are quality of service evaluations of different road as well as traffic control designs. Common output measures are average speed, flow, density, travel time, delay and queue length. Lately, there has been an increased focus on new applications of traffic simulation. Examples include analysis of Intelligent Transportation Systems (ITS) and traffic management strategies, as well as traffic simulation based safety and environmental impact analyses. There is also an increased focus on combining traffic simulation models and driving simulators, which is the focus of this thesis.

A driving simulator is designed to imitate driving a real vehicle. The driver interface can be realized with a real vehicle cabin or only a seat with a steering wheel and pedals, and anything in between. The surroundings are presented for the driver on a screen and, if available, in rear mirrors. A vehicle model is used to calculate the simulator vehicle's movements according to the driver's use of the steering wheel and the pedals. Some driving simulators use a motion system to support the driver's visual impression of the simulator vehicle's movements. Last but not least, a driving simulator includes a scenario module that includes the specification of the road, the environment, and all the other actors and events.

Driving simulators are used to conduct experiments in many different areas. Examples include alcohol, medicines and drugs, driving with disabilities, human-machine interaction, fatigue, road and vehicle design. Driving simulators can also be used for training purposes. One example is the TRAINER simulator (Gregersen et al., 2001) that was developed to work as a complimentary vehicle in driving schools. Driving simulators offer possibilities to practice actions that are unsafe, difficult or impossible to train in the real road network. This could be anything between basic maneuvering to emergency situations.

It is important that the performance of the simulator vehicle, the visual representation, and the behavior of surrounding objects are realistic, in order for a driving simulator to be a valid representation of real driving. For example, it is important that the surrounding vehicles behave in a realistic and trustworthy way. Surrounding vehicles influence a driver's mental load and ability to drive a vehicle. It is not only important that the behavior of a single driver is realistic, but also that the behavior of the whole traffic stream is realistic. For instance, drivers who drive fast expect to catch up with more vehicles than the number of vehicles that catch up with them and vice versa.

A realistic simulation of surrounding vehicles, and thereby traffic, can be achieved by combining a driving simulator with a model for microscopic simulation of traffic. However, traffic simulation models have traditionally not been used to simulate surrounding vehicles in driving simulators. The usual approach has instead been to strictly control the behavior of the surrounding vehicles. It is desirable for several reasons to keep the variation in test conditions between different drivers (henceforth called subjects) as low as possible. Traffic simulation models simulate autonomous vehicles, and by using autonomous surrounding vehicles, subjects will experience different situations at the microscopic level depending on how they drive. The use of autonomous vehicles makes it difficult to limit the variation in test conditions. The subjects' conditions will still be comparable at a higher, more aggregated, level, e. g. comparable traffic densities and average speeds. Whether comparable conditions at an aggregated level are sufficient or not varies depending on the type of experiment. For some experiments, comparable conditions at the microscopic level are essential, and it may not be suitable to use autonomous vehicles. In other experiments, comparable conditions at a higher level are sufficient. A related problem is that the use of autonomous surrounding vehicles also makes it more difficult to expose the subject to specific controlled situations or events.

This thesis deals both with models for the simulation of autonomous surrounding vehicles and methods for combining autonomous vehicles and controlled events. The thesis is organized as follows. Chapter 2 gives an introduction to the field of traffic simulation. The chapter includes a survey of commonly used behavioral models for car-following, lane-changing, overtaking, and speed adaptation. Chapter 3 gives an introduction to the field of simulating surrounding vehicles in driving simulators. The chapter starts with an introduction to driving simulator experiments, then follows a discussion on the differences between this application and more traditional applications of traffic simulation. The chapter ends with a survey of the most commonly used modeling approaches for simulating surrounding vehicles in driving simulators.

Chapter 4 presents the objectives, contributions, and delimitations of this thesis. The chapter also includes summaries of the five papers included and suggestions for future research.

2 Traffic simulation

The societies of today need well functioning traffic and transportation systems. Congestion and traffic jams have become recurrent problems in most of the larger cities and also more common in smaller cities. In order to avoid congestion and to optimize the traffic systems with respect to capacity, accessibility and safety, traffic planners need tools that can predict the effects of different road designs, management strategies, and increased travel demands. Therefore, in recent decades researchers and developers have developed many different types of models and tools that deal with these kinds of issues. The rapid development in the personal computer area has created new possibilities to develop enhanced traffic modeling tools. Traffic models are mainly based on analytical or simulation approaches. The analytically models often use queue theory, optimization theory or differential equations that can be solved analytical to model road traffic. These kinds of models are mainly used to study average situations and offer limited possibilities for studying how the dynamics of a traffic system varies over time. Simulation models on the other hand, offer good possibilities for this.

2.1 Classification of traffic simulation models

There are many different kinds of traffic models and there are also different ways to classify traffic models. Traffic simulation models are typically classified according to the level of detail at which they represent the traffic stream. Three categories are generally used, namely: Microscopic, Mesoscopic and Macroscopic.

Microscopic models represent the traffic stream at a high level of detail. They model individual vehicles and the interaction between them. Microscopic models incorporate sub-models for acceleration, speed adaptation, lane-changing, gap acceptance etc., to describe how vehicles move and interact with each other and with the infrastructure. Several models have been developed and the most well-known are probably AIMSUN

(Barceló and Casas, 2002; TSS, 2008), VISSIM (PTV, 2008), Paramics (Quadstone, 2004; Quadstone Paramics, 2008), MITSIMLab (Toledo et al., 2003), and CORSIM (FHWA, 1996).

Mesoscopic models often represent the traffic stream at a rather high level of detail, either by individual vehicles or packets of vehicles. The difference compared to micro models is that interactions are modeled with lower detail. The interactions between vehicles and the infrastructure are typically based on macroscopic relationships between flow, speed and density. Examples of mesoscopic simulation models are DYNASMART (Jayakrishnan et al., 1994), CONTRAM (Taylor, 2003), DYNAMEQ (Florian et al., 2006), and MEZZO (Burghout, 2004).

Macroscopic models use a low level of detail, both with regard to the representation of the traffic stream and interactions. Instead of modeling individual vehicles, the macro models use aggregated variables such as flow, speed and density to characterize the traffic stream. Macro models commonly use speed–flow relationships and conservation equations to model how traffic propagates through the network modeled. Examples of macroscopic simulation models are METANET/METACOR (Papageorgiou et al., 1989; Salem et al., 1994) and the Cell Transmission model (Daganzo, 1994, 1995).

2.2 Microscopic traffic simulation

Microscopic traffic simulation models simulate individual vehicles. The general approach is to treat a driver and a vehicle as one unit. As in reality, these vehicle–driver units interact with each other and with the surrounding infrastructure. Micro models consist of several submodels, henceforth called behavioral models, that each handle specific interactions. The most essential behavioral model is the car-following model, which handles the longitudinal interaction with preceding vehicles. Other important behavioral models include models for lane-changing, gap-acceptance, overtaking, ramp merging, and speed adaptation. The sub-models required depend on the type of road that the model is designed for. Lane-changing models are for instance only necessary when simulating urban or freeway environments and are not required in models for two lane highways with oncoming traffic. The most common behavioral models will be presented in more detail in Section 2.3.

Most micro models are designed for simulating urban or freeway networks. The most well known models for these environments are the ones presented in Section 2.1 (AIMSUN, VISSIM, Paramics, MITSIMLab, and CORSIM). Only a few models for two-lane highways with oncoming traffic have been developed. The state-of-the-art in rural road models includes the Two-Lane Passing (TWOPAS) model (Leiman et al., 1998), the Traffic on Rural Roads (TRARR) model (Hoban et al., 1991), and the VTISim model (Brodin and Carlsson, 1986). The VTISim model has been further developed in the Rural Road Traffic Simulator (RuTSim) model (Tapani, 2005, 2008).

In order to model how behavior and preferences vary among drivers, each vehicle–driver unit is assigned different vehicle and driver characteristics. These characteristics commonly include vehicle length, desired speed, desired following distance, possible or desired acceleration and deceleration rates, etc. The variation among the population is generally described by a distribution function and individual parameter values are drawn from the specified distribution. For example, we can assume that the desired speeds on freeways follow a normal distribution with a mean of 111 km/h and a standard deviation of 11 km/h. Micro models are generally time discrete, but some event based models have also been developed, see for instance Brodin and Carlsson (1986). In event based models, vehicles are only updated in the case of an event, e. g. when catching up with a preceding vehicle. The basic principle of a time discrete model is that the time is divided into small time steps, commonly between 0.1 and 1 seconds. At each time step, the model updates every vehicle according to the set of behavioral models. At the end of the time step, the simulation clock is increased and the simulation enters the next time step.

Microscopic simulation models have traditionally been used to conduct capacity and quality of service evaluations of different road designs and management strategies. During the last decade, micro models have also been used to a greater extent to evaluate different ITS-applications, for example Intelligent Speed Adaptation (Liu and Tate, 2000) or Adaptive Cruise Control systems (Champion et al., 2001; Kesting et al., 2007b; Tapani, 2008). Research has also been conducted within the area of combining micro simulation and different safety indicators to perform safety analysis of different road and intersection designs, see for example Archer (2005) and Gettman and Head (2003).

Even though micro models work on a micro level and simulate individual vehicles, they have mainly been used to generate macroscopic outputs such as average speeds, flows, and travel times. A large part of the calibration and validation of micro models is therefore generally performed at a macroscopic level. The different behavioral models have been calibrated and validated to various extents at a micro level. However, little effort has been put into calibrating and validating combinations of behavioral models at a micro level, for example if a car-following model in combination with a lane-changing model generates valid results at a micro level.

2.3 Behavioral model survey

In order to be usable and perform well, traffic simulation models have to be based on high-quality behavioral models. To generate realistic behavior is of course the most important property of a good behavioral model, but it is not the only desirable property. A realistic behavioral model is of little or no use if it cannot be calibrated or if this task is too time-consuming. It is therefore desirable to keep the number of model parameters as low as possible. When designing a behavioral model, the aim should be to find the best compromise between the number of parameters and output agreement. It is also desirable that the parameters used can easily be interpreted as known vehicle or driver factors. This simplifies the calibration work and allows the user to experiment, in a more straightforward and easy way, with different parameter settings with regard to the variation in behavior among drivers for example.

Different road environments require different kinds of behavioral models. A traffic simulation model for urban roads must include different types of behavioral models than a simulation model for rural environments. However, common to all environments is the need of a car-following model. A car-following model describes a vehicle–driver unit's acceleration with respect to preceding vehicles in the same lane, the driver's own goals and the vehicle's acceleration capabilities. Another behavioral model that is necessary in all road environments, is a speed adaptation model, which calculates a driver's preferred or desired speed along the road. In urban and freeway environments, models for lane-changing decisions are essential. However, on two-lane highways, a model that considers the whole overtaking procedure is required. Such a model cannot only deal with the lane change to the oncoming lane. It also has to consider the actual passing procedure when the vehicle is traveling in the oncoming lane and the lane change back into its own lane. As a part of both lane-changing and overtaking models, some type of gap-acceptance model is necessary. A Gap-acceptance model controls the decision to accept or reject an available gap, for example if a vehicle–driver unit that desires to change lane accepts the available gap between two subsequent vehicles in the target lane. Some kind of gap-acceptance model is also necessary when modeling intersections, lane drops or on-ramp merging situations.

The following sections will describe different kinds of car-following, lane-changing, overtaking, and speed adaptation models in more detail. The sections also include descriptions of different approaches to gap-acceptance in connection to lane-changes and overtakings.

2.3.1 Car-following models

A car-following model controls a driver's behavior with respect to preceding vehicles in the same lane. A vehicle–driver unit is classified as *following* when it is constrained by a preceding vehicle, and when driving at the desired speed will lead to a collision. When a vehicle–driver unit is not constrained by another vehicle, it is considered *free* and travels, in general, at its desired speed. The follower's action is commonly specified through the follower's acceleration, although some models, for example the car-following model by Gipps (1981), specify the follower's actions through the follower's speed. Some car-following models only describe drivers' behavior when they are actually following another vehicle, whereas other models are more complete and determine the behavior in all situations. In the end, a car-following model should deduce both in which regime or state a vehicle–driver unit is, and what actions it applies in each state.

Most car-following models use several regimes to describe the follower's behavior. A common setup is to use three regimes: one for free driving, one for normal following, and one for emergency deceleration. In the free regime, vehicle–driver units are unconstrained and try to achieve their desired speed, whereas in the following regime they adjust their speed with respect to the vehicle in front. Vehicles in the emergency deceleration regime decelerate to avoid a collision. Most car-following models consider only the interaction with the closest preceding vehicle. However, there are reports (see e. g. Hoogendoorn et al., 2006) that indicate that car-following models including several leaders fit empirical data better than models that include only one leader. An example of a model that includes several leaders is the Human Driver Model

(Treiber et al., 2006). The interested reader can consult Brackstone and McDonald (1998) for a historical review of car-following models and Janson Olstam and Tapani (2004) for a more detailed description of some of the car-following models presented in this section. The following notation will be used throughout this section to describe the car-following models, see also Figure 2.1:

a_n	acceleration, vehicle n, [m/s^2]
x_n	position, vehicle n, [m]
v_n	speed, vehicle n, [m/s]
Δx	$x_{n-1} - x_n$, space headway, [m]
Δv	$v_n - v_{n-1}$, approach speed, [m/s]
v_n^{des}	desired speed, vehicle n, [m/s]
L_{n-1}	length of vehicle $n-1$, [m]
s_{n-1}	effective length (L_{n-1} + minimum gap between stationary vehicles), vehicle $n-1$, [m]
T	reaction time, [s]

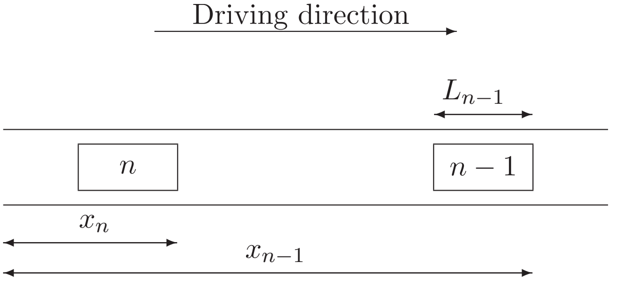

Figure 2.1: Car-following notation.

Classification of car-following models

Car-following models are commonly divided into classes or types depending on the logic utilized. The Gazis–Herman–Rothery (GHR) family of models is probably the model class that has been studied most. The GHR model is sometimes referred to as the general car-following model. The first version was presented in 1958 (Chandler et al., 1958) and several enhanced versions have been presented since then. The GHR model only controls the actual following behavior. The basic relationship between a leader and a follower vehicle in this case is a stimulus-response type of function. The GHR model states that the follower's acceleration depends on the speed of the follower, the speed difference between the follower and the leader, and the space headway (Brackstone and McDonald, 1998). That is, the acceleration of the follower at time t is calculated as

$$a_n(t) = \alpha \cdot v_n^{\beta}(t) \cdot \frac{v_{n-1}(t-T) - v_n(t-T)}{\left(x_{n-1}(t-T) - x_n(t-T)\right)^{\gamma}}, \tag{2.1}$$

where $\alpha > 0$, β and γ are model parameters that control the proportionalities. A GHR model can be symmetrical or unsymmetrical. A symmetrical model uses the same parameter values in both acceleration and deceleration situations, whereas an unsymmetrical model uses different parameter values in acceleration and deceleration situations. An unsymmetrical GHR-model is used for instance in MITSIM (Yang and Koutsopoulos, 1996) to calculate the acceleration in the following regime, and it is formulated as

$$a_n(t) = \alpha^{\pm} \cdot v_n^{\beta^{\pm}}(t) \cdot \frac{v_{n-1}(t-T) - v_n(t-T)}{\left(x_{n-1}(t-T) - l_{n-1} - x_n(t-T)\right)^{\gamma^{\pm}}}, \tag{2.2}$$

where $\alpha^{\pm}$, $\beta^{\pm}$ and $\gamma^{\pm}$ are model parameters. The parameters α^{+}, β^{+} and γ^{+} are used if $v_n \leq v_{n-1}$ and α^{-}, β^{-} and γ^{-} are used if $v_n > v_{n-1}$. Besides the following regime, the MITSIM model uses an emergency regime and a free driving regime.

The safety distance or collision avoidance models constitute another type of car-following models. In these models, the driver of the following vehicle is assumed to always try to keep a safe distance to the vehicle in front. Pipes' rule which says:

> "A good rule for following another vehicle at a safe distance is to allow yourself at least the length of a car between you and the vehicle ahead for every ten miles of hour speed at which you are traveling" (Hoogendoorn and Bovy, 2001),

is a simple example of a safety distance model. The safe distance is commonly specified through manipulations of Newton's equations of motion. In some models, this distance is calculated as the distance that is necessary to avoid a collision if the leader decelerates heavily. The most well known safety distance model is probably the one by Gipps (1981). In this model, the follower chooses the minimum speed of the one constrained by the follower's own vehicle and the one constrained by the leader vehicle, that is the minimum of

$$v_n^a(t+T) = v_n(t) + 2.5 \cdot a^m T \cdot \left(1 - \frac{v_n(t)}{v_n^{des}}\right) \cdot \sqrt{0.025 + \frac{v_n(t)}{v_n^{des}}} \quad (2.3)$$

and

$$\begin{aligned} v_n^b(t+T) = \; & d^m T + \Bigg((d^m T)^2 \\ & -d^m \left[2\left(\Delta x(t) - s_{n-1}\right) - v_n(t) T - \frac{v_{n-1}(t)^2}{\hat{d}_{n-1}} \right] \Bigg)^{0.5}. \end{aligned} \quad (2.4)$$

Here a^m and d^m is the maximum desired acceleration and deceleration for vehicle n, respectively, and $\hat{d}_{n-1}$ is an estimation of the maximum deceleration desired by vehicle $n-1$. The safe speed with respect to the leader (Equation 2.4) is derived from the Newtonian equations of motion. The equation calculates the maximum speed that the follower can drive at and still, after some reaction time, be able to decelerate down to zero speed and avoid a collision if the leader decelerates down to zero speed. Another safety distance model is the Intelligent Driver Model (IDM) by Treiber et al. (2000). The IDM also consists of one function for the acceleration with respect to the follower's own vehicle and one function for the acceleration with respect to the leader. In the IDM, the two functions are added together into one function as

$$a_n = a_0 \left[1 - \left(\frac{v_n}{v_n^{des}} \right)^4 - \left(\frac{s^*(v_n, \Delta v)}{s} \right)^2 \right], \quad (2.5)$$

where

$$s^*(v, \Delta v) = s_0 + v_n \cdot T^{des} + \frac{v_n \Delta v}{2\sqrt{a_0 b}}. \quad (2.6)$$

Here $s = \Delta x - L_{n-1}$ and the parameter a_0 and b determines maximum acceleration and deceleration, respectively. The parameter s_0 is the minimum distance between stationary vehicles and T_d is the desired following time gap.

In 1963 a new approach for car-following modeling were presented, (Brackstone and McDonald, 1998). Models using this approach are classified as psycho-physical or action point models. Psycho-physical models use thresholds or action points where the driver changes his/her behavior. Drivers are able to react to changes in spacing or relative velocity only when these thresholds are reached, (Leutzbach, 1988). The thresholds, and the regimes they define, are often presented in a relative space/speed diagram of a follower–leader vehicle pair; see Figure 2.2 for an example. The bold line symbolizes a possible vehicle trajectory.

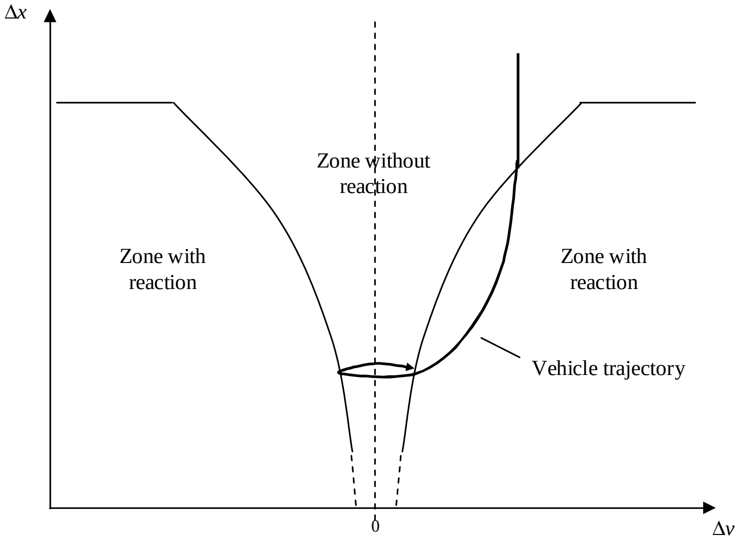

Figure 2.2: A psycho-physical car-following model (Source: Leutzbach, 1988).

Representative examples of psycho-physical car-following models are those by Wiedemann (1974); Wiedemann and Reiter (1992), see Figure 2.3, and Fritzsche (1994), see Figure 2.4.

Fuzzy-logic is another approach that to some extent has been utilized in car-following modeling. Fuzzy logic or fuzzy set theory can be used to model drivers' inability to observe absolute values. For example, human beings cannot deduce exact values of speed or relative distance, but they can give estimations like "above normal speed", "fast", "close", etc. In the models described above, drivers are assumed to know their exact own speed and distance to other vehicles etc. In order to get a more human-like modeling, fuzzy logic models assume that drivers are able to

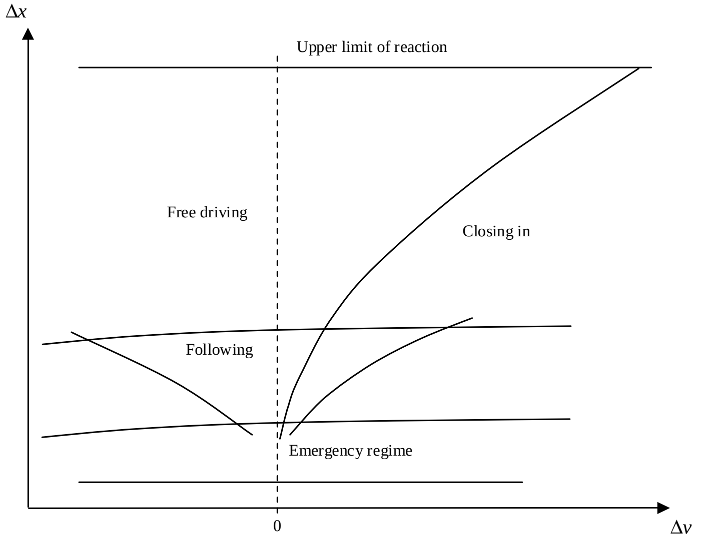

Figure 2.3: The different thresholds and regimes in the Wiedemann car-following model (Wiedemann, 1974; Wiedemann and Reiter, 1992).

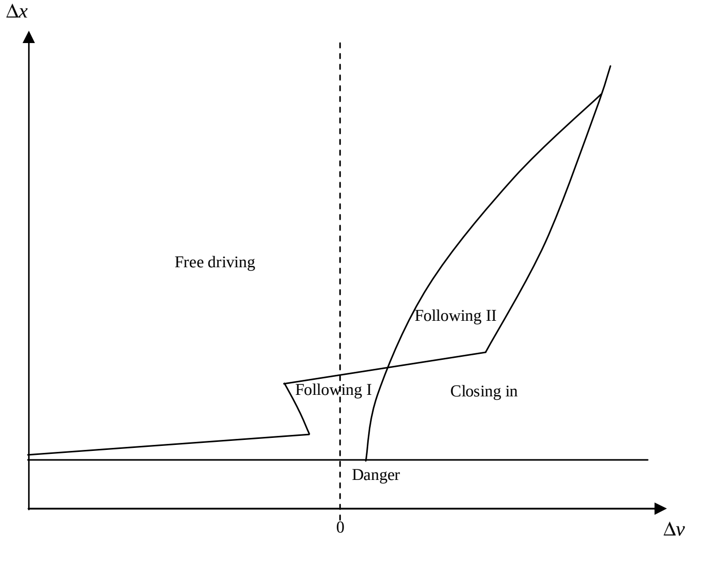

Figure 2.4: The different thresholds and regimes in the Fritzsche car-following model (Fritzsche, 1994).

conclude only if the speed of the front vehicle is very low, low, moderate, high, or very high for example. In many cases, the fuzzy sets overlap each other. To deduce how a driver will observe a current variable value, membership functions that map actual values to linguistic values have to be specified, see Figure 2.5 for an example.

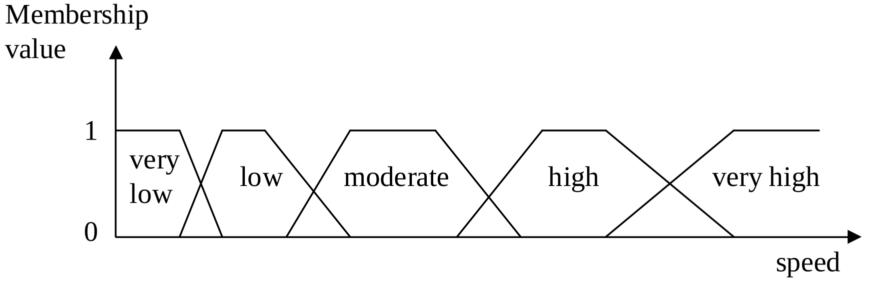

Figure 2.5: Example of membership functions for driving speed.

The strength of fuzzy logic is that the fuzzy sets can easily be combined with logical rules to construct different kinds of behavioral models. A possible rule can for instance be: if own speed is “low”, desired speed is “moderate” and headway is “large”, then increase speed. As seen in the previous sentence, it is rather easy to create realistic and workable linguistic rules for a specific driving task. However, one big problem is that the fuzzy sets need to be calibrated in some way. There have been attempts to “fuzzify” both the GHR model and a model named MISSION (Wiedemann and Reiter, 1992). However, no attempts to calibrate the fuzzy sets have been made, (Brackstone and McDonald, 1998).

Model properties

As presented in the previous section, there are different types of car-following models. Several car-following models, using different approaches, have been developed since the 1950’s. Despite the number of models that have already been developed, there is still active research in the area. One reason for this is that the preferred choice of car-following model may differ depending on the application. For example, the requirements placed on a car-following model used to generate macroscopic outputs, e. g. average flow and speed, is lower than the requirements on car-following models used to generate microscopic output values, such as individual vehicle trajectories.

Traffic simulation models and thereby car-following models are mostly utilized to study how changes in a network affect traffic measures such as average flow, speed, density etc. In other words, the simulation output of interest in such applications is macroscopic measures, hence the car-following models utilized should at least generate representative macroscopic results. Leutzbach (1988) presents a macroscopic verification of GHR-models. Through an integration of the car-following equation it is possible to obtain a relationship between average speed, flow and density. This relationship can then be compared to real data or to outputs from other macroscopic models. For a GHR-model with $\beta = 0$ and $\gamma = 2$, the integration becomes the well recognized Greenshield's relationship (see e. g. May, 1990):

$$q = v \cdot k = v^{des} \cdot \left(1 - \frac{k}{k_{max}}\right) \cdot k, \tag{2.7}$$

where q is the traffic flow (vehicles/hour), k is the density (vehicles/km) and k_{max} is the maximal possible density (jam density). A verification of this kind however is not possible for an arbitrary car-following model. It is for example not possible to integrate a psycho-physical model, since such models do not express the follower's acceleration in a mathematically closed form. However, macroscopic relationships can always be generated by running several simulations with different flows.

Drivers' reaction time is a parameter which is common in most car-following models. It is assumed that with long reaction times, vehicles have to drive with large gaps between each other in order to avoid collisions, hence the traffic density, and thereby the flow, will be reduced. Most car-following models use one common reaction time for all drivers. This is not realistic from a micro perspective but may be enough to generate realistic macro results.

The magnitude of drivers' reactions also influences the simulation results. How the output is affected is not as obvious as in the case of reaction time. High acceleration rates should lead to vehicles reaching their new constraint speed faster, which should decrease the vehicles travel time delay. High deceleration rates should also lead to less travel time delay, and thus the vehicles can start their decelerations later. High acceleration and deceleration rates may however result in oscillating vehicle trajectories in congested situations and thereby decrease the average speed.

There are many possible pitfalls in the modeling of car-following behavior. Firstly, driver characteristics such as reaction time and reaction magnitude vary among drivers. Driving behavior may also vary according to country or territory, due to different formal and informal driving and traffic rules. For example, drivers in the USA may, for example, not drive in the same way as European or Asian drivers. Behavioral models that are used to model traffic in different countries must therefore offer the possibility of using different parameter settings. The differences between countries may however be so big that even with different parameter values, the same car-following model cannot be used to describe the behavior in two countries with different traffic conditions. See e. g. Tapani et al. (2008) for further reading on simulation modeling of different regions. Furthermore, it may be necessary to use different parameters, or even different models, for different traffic situations, for example congested and non congested traffic. There are versions of the GHR model that use different parameter values for congested and non congested situations, (Brackstone and McDonald, 1998). For example, it is important to remember that driving characteristics such as reaction time are often treated as parameters, but that in reality they vary depending on the driving context. Drivers may be more alert in congested situations and thereby have a shorter reaction time than in non congested situations. A model that does not include sub-models for how parameters such as reaction time are affected by the driving context consequently require different parameter values for different traffic situations.

2.3.2 Lane-changing models

Lane-changing models describe drivers' behavior when deciding whether to change lane or not on a multi-lane road link. This type of behavioral model is essential and is important both in urban and freeway environments. When deciding whether to change lane, a driver needs to take several things into consideration. Gipps (1986) proposed that a lane-changing decision is the result of answering the questions

- Is it necessary to change lane?
- Is it desirable to change lane?
- Is it possible to change lane?

Gipps (1986) presented a framework for the structure of lane-changing decisions in the form of a decision tree. The proposed decision tree considered for instance the driver's desire to reach the desired speed, the driver's intended turn, any reserved lanes or obstructions, and the urgency of the lane change in terms of the distance to the intended turn. Several lane-changing models, for example the models by Barceló and Casas (2002), Hidas (2002, 2005), and Yang (1997), are based on the three basic steps proposed by Gipps (1986).

In the model by Gipps (1986) all lane changes are impossible if the gap available in the target lane is smaller than a given limit. This is a reasonable approach when a lane change is desirable. However, in situations where a lane change is necessary or essential but not possible, vehicles in the target lane often help the trapped vehicle by adjusting their speed to create a large enough gap for the trapped vehicle to enter. This behavior has been addressed for instance by Hidas (2002, 2005). Hidas (2002) describes a further developed version of the model by Gipps (1986), which also includes the cooperative behavior for vehicles in the target lane, see Figure 2.6.

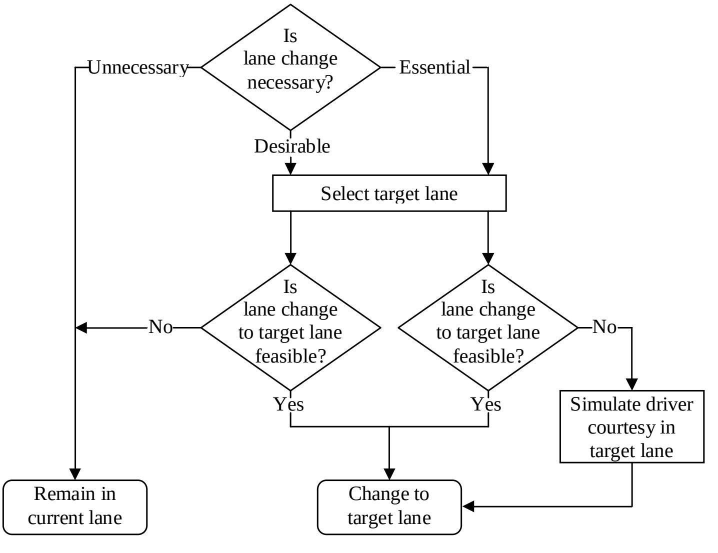

Figure 2.6: Structure for lane-changing decisions proposed in Hidas (2002).

In the model structure proposed by Hidas (2002), the necessary and desirable steps are merged into one necessary step with the possible outcomes: unnecessary, desirable, or essential. A similar approach for modeling cooperative lane-changing was proposed by Yang and Koutsopoulos (1996). This model classifies a lane change as either mandatory or discretionary. Mandatory lane changes correspond to the essential statement in the model by Hidas (2002), that is lane changes which are necessary in order to pass a lane blockage, reach an intended turn, avoid restricted lanes, etc. The term discretionary lane changes refers to lane changes made in order to gain speed advantages or avoid lanes close to on-ramps, etc. The discretionary lane changes can be compared to the desirable path in the structure by Hidas (2002). In both structures, the differences between mandatory and discretionary lane changes lies in the gap-acceptance behavior and the possibility that vehicles in the target lane may renounce their right of way in favor of a vehicle performing a mandatory lane change.

Toledo et al. (2005) pointed out that in principle, all lane-changing models only consider lane changes to an adjacent lane. The models evaluate whether the driver should change to an adjacent lane or stay in the current one. Thus, most models lack an explicit tactical choice with regard to their lane-changing behavior. Toledo et al. (2005) presented a model in which a driver chooses a target lane, not necessarily an adjacent lane, that is most beneficial for him/her. In this way the driver will strive to reach the most beneficial lane, sometimes which may need several lane changes to achieve. This model follows in principle, the basic decision structure proposed in Gipps (1986). However, the necessary and desired steps are merged into one target lane choice. This is possible since lanes that are less convenient, for example due to the next turning movement, will be less beneficial for the driver. In Toledo et al. (2005) a utility function is used to calculate the benefit of each lane and a discrete choice model is used to model the lane choice. This model will be described in more detail later on in this section when a driver's desire to change lane is discussed.

El Hadouaj et al. (2000) proposed a similar model as Toledo et al. (2005) in which drivers not only base their lane-changing decisions on the traffic situation in their own and the adjacent lanes, but instead, the decision is based on the situation in all lanes. The model considers not only the traffic situation in the driver's vicinity but also the situation further away. The area around a driver is divided into several areas, behind, in front and beside the driver. Lane changes are then based on the benefits in the different areas. This benefit is calculated through an assessment function that considers the speed and stability in the different areas around the driver. The model is based on psychological driver behavior studies performed at the French research institute INRETS and the Driving Psychology Laboratory (LPC), (El Hadouaj et al., 2000).

The urgency or necessity to change lane depends on the distance to an obstacle or an intended turn. This can be modeled in several different ways. Gipps (1986) used three different areas, close, middle distance, and remote, defined by two time distances to the intended turn or obstacle, see Figure 2.7 for an example.

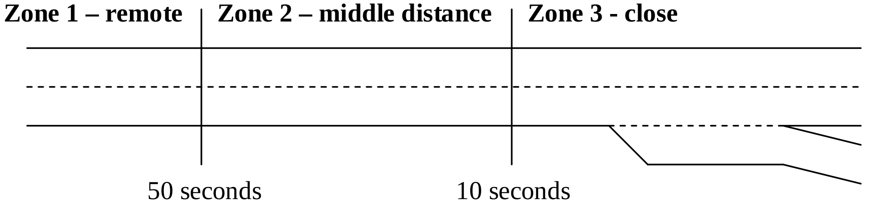

Figure 2.7: The three different lane-changing zones proposed by Gipps (1986).

After trials, suitable values of 10 s and 50 s for the two time distances were proposed, (Gipps, 1986). This zone division has later been adopted and further developed by Hidas (2002) and Barceló and Casas (2002). A similar zone division has also been presented in Wright (2000). The basic principle is that a vehicle–driver unit in zone 1 is considered far away from its intended turning or from any obstacle, and changes lane if it desires. A vehicle–driver unit in zone 2 is closer to the intended turn and is assumed to be a little bit more restrictive in its lane changing decisions. Vehicle–driver units in zone 2 seldom or never change to lanes further away from the lane suitable for the next turning. In zone 3, all lane-changing decisions exclusively focus on getting to the suitable lane for the next turning. A vehicle in zone 3 that is not traveling in the lane suitable for its intended turning will become more aggressive and start to accept smaller gaps. This will be discussed later under the sub-section about gap-acceptance.

Yang (1997) proposed another way of modeling the urgency of a driver's need to change lane. Instead of using different zones, vehicles are tagged to mandatory state according to a probability function. In Yang (1997) an exponential probability function was used, in which the probability of tagging a vehicle as mandatory mainly depends on the distance to the intended turning or obstacle. This strategy has also been adopted by Wright (2000), but the exponential distribution was replaced by a linear relationship in order to save computational time.

Modeling drivers' desire to change lane

A driver's desire to change lane can be modeled in several ways, for example by using

- A car-following model
- A pressure function
- Discrete choice theory
- Fuzzy logic

In the model proposed by Gipps (1986), a car-following model, more precisely the model presented by Gipps (1981) (see Equation 2.3 and 2.4), was used to calculate which lane has the least effect on the driver's speed. The model also accounted for the presence of heavy vehicles in the different lanes by calculating the effect of the next heavy vehicle in each lane as if they were the just preceding vehicles in respective lane. The model in Gipps (1986) also includes a relative speed condition for deciding if a driver is willing to change lane. Gipps (1986) used values of 1 m/s and -0.1 m/s for lane changes towards the center and the curb, respectively, i. e. vehicles do not intend to change lane to the left if they are not driving 1 m/s faster than the preceding vehicle in the current lane.

The lane-changing model MOBIL (Minimizing Overall Braking Induced by Lane change) by Kesting et al. (2007a) also utilizes a car-following model, more precisely the IDM (Treiber et al., 2000) (see Equation 2.5), for calculating the utility or gain of driving in the different lanes. The IDM is used to compare the acceleration that the driver can use in the different lanes and how a lane change will affect the acceleration of the current and the presumptive new follower, i. e. the nearest vehicle behind the driver in the evaluated lane.

Kosonen (1999) has proposed an approach similar to using a car-following model to evaluate which lane that is preferable. Instead of using the car-following model, a pressure function was defined. This pressure function is an approximation of the potential deceleration rate caused by the leading vehicle and it is defined as

$$P = \frac{\left(v^{des} - v^{obs}\right)^2}{2 \cdot s}, \tag{2.8}$$

where v^{des} is the desired speed, v^{obs} is the obstacle's speed, and s is the relative distance. The pressure function is used to model drivers lane-changing decisions according to the logic described in Figure 2.8. The logic is combined with a minimum time before a new lane change is allowed. This is done in order to avoid to frequent lane-changing behavior. For lane changes to the left, the rule is also combined with a minimum difference in desired speed condition, similar to that used by Gipps (1986).

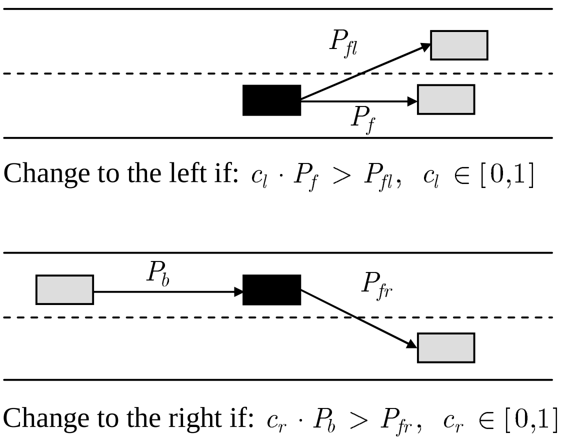

Figure 2.8: The lane-changing logic proposed by Kosonen (1999). P is calculated according to Equation 2.8. The parameters c_l and c_r are calibration parameters, which controls the driver's willingness to change to the left and right, respectively.

Toledo et al. (2005) presented a model in which the necessary and the desired steps are merged together into a target lane model. The model is based on discrete choice theory and calculates the benefit of each lane by using the utility function

$$U_{int}^{TL} = \beta_i^{TL} X_{int}^{TL} + \alpha_i^{TL} v_n + \varepsilon_{int}^{TL} \quad \forall i \in \{\text{lane}\,1, \text{lane}\,2, \ldots\}\,, \tag{2.9}$$

where U_{int}^{TL} is the utility of lane i as target lane for driver n at time t. The vector X_{int}^{TL} consists of the explanatory variables that affect the utility of lane i, for example lane density and speed conditions, speed difference to the preceding vehicle etc. The variable v_n is an individual-specific latent variable assumed to follow some distribution in the population. β_i^{TL} and α_i^{TL} are the corresponding vectors of parameters for X_{int}^{TL} and v_n, respectively. In Toledo et al. (2005), the random terms ε_{int}^{TL} are assumed to be independently identically Gumbel distributed. This leads to that the probability of choosing lane i being given by the multinomial logit model

$$P\left(TL_{nt} = i \middle| v_n\right) = \frac{\exp\left(V_{int}^{TL} \middle| v_n\right)}{\sum\limits_{j \in TL} \exp\left(V_{int}^{TL} \middle| v_n\right)} \qquad \forall i \in TL = \{\text{lane}\,1, \text{lane}\,2, \ldots\}, \tag{2.10}$$

where $V_{int}^{TL}\big| v_n$ are the conditional systematic utilities of the alternative target lanes. Toledo et al. (2005) also present an estimation of the model parameters for a road section of I-395 Southbound in Arlington VA., USA.

Drivers' willingness or desire to change lane can also be modeled by using fuzzy logic techniques. Wu et al. (2000) describe a lane-changing model that use the fuzzy sets in Table 2.1 and 2.2 for modeling lane changes to the left (LCO) and right (LCN), respectively.

Table 2.1: Fuzzy sets terms for lane-changing decisions to the off-side/left, (Wu et al., 2000).

Overtaking benefit	Opportunity	Intention of LCO
High	Good	High
Medium	Moderate	Medium
Low	Bad	Low

Table 2.2: Fuzzy sets terms for lane-changing decisions to the near-side/right, (Wu et al., 2000).

Pressure from Rear	Gap satisfaction	Intention of LCN
High	High	High
Medium	Medium	Medium
Low	Low	Low

A typical lane-changing rule for changing to the left according to Wu et al. (2000) is:

If Overtaking Benefit is **High** and Opportunity is **Good** then Intention of LCO is **High**

In Wu et al. (2000) triangular membership functions were used for all fuzzy sets. The sets were calibrated to freeway data and quite good agreements of lane-changing rates and lane occupancies were obtained. However, the paper does not include any information about the best-fit parameter values.

Gap-acceptance

Even if a lane change is desirable and perhaps also necessary it might not be possible or safe to perform it. In order to evaluate whether a driver safely can change lane, some kind of gap-acceptance model is generally used. A driver has to decide whether the gap between two subsequent vehicles in the target lane is large enough to perform a safe lane change. This decision-making is generally modeled as evaluating the available lead and lag gaps, see Figure 2.9.

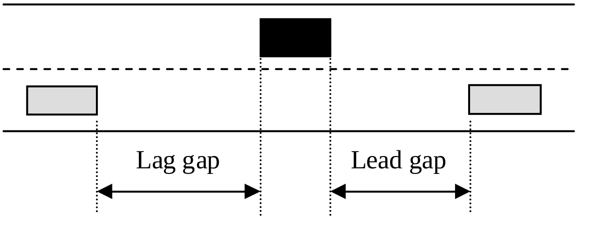

Figure 2.9: Illustration of lead and lag gaps in lane-changing situations.

The common approach is to define a critical gap that determines which gaps drivers accept and which they not accept. In reality, this critical gap varies both among drivers and over time. It also varies between lane changes to the right and to the left and between lead and lag gaps. However, critical gaps are difficult to measure, in principle, only accepted gaps and to some extent rejected gaps can be measured. Thus, it is difficult to measure how critical gaps, for example, vary among drivers and over time for a specific driver. One approach is therefore to use one critical gap for all drivers, but different critical values for lead and lag gaps and for changes to the right and left. This approach is used in the model by Kosonen (1999) for instance. Even though critical gaps are difficult to measure some models have used the approach of using critical gap distributions. For instance, in Ahmed (1999) and later in Toledo et al. (2005) critical gaps are assumed to follow log-normal distributions.

The models by Gipps (1986), Hidas (2002), and Kesting et al. (2007a) are based on a similar but to some extent different approach. Instead of looking at the available and critical gap, a "critical" (or rather an acceptable) deceleration rate is used. In Gipps (1986) a car-following model, namely the model in Gipps (1981), was used to calculate the deceleration rate required to change lane into the available gap. This deceleration rate was compared to an acceptable deceleration rate. If the deceleration rate required was unacceptable to the driver, the lane change is not feasible. For lead gaps, the car-following model was applied on the subject vehicle with the preceding vehicle in the target lane as leader. For lag gaps, the car-following model was applied on the lag vehicle in the target lane with the subject vehicle as the leader vehicle.

The gap-acceptance model also has an important role in the modeling of the urgency of a lane change. When getting closer to an obstacle or an intended turn, i. e. when in zone 2 or 3 in Figure 2.7, it is more urgent for drivers to get to the target lane. In these situations, drivers generally accept smaller gaps, or following the approach in Gipps (1986), Hidas (2002), and Kesting et al. (2007a) higher deceleration rates. In Yang and Koutsopoulos (1996) this is modeled by a linear decrease of the critical gap from a standard critical value to a minimum value, which is attained at some critical point for the lane change. The models by Gipps (1986) and Hidas (2002) use a similar approach, where the acceptable deceleration rate increases linearly with the distance left to the intended turn.

2.3.3 Overtaking models

On roads without barriers between oncoming traffic, it is not enough to consider only the actual lane change to the oncoming lane. Instead, a model that considers the whole overtaking process is required. As in the case of lane-changing decisions, overtaking decisions can be divided into several sub-models or questions. For instance, an overtaking decision can be the answer to the following questions, (Brodin and Carlsson, 1986):

- Is the overtaking distance free from overtaking restrictions?
- Is the available gap long enough?
- Is the vehicle–driver unit able to perform the overtaking?

- Is the driver willing to start an overtaking with the available gap?

Drivers in general do not start overtaking when there are overtaking restrictions. However, not all drivers behave legally in this matter and depending on the proportion of lawbreakers, the model may have to account for vehicles that do not obey the present overtaking restrictions. Generally, drivers do not start overtaking if the available gap is shorter than the estimated overtaking distance. Another constraint for overtaking can be the performance of the overtaking vehicle, for example maximum acceleration or speed. Even though a vehicle might be able to conduct an overtaking maneuver, the driver will probably not execute it if the overtaking distance is unreasonable long, for example more than one kilometer. Even if the driver is able to overtake, it is not sure that he/she is willing to do so in the available overtaking gap. Drivers' willingness to accept an overtaking opportunity vary. One driver may reject a gap when another accepts the same gap, and one driver that accepts a gap at one point in time can reject an similar gap at another point in time.

A driver's willingness to accept an available gap is generally modeled with some kind of gap-acceptance model. As in the lane-changing case, the most simple way to model this is to use one common critical gap for all drivers. This approach is used for example in the model by Ahmad and Papelis (2000). However, drivers' willingness to accept an available gap varies both among drivers and over time for a specific driver. Therefore, the modeling of overtaking behavior requires more advanced gap-acceptance models than in the lane changing case. The overtaking models are commonly based on an assumption of either consistent or inconsistent driver behavior. In an inconsistent model, drivers' overtaking decisions do not depend on their previous overtaking decisions, i. e. every overtaking decision is made independently. The opposite is a consistent driver model, which instead assumes that all variability in gap-acceptance are related to the variability among drivers. That is, each driver is assumed to have a critical gap, such that the driver would accept gaps that are longer and reject gaps that are shorter than the his/her critical gap at all times. According to McLean (1989), there are at least two studies which state that the variance over time for a specific driver is larger than the variance among drivers with respect to overtaking decisions. In the first study (Bottom and Ashworth, 1978), it was found that more than 85 % of the total variance in gap-acceptance is an over time variation for a specific driver. The conclusion was that an inconsistent model would be a better representation of real overtaking gap-acceptance behavior than a consistent model, (McLean, 1989). The high over time variance is however questioned in McLean (1989), which means that the result could have been affected by the experimental design. On the other hand, the second study (Daganzo, 1981) also found that the over-time-driver-variance is larger than the among-driver-variance. Daganzo (1981) found that about 65 % of the total variance is over-time-driver-variance, which also supports the use of an inconsistent model. The best way to model gap-acceptance is of course to use a model that includes both over-time and among-driver-variance. However, a big problem, which is pointed out in Daganzo (1981), is that it is difficult to estimate appropriate distributions for such an approach, (McLean, 1989).

Gap-acceptance behavior does not only vary among drivers and over time, but it also varies depending, for example, on type of overtaking and the speed of the overtaken vehicle. McLean (1989) includes a presentation of the following five basic descriptors, which are also used in the work of Brodin and Carlsson (1986), for classifying an overtaking decision:

- Type of overtaken vehicle: A driver behaves differently depending on the type of vehicle to overtake, a driver can for example be expected to be more willing to overtake a truck than a car.

- Speed of the overtaken vehicle: The speed affects both the required overtaking distance and the probability of accepting an available gap.

- Type of overtaking vehicle: Overtaking behavior can be expected to differ between for example high performance cars and low performance trucks.

- Type of overtaking: If a vehicle has the possibility to conduct a flying overtaking, i. e. start to overtake when it catches up with a preceding vehicle, a driver behaves differently compared to situations where the driver first has to accelerate in order to conduct the overtaking maneuver.

- Type of gap limitation: Drivers' willingness to start overtaking is dependent on whether the available gap is limited by an oncoming vehicle or a natural vision obstruction. For instance, drivers are generally more willing to accept a gap limited by a natural vision obstruction than similar gaps limited by oncoming vehicles.

Using these descriptors, the probability of accepting a certain overtaking gap does not only depend on the length of the gap but also on the other descriptors. This leads to one probability function for each combination of descriptors. Quite a large data bank is required to estimate all these functions. Some studies and estimations of the overtaking probability have been conducted, see McLean (1989) for an overview. Figure 2.10 shows examples of probability functions for overtaking situations with an oncoming vehicle in sight. The functions are estimations for Swedish roads which are presented in Carlsson (1993). As can be seen in the figure, the overtaking probability for a flying overtaking was estimated to be higher than the probability for an accelerated overtaking with the same available gap.

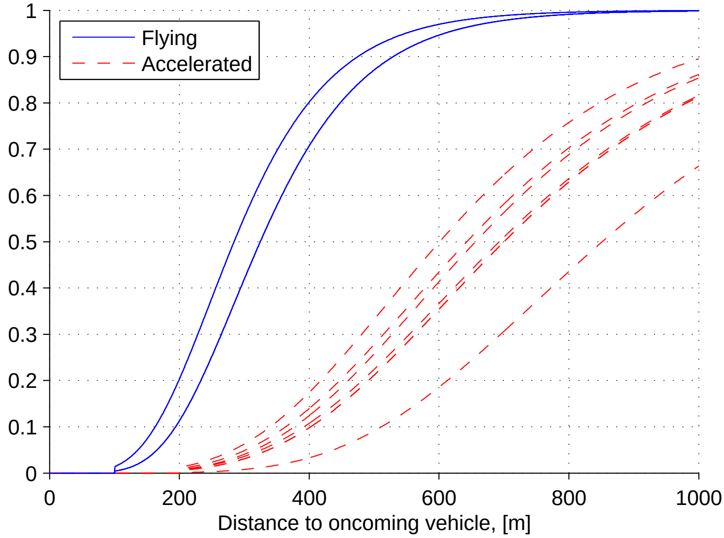

Figure 2.10: Probability functions for overtaking decisions, combinations of descriptors with oncoming vehicle in sight, (Carlsson, 1993).

2.3.4 Speed adaptation models

Most traffic simulation models use some desired speed parameter to describe drivers' preferred driving speed. Generally, a normal distribution is used to model the variation in desired speed among drivers. However, a driver's desired speed is not constant. The desired speed varies depending on the current road design. On urban roads or freeways, a driver's desired speed mainly depends on the speed limit. However, on rural roads, like two-lane highways, the desired speed also varies with road width and horizontal curvature for example. To model that a driver's desired speed varies depending on the road design, some kind of speed adaptation model is required.

One possible modeling approach for roads where the speed limit is the only or the main determining factor of the desired speed is to assign each driver a desired speed for each possible speed limit. This gives a flexible model which can catch the variation in desired speed with regard to speed limits. A similar but little less flexible way, is to define a relative desired speed distribution. A driver's desired speed is then calculated by adding the assigned relative speed to the speed limit. This approach was used by Yang (1997) and Ahmed (1999) for example. In Barceló and Casas (2002) a similar approach was used, whereby drivers' desired speeds were deduced by multiplying the speed limit with an individual speed acceptance parameter. The speed acceptance parameter follows a normal distribution among drivers.

On rural roads, drivers' desired speed is also affected by the road geometry. In addition to the speed limit, the desired speed can for instance depend on the road width and the horizontal curvature. Brodin and Carlsson (1986) include a presentation of a speed adaptation model in which a driver's desired speed is affected by the speed limit, the road width, and the horizontal curvature. In this model, each driver is assigned a basic desired speed, which is adjusted to a desired speed for each road section. This is done by reducing the median speed according to three sub-models, one for each of the above mentioned factors. However, in this model, a driver's desired speed is not only the result of a shift of the distribution curve, which is the case in the models by Yang (1997), Ahmed (1999), and Barceló and Casas (2002). In the model by Brodin and Carlsson (1986), the desired speed distribution curve is also rotated around its median, see the example in Figure 2.11. This makes it possible to tune the model in such a way that drivers with high desired speeds are more affected by a speed limit than drivers with low desired speeds. How much the curve is rotated depends on the factors that addressed the reduction. Different rotation parameters are used for adaptation caused by the road width, the speed limit, and the horizontal curvature.

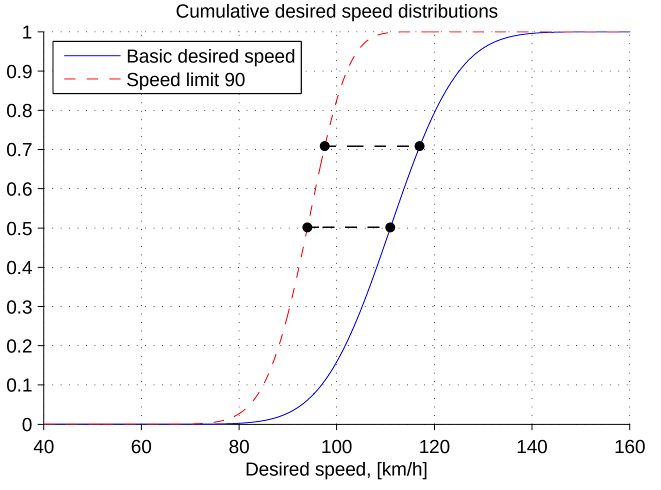

Figure 2.11: Example of shift and rotation of a desired speed distribution.

3 Surrounding vehicles in driving simulators

It is well known that the surrounding road and traffic environment influences drivers and their behavior. For example, the road environment affects drivers' desired speed, lateral positioning, and overtaking behavior. Another main influence factor is of course other road users. Other vehicles certainly affect a driver's travel speed and travel time, but they also influence a driver's awareness. In order to be a valid representation of real driving, driving simulators need to present a realistic visualization of the driver's environment. Thus, the road and traffic environment should affect drivers in the same way as in reality. Realism is a quite abstract word and it is not obvious what is meant with a realistic simulation of vehicles. In Bailey et al. (1999) and later in Wright (2000) the following requirements for a realistic traffic behavior are outlined:

- Intelligence: The individual vehicles must be able to drive through a network in a way corresponding to a possible human being.
- Unpredictability: The simulated traffic should be able to mimic the unpredictability of real traffic, e. g. dealing with the variation in driver behavior among drivers and also over time for a specific driver.
- Virtual personalities: This third category can be seen as a further specification of the unpredictability requirement. Wright (2000) suggests that a realistic traffic environment should include various driver types such as normal, fatigued, aggressive and drunk.

Excluding the requirement on virtual personalities, a microscopic traffic simulation model should be able to reproduce realistic driver behavior including the variation in driver behavior both among drivers and over time for a specific driver. This implies not only intelligence and unpredictability but also unintelligence and predictability. It is equally important that the simulator drivers feel that they can predict other drivers' actions to the same extent as in reality and that other drivers act unintelligently to the same extent as in reality. In the end, it is important that the driving simulator and its sub-models induce realistic subject driving behavior at operational, tactical and strategical level (using the definitions of operational, tactical, and strategical level presented in Michon (1985)).

The need for a realistic representation of the traffic environment sometimes stands in contradiction to the design of useful driving simulator experiments. To gain a deeper understanding of the background to this dilemma, this chapter starts with a presentation of driving simulator experiments and scenarios. Differences between traditional applications of traffic simulation and this application is discussed in Section 3.2. Section 3.3 includes a survey of common modeling approaches for the simulation of surrounding vehicles in driving simulators.

3.1 Driving simulator experiments

Driving simulators offer the possibility to conduct many different kinds of experiments. One of the strengths of driving simulator experiments is the possibility they provide to study situations or conditions that rarely occur in reality. It is also possible to study situations or conditions that are too risky or un-ethical to study in real traffic, for example fatigue or drunk drivers. Another strength is the possibility they provide for systematic variation of test parameters in order to distinguish differences or correlations between different variables. A driving simulator experiment is specified through an experimental design which may involve one or several scenarios which in turn, may contain one or several events.

3.1.1 Scenarios, events and experimental designs

A driving simulator scenario is a specification of the road and traffic environment along the road. This includes a specification of the road environment e. g. specification of road geometry, road surface, weather conditions, and surroundings such as trees and houses. A scenario must also include a specification of other road users and their actions. A scenario can be seen as a constellation of consecutive traffic situations or events, which starts when a certain condition is met and ends when another condition is met, (van Wolffelaar, 1999), or following the terminology used in Alloyer et al. (1997), a constellation of scenes. Alloyer et al. (1997) define a scene as a specification of: the area in which the scene will take place, which actors will be present, what is going to happen, and in which order things are going to happen.

Predefined events are often used in order to conduct accelerated testing. Some traffic situations or events occur seldom, and many simulator hours are thus required to study drivers' behavior in such situations if we should wait until they arise by themselves. One of the strengths of driving simulators is that it is possible to shorten the time between these situations. An example of an event, taken from Bolling et al. (2004), is a situation in which a bus is standing at a bus stop in a low complexity urban environment. Four seconds before the simulator driver reaches the bus stop, the bus switches on its left indicator and starts to pull out into the main road. When approaching the bus stop, the driver meets a quite high oncoming traffic flow, which makes it difficult to overtake the bus. If the driver does not yield for the bus, the bus will remain at the bus stop. But if the driver yields for the bus, the bus will accelerate up to a speed of 50 km/h and then stops at the next bus stop. During the drive to the next bus stop, oncoming traffic flow is kept at a high level in order to prevent the subject from overtaking. To sum up, a scenario is a specification of the road environment and a number of events, including information about when and where the events will take place.

The experimental design for a driving simulator experiment includes the specification of how many participants should be involved in the experiment and which scenarios they should drive. The experimental design also includes the specification of which independent variables to use. The independent variables can for example be an Advanced Driver Assistance System (ADAS), the friction on the road, or road type. It is also necessary to specify how the independent variables should be varied among the participants. One possibility is to use a between group design, in which an independent variable is varied between different groups of participants. A possible between group design for the study of an ADAS is to let half of the participants drive with an ADAS letting the other half be a control group, i. e. driving the same scenario without the ADAS. Another possibility is to use a within group design, which implies that all participants drive under all premises, for example both with and without an ADAS. It is also possible to use mixed designs, for example a between group design for one independent variable and a within group design for another independent variable.

3.1.2 Design issues

Designing useful driving simulator experiments and scenarios which work well is not trivial. There are few written references on aspects to be considered when designing driving simulator experiments and scenarios. The design is often based on the massive experience at the different driving simulator sites. It seems difficult to present general rules or recommendations on how to design experiments and scenarios. One reason is that the design of driving simulator experiments and scenarios depends to a large extent on the application. However, some attempts have been made to define common methodologies for driving simulator experiments. Two examples are the European HASTE-project (Östlund et al., 2004) and the European ADVISOR-project (Nilsson et al., 2002), in which common methodologies for studying assessments of IVIS and ADAS, respectively, were defined and tested.

Driving behavior experiments are used to assess some hypotheses on how drivers behave in some specific driving context. Driving behavior experiments follow traditional experimental design. In order to increase the knowledge of some particular scientific question, a specific measurable instance of this question is studied. As in all types of experiments, the experimenter wants to limit the number of confounding variables in order to avoid that an observed change in any of the dependent variables being due to something other than a change in one of the independent variables. Due to the complex and dynamic nature of traffic, limiting confounding variables is difficult and consequently is a key issue in the design of driving behavior experiments. One way to limit confounding variables is to limit the variation in test conditions between subjects by strictly controlling the scenarios and the associated events. This is commonly done by strictly controlling the actions and the behavior of the surrounding vehicles.

In order to get usable results from a driving simulator experiment, the number of independent variables is normally kept low, at most two or three. Using too many independent variables can make it difficult to distinguish cause and effects. It is better to conduct several experiments. For example, instead of conducting one experiment with the variables: mobile phone or not, handheld or handsfree, and rural or urban environment, it is probably better to conduct several experiments, for example one experiment that investigates the effects of using a handheld or a handsfree phone or not using any phone at all, and other experiments that look at the effects of using mobile phones or not in different road environments.

3.2 Differences compared to traditional applications of traffic simulation

One approach for the simulation of the surrounding vehicles is to use available commercial microscopic traffic simulation tools. The recent development in software interfaces, so called APIs, for the commercial traffic simulation models have made it possible to integrate these models and driving simulators. Some trials using software packages such as AIMSUN (Barceló and Casas, 2002; TSS, 2008) and VISSIM (PTV, 2008) to simulate surrounding vehicles in driving simulators have been conducted; see for example Bang and Moen (2004), Ciuffo et al. (2007) and Jenkins (2004). The approach of using more traditional microscopic traffic simulation for the simulation of surrounding vehicles has also been utilized in Kuwahara and Sarvi (2004). However, the traditional traffic simulation models cannot directly be used to simulate surrounding vehicles in a driving simulator. There are a couple of factors that make the simulation of surrounding traffic for a driving simulator different from the common use of traffic simulation.

Firstly, most applications of traffic simulation imply simulation of all vehicles, while this application includes a non-simulated vehicle which instead is driven by the human driver in the driving simulator. Here, the interesting output of the traffic simulation is the behavior of the surrounding vehicles. This implies higher demands on the microscopic behavioral modeling compared to in the case of more common applications of traffic simulation, like quality of service evaluations. Traffic simulation is usually used to generate aggregated macroscopic output data such as average travel times, speed, and queue lengths. In order to generate correct results at a macro level, a traffic simulation model must of course have a reasonably good agreement at the micro level, e. g. reasonably realistic behavioral models. Traffic simulation models often include assumptions and simplifications that do not affect the model validity at the macro level but that sometimes affect the validity at the micro level. One typical example is the modeling of lane-changing movements. In many simulation models, vehicles change lanes instantaneously. This is not realistic from a micro-perspective but does not affect macro measurements considerably. When simulating surrounding vehicles for a driving simulator, this is more important. It is also important that the behavior of the surrounding vehicles is safe, in the sense that the simulator driver should not be exposed to any critical situations or events that are not specified in the scenario or caused by the simulator driver himself.

Secondly, in some driving simulator experiments, the participants are exposed to one or several situations or events that may be critical. This can for example be an animal that runs out to the road or surrounding vehicles that suddenly brake or make other maneuvers. The situations and events in a driving simulator scenario often involve other vehicles. When exposing the driver to the specified situation, these surrounding vehicles should be located at specific positions and travel at specific speeds, in order to ensure reproducibility. The basic idea is that at certain points in time or space, a predetermined situation or event will occur. When the event or situation occurs, the vehicles' types, positions, and speeds must agree with those specified in the scenario. Hence, a big differences compared to traditional applications is that we sometimes want the simulation model to create a pre-specified situation, i. e. controlling the output of the simulation. The traffic simulation models of today have to be extended to be able to create such pre-specified situations.

Thirdly, applications of traffic simulation normally deal with the simulation of a geographically limited study area. The size of this area can vary between one intersection up to parts of a city, freeway or highway. Vehicles are normally generated and removed to and from the model at specified geographical origins and destinations in the simulated road network. The same methodology can be used for simulating surrounding vehicles in a driving simulator. However, when simulating traffic for a driving simulator, the area of interest is the closest neighborhood of the driving simulator vehicle. It is in principle enough to only simulate vehicles within this area. However, the edges of this area will move with the speed of the simulator vehicle, which implies that the places at which vehicles should be generated also move with the speed of the simulator vehicle. Using the ordinary generation methodology, both fast and slow vehicles will be generated both behind and in front of the simulator vehicle. However, vehicles that are generated behind the simulator vehicle and which drive slower than the driving simulator vehicle will never catch up with either the simulator vehicle or the back edge of the window. Therefore it is necessary to use an algorithm that only generates faster vehicles behind the simulator vehicle and slower vehicles in front, but that still generates the correct frequency of fast and slow vehicles, respectively. The approach of only simulating vehicles within a certain window around the simulator vehicle has been used for example in the models presented in Espié (1995) and Bonakdarian et al. (1998).

It may not be necessary to use microscopic traffic simulation to simulate all the vehicles around the simulator vehicle. Vehicles further away from the simulator vehicle can be simulated using methods that are less time consuming, for instance using mesoscopic or macroscopic approaches. In the model presented in Espié (1995) the vehicles further away are simulated according to a macroscopic model. The approach of only using microscopic simulation to simulate the most interesting region has also been tested within more common applications of traffic simulation. See Burghout (2004) for an overview of the research area of combining micro-, meso-, and macro simulation models.

3.3 Common modeling approaches

Some research has been carried out within the area of simulating surrounding vehicles in driving simulators. As seen in the previous section, a couple of models (Bonakdarian et al., 1998; Espié, 1995) have used the approach of only simulating vehicles in the closest neighborhood of the simulator vehicle.

Surrounding vehicles in driving simulators have traditionally been modeled using non-autonomous deterministic models. The main reason for this is the need for limiting confounding variables, see the discussion in Section 3.1.2. The aim is to keep both the variation in test conditions and the number of participants required as low as possible. This is commonly achieved by strictly specifying the behavior of the surrounding vehicles. The behavior of the surrounding vehicles is often connected to the actions of the simulator driver. It is for example common to define the behavior of the surrounding vehicles in terms of places at which they should meet, catch-up with, or be caught up by the simulator vehicle. In this way, the scenario programmer knows that each subject will meet, catch-up, or be caught up with the same number of vehicles and at the same places. This approach is useful for creating reproducible scenarios, but it often results in the behavior of the surrounding vehicles differing from what one could expect from real drivers. The realism in the surrounding vehicles' behavior can be increased by using autonomous surrounding vehicles. Autonomous vehicles do not treat the simulator vehicle differently to other vehicles on the road. The autonomous vehicles act according to their defined behavioral models (see examples in Section 2.3) and try to achieve their own goals, like driving at their desired speed or keeping a preferred distance to preceding vehicles. This leads to the fact that the traffic situation around a subject is dependent on the subject's actions, leading to the traffic conditions differing between subjects, at least at a microscopic level. The test conditions will still be comparable at a more aggregated level, i. e. the participants will experience the same traffic conditions, with regard to intensity and composition, etc. Whether equal conditions at a higher level are sufficient or not varies between different driving simulator experiments. Equal conditions at a micro level can be important in some driving simulator experiments and less crucial in others. The difficult task is to find a workable compromise between realism and reproducibility, i. e. to design experiments so that they generate both valid and useful results.

Most models developed for the simulation of autonomous surrounding vehicles have adopted the framework by Michon (1985) for describing the driving task. This framework divides the driving task into three levels: Strategical, Tactical, and Operational, see Figure 3.1.

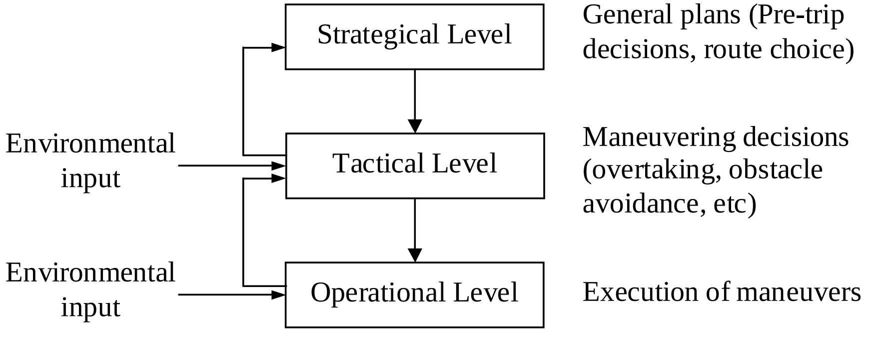

Figure 3.1: The hierarchical structure for the driving task presented in Michon (1985).

The strategical level includes "long-term" planning decisions such as route or modal choices. The tactical level consists of maneuvering decisions like lane-changing, overtaking, obstacle avoidance, etc. The maneuvering decision is of course affected by the decisions at the strategic level and vice versa, represented by the arrows in the figure. The decisions at the tactical level are also affected by different environmental inputs such as road design and weather and road conditions. The lowest level is the operational level at which the maneuver decisions at the tactical level are executed, for example by braking or steering. The framework proposed in Michon (1985) has been adopted for example in Champion et al. (1999) and Wright et al. (2002).

Most of the developed models focus on freeways or urban roads, see for example Ahmad and Papelis (2001), Al-Shihabi and Mourant (2002), Champion et al. (1999, 2002), van Wolffelaar (1999), and Wright (2000). Little effort has been put into the modeling of rural highways with oncoming traffic. According to Champion et al. (1999) the SCANeR©II software, developed at Renault, can be used to simulate vehicles on any road type. Unfortunately, the reference does not describe the model used for rural roads. Ahmad and Papelis (2000) state that the traffic simulation model used in the National Advanced Driving Simulator (NADS) is able to simulate vehicles on rural roads. This model includes a simple overtaking model, which for instance uses one critical gap for all drivers. The validity of such an approach can be questioned, see the discussion in Section 2.3.3. It is also assumed that the overtaking vehicle obeys the speed limit during the whole overtaking process, which is not always the case in the real world.

There has been little or no focus on algorithms for generating realistic traffic streams. If only simulating vehicles in a limited area around a simulator vehicle, the generation of new vehicles cannot be done in the same way as in traditional traffic simulation models, as discussed in Section 3.2. Another important vehicle generation issue concerns the generation of vehicle platoons on rural highways with oncoming traffic. Due to limited overtaking possibilities, vehicles often end up in platoons on these roads. A simulation model for this road type should therefore generate vehicle platoons rather than only generating vehicles.

Research within the area of simulating vehicles for driving simulators has focused to a large extent on decision making modeling concepts or techniques. Three commonly used techniques are Rule based models, State Machines, and Mathematical or probabilistic models. Other techniques used are for instance the eco-resolution principle (El Hadouaj and Espié, 2002; Espié, 1995) and combinations of fuzzy logic and rule-based or probabilistic techniques. Some models use the same decision-making technique for all kinds of decisions while other models use different techniques for different decisions, for example a rule based approach for lane-changing and a mathematical approach for car-following. In the next sections some of the above-mentioned techniques will be described in further detail.

3.3.1 Rule based models

Rule based models are also known as knowledge-based systems, expert systems or production systems. They use a set of rules of the form ”if (condition) then (action)” to model, for example, driver behavior (Wright, 2000). Drivers' behavior is deduced by running through the set of rules. If a rule is true, the corresponding action is executed. The following three rules could be a possible subset of rules for modeling free driving behavior.

1. IF (speed < desired speed) THEN (increase speed)
2. IF (speed > desired speed) THEN (decrease speed)
3. IF (new speed limit) THEN (change desired speed)

For instance, if a driver is driving at a lower speed than he/she desires, he/she accelerates in order to reach the desired speed. This type of model is deterministic and will lead to every driver reacting in the same way. In reality, driving behavior varies both among drivers and over time. To overcome this, a probability value can be added to each rule (Wright, 2000). The probability value represents the probability that the stated action will be executed if the condition is true.

In many cases the actions to be executed will be in conflict with each other. If for example the following rule is added:

4. IF (speed > front vehicle speed) THEN (decelerate to front vehicle speed)

a common conflict will be that the driver is driving slower than his/her desired speed but faster than the front vehicle. In these cases, a conflict resolution criteria is needed. For speed control, a most restrictive choice is most commonly used, i. e. the lowest speed is chosen. Another way to solve this is to give the rules different priorities, for an example see Espié et al. (2008). A third way is to make use of the rules' probability values, for example by a weighted average of the outcome of the different rules. However, this can imply unintelligent speed choices for example.

The main advantage of rule-based systems is that they are simple and flexible. A rule-based model can easily be modified by adding, changing, or deleting rules. However, modeling advanced behaviors often requires a great number of rules, which can make rule-based models hard to visualize and debug (Wright, 2000). Michon (1985) includes a simple estimation of how many rules are needed to model the complete driving task. Such a model would then model everything from gear shifting to route choice and would need between 10 000 and 50 000 rules.

Rule based approaches have been used for example in Salvucci et al. (2001) and van Wolffelaar (1999). It is quite common to combine the rule based approach with fuzzy logic, which results in a set of fuzzy if-then rules, see Section 2.3.1 for an example of a car-following model based on fuzzy logic. Such an approach has been proposed in Al-Shihabi and Mourant (2002) for instance.

3.3.2 State machines

State machine models are based on the idea that a system can be represented by a set of states. The system can change between the different states but there can only be one active state. A state can have one or several possible next states, depending on the structure of the modeled system. Figure 3.2a illustrates a simple state machine for a driver's speed control behavior. The system includes 4 states: Free driving, speed up, slow down, and stopped. The system changes from one state to another if the corresponding transition conditions are fulfilled. Thus, state changes follow deterministically from evaluating the transition conditions from the present state (Wright, 2000).

The state machines' single-minded focus and sequential logic make them difficult to use for modeling systems requiring simultaneous attention and actions (Cremer et al., 1995). Thus, state machines are not very suitable for modeling complex systems like driver behavior. To overcome these drawbacks Cremer et al. (1995) extended the state machine models to also include hierarchy, concurrency and communication between states. This enhanced type of state machines is called Hierarchical Concurrent State Machines or HCSMs. In HCSMs the distinction between states and state machines is dropped. Instead of containing states, HCSMs contain multiple, concurrently executing child state machines (Cremer et al., 1995). For example an HCSM for car driving could include one child HCSM for speed control and one for steering, as illustrated in Figure 3.2b. A useful model for driving behavior must in the end include several more child HCSMs, for example for lane-changing, intersection navigation, overtaking, oncoming avoidance, etc. The introduction of the concurrency characteristic makes it possible to have several active states simultaneously. This also leads to the fact that concurrent states can generate conflicting outputs. Thus, as for more advanced rule-based systems high-quality conflict resolution principles are needed to solve the different conflicts. In a hierarchical state machine structure, conflict resolution is only necessary at the lowest child HCSM level. At higher "parent" HCSM levels, conflicts are simply assumed to be solved at the lower child HCSM level. HCSM has been used for example in the autonomous driver behavioral models utilized in the simulators HANK (Cremer et al., 1997) and NADS (Ahmad and Papelis, 2001).

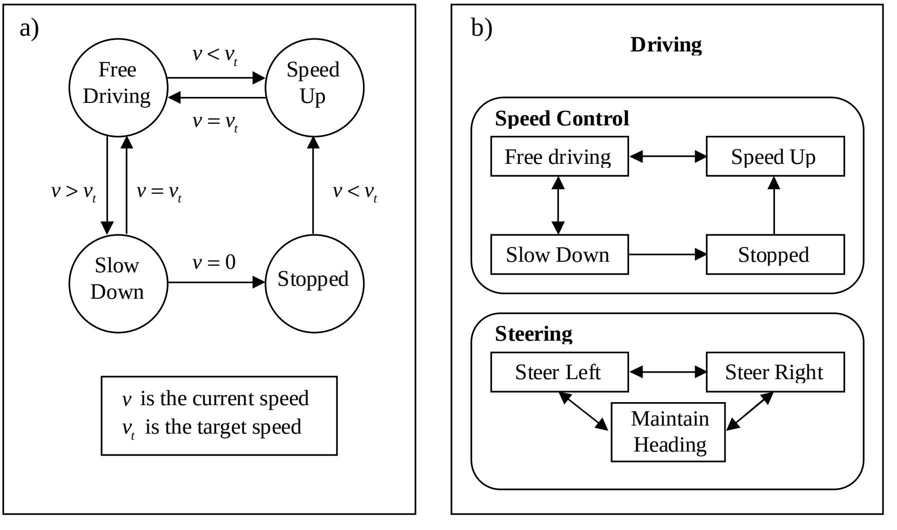

Figure 3.2: (Source: Wright, 2000)
a) Illustration of a state machine for speed control
b) Illustration of a hierarchical concurrent state machine for speed and steering control

3.3.3 The eco-resolution principle

Researchers at the French research institute INRETS have developed a model called ARCHISIM that can run as a traditional traffic simulation model or host a driving simulator (El Hadouaj and Espié, 2002; Espié, 1995; Espié et al., 1995). This model is based on what the authors call an eco-resolution principle. The principle states that any traffic situation is the result of the behavior of individual actors and the interactions between them. The model is based on a conceptual model of decision-making during driving based on psychological studies. The actor's behavior is based on a few fundamental principles. In the model, each driver tries to minimize the interaction with its environment, including the surrounding vehicles. In the case of lane driving, the following "law" was identified by the psychological studies.

Interaction + long duration + suppression possibility
$\Rightarrow$ interaction suppression
Interaction + short duration + suppression possibility
$\Rightarrow$ short term adaptation
Interaction + long duration + impossibility of suppression
$\Rightarrow$ long term adaptation

The driver first identifies possible interactions with other actors and with the infrastructure. The interactions can be both observed and anticipated interactions. The driver then estimates the duration of the interaction, meaning the time before the interaction will disappear. For example, a slower vehicle in front will lead to an interaction but the duration of the interaction can be estimated as short if the obstacle vehicle has turned on its indicator in order to leave the lane. The basic principle is to minimize interactions both in a short and a long-term perspective. In cases where the interaction duration is estimated to be short, the driver chooses to adapt to the situation and thereby stay in the current lane. In these short term adaptation periods, the drivers may keep a short time headway to the preceding vehicle. If the interaction duration is estimated to be long and there are no possibilities to suppress it in the near future, the driver will long term adapt to the situation by keeping a safe following headway to the leader. If it is possible to suppress the interaction, the driver will instead look at the possibilities of changing lane. In the example of lane driving on multi-lane roads, the ARCHISIM model uses the following decision rules for choosing lane:

```
While (not end-simulation)
Begin
   Information-deduction
   Estimation-of-interaction-duration

   If(duration = short) then
      Adaptation
   Else
      Calculate-gain-for-each-lane(area parameters)
      Chosen lane = lane with highest gain value
   End if
End
```

(Source: El Hadouaj and Espié, 2002)

The gain for each lane is based on the traffic conditions in the different areas around the driver, mainly the maximum speed in the area and the stability of the road users' behavior in the area, measured as the variation in speed between the actors in the area.

4 The present thesis

This thesis deals with questions and models related to surrounding vehicles in driving simulators. The main theme is the microscopic traffic simulation of autonomous surrounding vehicles as a tool for increasing realism and the range of applications of driving simulators. This chapter presents the objectives, contributions and delimitations of the work presented in this thesis. The chapter also includes summaries of the five papers included, together with a discussion of future research needs.

4.1 Objectives

This thesis has two main objectives. The first objective is to develop, implement, and validate a traffic simulation model that is able to generate and simulate realistic surrounding vehicles in a driving simulator. The model should be integrated and tested with a real driving simulator. It should both simulate the individual vehicle–driver units and the traffic stream of which they are a part of, in a realistically way. The simulated vehicle–driver units should behave realistic with regard to acceleration, lane-changing, and overtaking behavior, as well as with regard to speed choices. The vehicles should also appear in the traffic stream in such a way that headways, vehicle types, number of active and passive overtakings, etc. correspond to real traffic conditions.

The second objective is to develop a methodology and an algorithm for combining autonomous vehicles and controlled events in driving simulator scenarios. Such a combination can imply increased realism without losses in reproducibility. The aim is to make it possible to use autonomous vehicles for the simulation of surrounding vehicles between the situations at which the driver are exposed to predefined events. The algorithm should change the simulation of the surrounding vehicles in a non-conspicuous way from the autonomous mode into the predefined initial conditions for a specific event.

4.2 Contributions

The thesis makes the following contributions:

- A traffic simulation model for the simulation of autonomous surrounding vehicles in driving simulators is developed. The model is able to simulate traffic on freeways and on rural roads with oncoming traffic.
- A new technique for generating traffic on a moving area around a driving simulator is developed. The technique is applied both to freeways and rural roads with oncoming traffic.
- An enhanced version of the VTISim (Brodin and Carlsson, 1986) overtaking model is developed. The enhanced model includes new models for driver behavior during overtaking and at abortion of overtaking.
- An integration of the developed simulation model and the VTI Driving simulator III (VTI, 2008) is conducted. The integration does not only increase the realism in the driving simulator but it also creates new additional ways for calibrating and validating traffic simulation models. The validity of a model can now also be checked by driving around in the simulated traffic.
- Insights into the difficulties, advantages and disadvantages of using microscopic traffic simulation for the simulation of surrounding autonomous vehicles in driving simulators are gained. The main benefits are increased realism and an increased range of applications. The difficulties include the requirement of new vehicle generation techniques and more detailed behavioral models for example. The main disadvantage is decreased controllability and thereby decreased reproducibility.
- A methodology and an algorithm for combining autonomous vehicles and controlled events in driving simulator experiments is developed. The algorithm has been tested and evaluated in the VTI driving simulator III.
- Insights into the difficulties, advantages and disadvantages of combining autonomous vehicles and controlled events in driving simu-

lator experiments are gained. The main benefits are increased realism without decreased reproducibility. In addition, one of the driving simulator experiments conducted showed that the controlled everyday life traffic normally used in the VTI driving simulator makes subjects drive faster than in the model developed for autonomous traffic. The main difficulty is to create non-conspicuous transitions from the autonomous traffic to the predefined situations.

- An enhanced version of the Intelligent Driver Model (Treiber et al., 2000) is developed. The enhanced model gives freeway speed–flow relationships that are closer to empirical observations on Swedish freeways.

- Insights into the importance of a correct modeling of the interaction between a follower-leader pair when using car-following models that include several leaders are gained. Effects of an error in the modeling of interaction acceleration for a vehicle pair increases if several leaders are considered.

4.3 Delimitiations

The simulation model developed only deals with freeways with two lanes in each direction and rural roads with oncoming traffic. The model does not deal with ramps on freeways or intersections on rural roads. Consequently, the current model cannot be used for simulations of urban traffic situations. The simulation model has been developed for simulations of road stretches, and thus simulations of road networks are not considered.

The algorithm developed for combining autonomous vehicles and controlled events mainly considers multi-lane roads and has not been tested on urban streets or highways with oncoming traffic. The algorithm is designed to be generic and thereby applicable together with any traffic simulation model, but the algorithm has so far only been tested with one traffic simulation model.

4.4 Summary of papers

Five papers are included in this thesis. Paper I presents an initial model for rural roads while Paper II describes the development and evaluation of an enhanced version of the model which also deals with freeways. Papers III-IV deal with the combination of autonomous vehicles and controlled events in driving simulator experiments. Paper III gives an introduction to the problem, while paper IV describes the development and evaluation of an algorithm for solving the problem. Paper V presents an enhanced version of one of the car-following models used.

The remaining part of this section includes brief summaries of the five papers, together with specifications of the contributions of the author of this thesis to the co-authored papers.

Paper I: Simulation of rural road traffic for driving simulators

Paper I describes a model for the generation and simulation of surrounding rural road traffic in a driving simulator. The model developed is built on established techniques for microscopic traffic simulation. The model is designed to generate a traffic stream corresponding to a given target flow. The model uses the principle of only simulating the closest neighborhood of the driving simulator vehicle (cf. Chapter 3). This closest neighborhood moves with the same speed as the simulator vehicle and it is interpreted as a moving window, which is centered on the simulator vehicle. This neighborhood is divided into one inner region and two outer regions. Vehicles in the inner region are simulated according to behavioral models, while vehicles in the outer regions are updated according to a less time-consuming model. The main parts of the utilized behavioral models are based on behavioral models from the TPMA model (Davidsson et al., 2002) and the VTISim model (Brodin and Carlsson, 1986). The paper includes a new model for the generation of realistic vehicle platoons when using the moving window approach.

The paper also includes a discussion of different approaches for calibrating and validating the model. The main output of this model is the actual behavior of the simulated vehicles and not the average speed, delay, queue length, etc. which is often the main focus of traditional applications of traffic simulation. For example, new validation methods using human observers are discussed.

A discussion about how autonomous vehicles could be combined with predefined events is also included. The necessary steps and the related difficulties for achieving transitions from the autonomous mode to a predefined traffic situation are discussed.

Paper I is published in:

- Janson Olstam, J. (2005) Simulation of rural road traffic for driving simulators. In *Proceedings of the 84th Annual meeting of the Transportation Research Board*, Washington D.C., USA.

The content of Paper I has been presented at:

- *Transportforum*, Linköping, January 14-15, 2004.

- The *84th Annual meeting of the Transportation Research Board*, Washington D.C., USA, January 9-13, 2005.

Paper II: A framework for simulation of surrounding vehicles in driving simulators

Paper II describes a framework for generating and simulating surrounding vehicles in a driving simulator. The framework is a further development of the model presented in paper I. The framework deals with methods for generating and simulating both freeway and two-lane highway traffic. Also here, the moving window is divided into one inner area and two outer areas. Vehicles in the inner area are simulated according to a microscopic simulation model including sub-models for driving behavior, while vehicles in the outer areas are updated according to a less time-consuming mesoscopic simulation model.

The paper includes a presentation of the framework, the microscopic and the mesoscopic simulation models, the model for transitions between the microscopic and the mesoscopic model, and the model for the generation of new vehicles. The framework was validated on the number of vehicles that catch up with the driving simulator vehicle and vice versa. The agreement was good for active and passive catch-ups on rural roads and for passive catch-ups on freeways, but less good for active catch-ups on freeways. The reason for this seemed to be deficiencies in the lane-changing model utilized. It was verified that the framework was able to achieve the target flow and that there was a gain in the computational time when using the outer areas.

The framework was integrated with the VTI Driving simulator III and a small driving simulator experiment was conducted. The experiment included 10 participants who drove both in the freeway environment and in the rural road environment. After the drive, the participants were asked to give comments about the behavior of the simulated vehicles. The overall conclusion was that the simulated vehicles behave quite realistically but that there is room for enhancements. The most typical comments were that the simulated drivers drove aggressively on the rural road and that the simulated drivers in general drove more slowly than real drivers.

This paper is co-authored with Jan Lundgren, Mikael Adlers, and Pontus Matstoms. The author of this thesis has contributed to the paper as main author and by major involvement in the research planning, in the modeling and simulation work and in the analysis of the results.

Paper II is published in:

- Janson Olstam, J., Lundgren, J., Adlers, M., and Matstoms, P. (2008). A Framework for Simulation of Surrounding Vehicles in Driving Simulators. *ACM Transactions on Modeling and Computer Simulation 18(3):9:1–9:24*.

Parts of the content of paper II have also been published in the following publications:

- Janson Olstam, J. (2008). Simulation of vehicles in a driving simulator using microscopic traffic simulation. In E. Chung and A.-G. Dumont, editors, *Transport Simulation: Beyond Traditional Approaches*, EPFL Press, Lausanne, Switzerland, 2008.

- Janson Olstam, J. (2006). Simulation of vehicles in a driving simulator using microscopic traffic simulation. In *Proceedings of the 2nd International Symposium on Transport Simulation*, Lausanne, Switzerland, 2006.

- Janson Olstam, J. (2006). Generation and simulation of surrounding vehicles in a driving simulator. In *Proceedings of the Driving Simulation Conference (DSC'06)*, Paris, France, 2006.

The content of Paper II has been presented at:

- *Transportforum*, Linköping, January 11-12, 2006.

- The *2nd International Symposium on Transport Simulation*, Lausanne, Switzerland, September 4-6, 2006.
- The *Driving Simulation Conference (DSC'06)*, Paris, France, October 4-6, 2006.

Paper III: Combination of autonomous and controlled vehicles in driving simulator scenarios

Paper III presents an alternative design methodology for driving simulator experiments. In the methodology, periods with "fully" autonomous simulated road-users are combined with periods with only controlled simulated road-users. A "fully" controlled road-user is a road user that only follows instructions from some supervisor while an autonomous road-user is a road-user that tries to achieve his/her own goals. For some types of driving simulator experiments, the methodology presented can imply a gain in realism without too great losses in reproducibility. The basic idea is to let the surrounding vehicles run in autonomous mode between the predefined situations at which measurements are taken. When the simulator vehicle gets closer to the place where a situation is going to happen, the simulation of the surrounding vehicles should, in a way which is unnoticeable for the subject, change from autonomous to controlled mode.

The paper discuss advantages, disadvantages, and difficulties of combining autonomous vehicles and controlled events in driving simulator scenarios. The paper also includes a discussion on means and methods for how the transition from the autonomous to the controlled mode can be made. To illustrate the problem, a theater metaphor is presented. In the theater metaphor, a scenario is broken down into three base elements: everyday life driving, play preparations, and plays. The paper defines the transition from autonomous everyday life driving to less autonomous directed plays as the play preparation problem. The play preparation problem consists of estimating the start time of the play, casting, transporting actors to the stage and transporting actors from the stage.

This paper is co-authored with Stéphane Espié. The author of this thesis has contributed to the paper as main author and by major involvement in the research planning and the modeling.

Paper III is published in:

- Janson Olstam, J. and Espié, S. (2007). Combination of autonomous and controlled vehicles in driving simulator scenarios. In *Proceedings of Road Safety and Simulation (RSS2007)*, Rome, Italy.

The content of Paper III has been presented at:

- The conference *Road Safety and Simulation (RSS2007)*, Rome, Italy, November 7-9, 2007.

Paper IV: An algorithm for combining autonomous vehicles and controlled events in driving simulator experiments

Paper IV presents an algorithm for solving the play preparation problem which was presented in paper III. The play preparation problem is divided into three sub-problems: estimation of the start time of the play, casting, and transportation of actors. A transition from autonomous everyday life driving to a controlled play includes two trigger points. These points trigger when the driving simulator vehicle passes a specific position along the road. The first point triggers the start of the play preparation and the second point triggers the hand over from the autonomous to the controlled mode. The start time estimation problem consists of estimating when the simulator driver will reach the second trigger point. The casting problem consists of finding actors that can play the roles in the coming play and assigning the roles to the most suitable actors. The transportation problem consists of moving the actors to their assigned initial positions. If there are no suitable actors on the stage, new ones have to be created out of sight of the simulator driver.

The algorithm developed was implemented and tested in the VTI driving simulator III with promising results. In most of the cases, the algorithm could reconstruct the specified start condition and conduct the transition from the autonomous to the controlled mode in a non-conspicuous way. Some problems were observed with regard to moving unwanted vehicles away from the area closest to the simulator vehicle. The experiment also showed that the controlled everyday life traffic normally used in the VTI driving simulator makes subjects drive faster than in autonomous everyday life traffic.

This paper is co-authored with Stéphane Espié, Selina Mårdh, Jonas Jansson, and Jan Lundgren. The author of this thesis has contributed to the paper as main author and by major involvement in the research planning, in the modeling and simulation work and in the analysis of the results.

Paper IV is submitted to:

- *Transportation Research C*

The content of Paper IV has been presented at:

- The *Workshop on Traffic Modeling: Traffic Behavior and Simulation*, Graz, Austria, June 30 - July 2, 2008.

Paper V: Enhancements to the Intelligent Driver Model

Paper V presents an enhanced version of the Intelligent Driver Model (IDM). The IDM is a safety distance car-following model used in the microscopic simulation of traffic. It is found that the IDM takes a preceding vehicle into consideration even in situations where the distance to the preceding vehicle is much longer than the safety distance that the IDM estimates. It was found that the design of the interaction acceleration function in IDM leads to the simulated drivers not being able to reach their desired speeds. The deficiency observed also leads to strange behavior in connection with lane change situations. For example there are situations in which a human driver can be expected to change lane and continue to drive at his/her desired speed, but in which the IDM would impose a deceleration. Compared to real freeway traffic, these problems will lead to a lower average speed and to a greater impact of increasing traffic flow on speed, i. e. a steeper speed–flow relationship.

The paper presents a modified version of the IDM in which the function that describes accelerations due to the interaction with a preceding vehicle is changed. The new function only takes a preceding vehicle into account if it is reasonably close. The modified IDM includes one new parameter β that controls the gap to safety gap ratio at which the interaction acceleration is evaluated to zero. The parameter β is set to 1.35, which means that a driver will not consider vehicles which are more than 1.35 times the estimated safety gap ahead.

The paper presents simulation results for a two lane freeway for both the original and the modified model. A comparison of the results of the simulations with the original and the modified IDM showed that the modified IDM resulted in a higher average speed for a specific flow, a less steep speed–flow relationship, a higher capacity and a overall better fit to speed–flow relationships for Swedish freeways. It was also found that these effects increase if the IDM was extended with the Human Driver Model, which takes several leaders into account.

This paper is co-authored with Andreas Tapani. The author of this thesis has contributed to the paper as main author and by major involvement in the research planning, in the modeling and simulation work and in the analysis of the results.

Paper V is submitted to:

- *Physical Review E*

4.5 Future research

The work presented in this thesis raise several interesting issues for future research. The model developed for simulating autonomous surrounding vehicles is only able to simulate road links, i. e. roads without intersections and ramps. In order to increase the range of applications, the model should also be able to handle on and off ramps on freeways. This implies detailed modeling of lane-changing and acceleration behavior in merging situations. As for all microscopic traffic simulation models, further calibration and validation both at a macroscopic and microscopic level are important and essential tasks. To achieve a more complete modeling of rural roads, the model should be extended to include modeling of intersections and roads with a barrier between oncoming lanes, for example so called 1+1 and 2+1 roads which are common in the Swedish road network. The model should also be extended to deal with urban roads with roundabouts and signalized intersections.

The model developed for simulating autonomous surrounding vehicles in a driving simulator does not only increase realism but also creates possibilities to develop new or enhance existing traffic simulation models. Data concerning all movements, including the driving simulator vehicle's movements, can be gathered. This data can then be used to study car-following, lane-changing, overtaking behavior, etc. in order to create more realistic sub-models for driving behavior. The combination of a driving simulator and a traffic simulation model also creates new additional ways for validation of traffic simulation models. The validity of a model can now also be checked by driving around in the simulated traffic, and such subjective or qualitative analysis can be a good complement to the traditional comparisons of speeds, flows, queue lengths, etc. Therefore, further research should also explore the possibilities and develop methods for using driving simulators in combination with traffic simulation for enhancing, calibrating and validating traffic simulation models.

The approach of combining autonomous surrounding vehicles and controlled events shows great potential and gives rise to several directions of research. The algorithm developed has only been tested on two types of plays and for one traffic condition. Further tests with different kinds of plays, start conditions and traffic conditions (especially more dense conditions) are needed. It would also be desirable to test the algorithm within a "real" driving simulator experiment and not only in an experiment designed to test and evaluate the algorithm itself. The model development and testing has been limited to freeways, thus further development and tests for other road environments like rural highways and urban arterials are desirable. In order to investigate the algorithm's independence with respect to the choice of which driving simulator and traffic simulation model to use, the algorithm should be tested with another model for the simulation of the autonomous vehicles and together with another driving simulator.

In the development of the modified IDM, the original and modified model were only compared for freeway simulations. Further research should therefore investigate if the observed effects are limited to the driving conditions on freeways or if it also applies to urban streets and rural highways. Future work should also include more extensively calibration of the added parameter β and further validation at a microscopic level using trajectory data.

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