

Linköping Studies in Science and Technology  
Licentiate Thesis No. 1203

# **A model for simulation and generation of surrounding vehicles in driving simulators**

Johan Janson Olstam



**Linköpings universitet**  
**INSTITUTE OF TECHNOLOGY**

LiU-TEK-LIC- 2005:58

Dept. of Science and Technology  
Linköpings Universitet, SE-601 74 Norrköping, Sweden

Norrköping 2005

**A model for simulation and generation of surrounding vehicles in driving simulators**

© 2005 Johan Janson Olstam  
*johja@itn.liu.se*

*Department of Science and Technology  
Linköpings universitet,  
SE-601 74 Norrköping,  
Sweden.*

ISBN 91-85457-51-5

ISSN 0280-7971

LiU-TEK-LIC 2005:58

Printed by UniTryck, Linköping, Sweden 2005

## **Acknowledgements**

First of all I would like to thank my supervisors Jan Lundgren, Linköping University (LiU), Department of Science and Technology (ITN), and Pontus Matstoms, VTI, for their invaluable support and advices. Many thanks also to Mikael Adlers, VTI, who I have been working with during the integration and testing within the VTI Driving simulator III. He has a great part in that integration went successfully. Thanks also to the Swedish Road Administration (SRA), Ruggero Ceci, for funding this work.

I would also like to show appreciation to my other colleagues at ITN/LiU and VTI, whom make ITN/LiU and VTI stimulating places to work at. Special thanks to my roommate and PhD student colleague Andreas Tapani and to my other PhD student colleagues for very interesting and useful discussions, to Arne Carlsson, VTI, for sharing his knowledge within the traffic theory and simulation area, to Anne Bolling and Selina Mård Berggren, VTI, for their help during the design and the realization of the conducted driving simulator experiment, to Lena Nilsson and Jerker Sundström, VTI, for invaluable comments, and to the members of the VTI driving simulator group, Staffan, Mikael, Mats, Håkan, Håkan, and Göran, for sharing their massive experience within the driving simulator area.

I would also like to express my gratitude to my family and friends for their encouragement and support. Last but not least, I would like to give all my love to Lin and to my two cuddly cats Marion and Morriz.



## **Abstract**

Driving simulators are used to conduct experiments on for example driver behavior, road design, and vehicle characteristics. The results of the experiments often depend on the traffic conditions. One example is the evaluation of cellular phones and how they affect driving behavior. It is clear that the ability to use phones when driving depends on traffic intensity and composition, and that realistic experiments in driving simulators therefore has to include surrounding traffic.

This thesis describes a model that generates and simulates surrounding vehicles for a driving simulator. The proposed model generates a traffic stream, corresponding to a given target flow and simulates realistic interactions between vehicles. The model is built on established techniques for time-driven microscopic simulation of traffic and uses an approach of only simulating the closest neighborhood of the driving simulator vehicle. In our model this closest neighborhood is divided into one inner region and two outer regions. Vehicles in the inner region are simulated according to advanced behavioral models while vehicles in the outer regions are updated according to a less time-consuming model. The presented work includes a new framework for generating and simulating vehicles within a moving area. It also includes the development of enhanced models for car-following and overtaking and a simple mesoscopic traffic model.

The developed model has been integrated and tested within the VTI Driving simulator III. A driving simulator experiment has been performed in order to check if the participants observe the behavior of the simulated vehicles as realistic or not. The results were promising but they also indicated that enhancements could be made. The model has also been validated on the number of vehicles that catches up with the driving simulator vehicle and vice versa. The agreement is 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.



# Contents

<b>1</b>	<b>INTRODUCTION .....</b>	<b>1</b>
1.1	BACKGROUND.....	1
1.2	AIM.....	3
1.3	DELIMITATIONS .....	3
1.4	THESIS OUTLINE.....	3
1.5	CONTRIBUTIONS .....	4
1.6	PUBLICATIONS .....	5
<b>2</b>	<b>TRAFFIC SIMULATION .....</b>	<b>7</b>
2.1	CLASSIFICATION OF TRAFFIC SIMULATION MODELS .....	7
2.2	MICROSCOPIC TRAFFIC SIMULATION.....	8
2.3	BEHAVIORAL MODEL SURVEY .....	9
2.3.1	<i>Car-following models .....</i>	<i>10</i>
2.3.2	<i>Lane-changing models.....</i>	<i>16</i>
2.3.3	<i>Overtaking models .....</i>	<i>22</i>
2.3.4	<i>Speed adaptation models .....</i>	<i>25</i>
<b>3</b>	<b>SURROUNDING TRAFFIC IN DRIVING SIMULATORS .....</b>	<b>27</b>
3.1	DRIVING SIMULATOR EXPERIMENTS.....	27
3.1.1	<i>Experiments, scenarios, and scenes.....</i>	<i>27</i>
3.1.2	<i>Design issues.....</i>	<i>28</i>
3.2	USING STOCHASTIC TRAFFIC IN DRIVING SIMULATOR SCENARIOS .....	29
3.2.1	<i>The stochastic traffic – Driving simulator dilemma.....</i>	<i>29</i>
3.2.2	<i>Stochastic traffic simulation and critical events.....</i>	<i>30</i>
3.3	DEMANDS ON TRAFFIC SIMULATION WHEN USED IN DRIVING SIMULATORS .....	31
3.4	RELATED RESEARCH .....	32
3.4.1	<i>Rule-based models .....</i>	<i>34</i>
3.4.2	<i>State machines .....</i>	<i>35</i>
3.4.3	<i>The eco-resolution principle.....</i>	<i>36</i>
<b>4</b>	<b>THE SIMULATION MODEL.....</b>	<b>39</b>
4.1	THE SIMULATION FRAMEWORK.....	39
4.1.1	<i>Representation of vehicles and drivers.....</i>	<i>39</i>
4.1.2	<i>The moving window .....</i>	<i>40</i>
4.1.3	<i>The simulated area.....</i>	<i>42</i>
4.1.4	<i>The candidate areas.....</i>	<i>42</i>
4.1.5	<i>Vehicle update technique .....</i>	<i>45</i>
4.2	VEHICLE GENERATION .....	48
4.2.1	<i>Generation algorithm .....</i>	<i>48</i>
4.2.2	<i>Generation of new vehicles on freeways.....</i>	<i>50</i>
4.2.3	<i>Generation of new vehicle and vehicle platoons on rural roads... </i>	<i>53</i>
4.2.4	<i>Initialization of the simulation.....</i>	<i>54</i>
4.3	BEHAVIORAL MODELS .....	55
4.3.1	<i>Speed adaptation.....</i>	<i>55</i>
4.3.2	<i>Car-following.....</i>	<i>57</i>
4.3.3	<i>Lane-changing.....</i>	<i>60</i>
4.3.4	<i>Overtaking .....</i>	<i>61</i>

4.3.5	<i>Passing</i> .....	64
4.3.6	<i>Oncoming avoidance</i> .....	64
<b>5</b>	<b>INTEGRATION WITH THE VTI DRIVING SIMULATOR III</b> .....	<b>67</b>
5.1	THE VTI DRIVING SIMULATOR III .....	67
5.2	THE INTEGRATED SYSTEM.....	67
5.3	COMMUNICATION WITH THE SCENARIO MODULE .....	68
<b>6</b>	<b>VALIDATION</b> .....	<b>71</b>
6.1	HOW SHOULD THE MODEL BE VALIDATED? .....	71
6.2	NUMBERS OF ACTIVE AND PASSIVE OVERTAKINGS.....	72
6.2.1	<i>Simulation design</i> .....	73
6.2.2	<i>Results</i> .....	74
6.3	USER EVALUATION .....	79
6.3.1	<i>Experimental design</i> .....	79
6.3.2	<i>Scenario design</i> .....	80
6.3.3	<i>Evaluation design</i> .....	81
6.3.4	<i>Results and analyses of the questionnaire</i> .....	82
6.3.5	<i>Results and analyses of the interview questions</i> .....	83
6.4	DISCUSSION .....	86
6.4.1	<i>Some additional observations</i> .....	87
<b>7</b>	<b>CONCLUSIONS AND FUTURE RESEARCH</b> .....	<b>89</b>
<b>8</b>	<b>REFERENCES</b> .....	<b>91</b>

## **Appendices**

**APPENDIX A – DRIVER/VEHICLE PARAMETER VALUES**

**APPENDIX B – OVERTAKING PARAMETERS**

**APPENDIX C – QUESTIONNAIRE**

**APPENDIX D – INTERVIEW QUESTIONS**

**APPENDIX E – ANSWERS FROM THE INTERVIEW QUESTIONS**



# 1 Introduction

## 1.1 Background

Traffic safety is a severe and important problem. Many accidents are caused by failures in the interaction between the driver, the vehicle, and the traffic system. The number of driving related interactions is increasing. Drivers nowadays also interact with different intelligent transportation systems (ITS), advanced driver assistance systems (ADAS), in-vehicle information systems (IVIS), and NOMAD devices, such as mobile phones, personal digital assistants, and portable computers. These technical systems influence drivers' behavior and their ability to drive a vehicle. To be able to evaluate how different ITS, ADAS, IVIS, NOMAD-systems, or road and signal control designs etc influence drivers, knowledge about the interactions between drivers, vehicles and environment are essential.

To get this knowledge researchers conduct behavioral studies and experiments, which either can be conducted in the real traffic system, on a test track, or in a driving simulator. The real world is of course the most realistic environment, but it can be unpredictable regarding for instance weather-, road- and traffic conditions. It is therefore often hard to design real world experiments from which it is possible to draw statistically significant conclusions. Some experiments are also too dangerous or expensive to conduct in the real world and other are impossible due to laws or ethical reasons. Test tracks offer a safer environment and the possibility of giving test drivers more equal conditions and thereby decreasing the statically uncertainty. However, test tracks lack a lot in realism and it can be hard to evaluate how valid results from a test track study are for driving on a real road. Driving simulators on the other hand offer a realistic environment in which test conditions can be controlled and varied in a safe way.

A driving simulator is designed to imitate driving a real vehicle, see Figure 1.1 for an illustration. The driver place 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. 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 in order to support the driver's visual impression of the simulator vehicle's movements. Last but not least a driving simulator include a scenario module that includes the specification of the road, the environment, and all other actors and events.



**Figure 1.1** *The VTI Driving Simulator III (Source: Swedish National Road and Transport Research Institute (VTI) (2004))*

Driving simulators are used to conduct experiments in many different areas such as:

- Alcohol, medicines and drugs.
- Driving with disabilities.
- Technical systems, such as ITS, ADAS, IVIS, and NOMAD systems.
- Fatigue
- Road design
- Vehicle design

Driving simulators can also be used for training purposes. One example is the TRAINER simulator that was developed to work as a complimentary vehicle in driving license schools, (Gregersen et al., 2001). The TRAINER simulator offers great possibilities to train 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 the driving simulator to be a valid representation of real driving. It is for instance clear that the ambient vehicles must behave in a realistic and trustworthy way. Ambient vehicles influence the driver's mental load and thereby his or her ability to drive the vehicle. A good representation of the ambient vehicles is especially important in simulator studies where the traffic intensity and composition has a large impact on the driver's ability to drive the vehicle. This can for instance be in experiments concerning road design, the use of new technical equipment, or fatigue. 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 catches 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. Micro-simulation has become a very popular and useful tool in studies of traffic systems. Micro models use different sub-models for car-following, lane-changing, speed adaptation, etc. to simulate driver behavior at a microscopic level. The sub-models, hereby called *behavioral models*, use the current road and traffic situation as inputs and generates individual driver's decisions regarding for example which acceleration to apply and which lane to travel in as outputs. Stochastic functions are often used to model variation in driver behavior, both among drivers and over time for a specific driver. However, stochastic traffic simulation models have traditionally not been used to simulate ambient vehicles in driving simulators. The usual approach has instead been to simulate the ambient vehicles according to deterministic models. There are for several reasons desirable to keep the variation in test conditions between different drivers as low as possible. By using stochastic simulation of ambient traffic, drivers will experience different situations at the micro level depending on how they drive. The simulator driver's conditions will still be comparable at a higher, more aggregated, level, if this is sufficient or not varies depending on the type of experiment. For some experiments, equal conditions at the micro level are essential and stochastic simulation may not be suitable to use. In other experiments, comparable conditions at a higher level are sufficient.

## **1.2 Aim**

The aim of this thesis is to develop, implement, and validate a real-time running traffic simulation model that is able to generate and simulate surrounding vehicles in a driving simulator. This includes integration of the developed model and a driving simulator. The model should both simulate individual vehicle-driver units and the traffic stream that they are a part of, in a realistic way. The simulated vehicle-driver units should behave realistically concerning acceleration, lane-changing, and overtaking behavior, as well as concerning speed choices. The vehicles should also appear in the traffic stream in such a way that headways, vehicle types, speed distributions, etc. correspond to real data.

## **1.3 Delimitations**

The simulation model has been delimited to only deal with freeways with two lanes in each direction and to rural roads with oncoming traffic. The model does not deal with ramps on freeways or intersections on rural roads. Consequently, the thesis does not deal with simulation of urban traffic situations.

Some driving simulator experiments include critical situations or events. To create such situations autonomous vehicles has to be combined with vehicles with predetermined behavior. The thesis only discusses this topic to a limited extent.

## **1.4 Thesis outline**

Chapter 2 gives an introduction to the field of microscopic simulation of traffic. The chapter includes a survey of common car-following, lane-changing, overtaking, and speed adaptation models.

Chapter 3 includes an introduction to driving simulator experiments and to the field of simulation of surrounding vehicles in driving simulators. It also includes a discussion on the advantages, disadvantages, and difficulties of using stochastic traffic simulation for simulating surrounding vehicles in driving simulators. The chapter ends with a description of related research.

In Chapter 4 the proposed model is presented. First, the simulation framework is presented. Then follows the presentation of the technique used to generate new vehicles. The chapter ends with a description of the utilized behavioral models and calibration of the involved parameters.

Chapter 5 describes the integration of the proposed simulation model and the VTI driving simulator III. The chapter starts with a short description of the driving simulator and then follows the description of the integrated system.

The performed validation of the model is presented in Chapter 6. The chapter starts with a discussion on how to validate this kind of models. Then follows a description and results from a validation of the number of vehicles that catches up with the driving simulator vehicle and vice versa. The third section describes a driving simulator experiment that was conducted in order to validate the simulated vehicles' behavior. The chapter ends with a discussion and some additional observations made during tests in the driving simulator.

Chapter 7 ends the thesis with a summary and a discussion on future research needs and possibilities.

## 1.5 Contributions

The main contribution of this thesis is the developed traffic simulation model, which is able to simulate ambient vehicles in a driving simulator on freeways and on rural roads with oncoming traffic. The contributions also include:

- A summary over commonly used behavioral models for car-following, lane-changing, overtaking, and speed adaptation.
- An investigation of difficulties, benefits, advantages and disadvantages with using stochastic micro simulation of traffic for simulation of ambient traffic in a driving simulator.
- Improvements of a technique for generating freeway traffic on a moving area around a driving simulator and a further development of this technique to also fit generation of vehicles on rural roads without a barrier between oncoming traffic.
- A new simple mesoscopic traffic simulation model that simulates individual vehicles using speed-flow diagrams. The model is used to simulate vehicles far away from the simulator vehicle.
- A new version of the TPMA (Davidsson et al., 2002) car-following model, including a new deceleration model.
- An enhanced version of the VTISim (Brodin et al., 1986) overtaking model, which includes new models for the behavior during the overtaking and at abortion of overtakings.
- Integration of the simulation model and the VTI Driving simulator III
- Presentation of different approaches that can be used to validate models for simulating surrounding vehicles in driving simulators.

## 1.6 Publications

Some parts of this thesis have been published in other publications. The first version of the framework for generation and simulation of vehicles on freeways was originally presented in

Janson Olstam, J. and J. Simonsson (2003), *Simulerad trafik till VTI:s körsimulator - en förstudie (Simulated traffic for the VTI driving simulator - a feasibility study, In Swedish)*. VTI Notat 32-2003. Swedish National Road and Transport Research Institute (VTI), Linköping, Sweden.

A partly enhanced version of this framework was later presented in

Janson Olstam, J. (2003). "Traffic Generation for the VTI Driving Simulator". In Proceedings of: *Driving Simulator Conference - North America, DSC-NA 2003*, Dearborn, Michigan, USA.

The generation and simulation framework for simulation of rural road traffic for driving simulators was first presented in:

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

Section 2.3.1 in the thesis includes a survey over car-following models. The main part of this survey has been presented in:

Janson Olstam, J. and A. Tapani (2004), *Comparison of Car-following models*. VTI meddelande 960A and LiTH-ITN-R-2004-5. Swedish National Road and Transport Research Institute (VTI) and Linköping University, Department of Science and Technology, Linköping, Sweden.



## 2 Traffic simulation

The societies of today need well working 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. Researchers and developers have therefore during the last decades 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 analytical models often use queue theory, optimization theory or differential equations that can be solved analytical to model road traffic. These kinds of models are very useful, but often lack the possibility of studying how the dynamics of a traffic system varies over time. Simulation models on the other hand offer this possibility. They model how the traffic changes over time and use stochastic functions in order to reproduce the dynamics of a traffic system.

Traffic simulation has become a powerful and cost-efficient tool for investigating traffic systems. It can for instance be used for evaluation of different road and regulation designs, ITS-applications or traffic management strategies. Traffic simulation models offer the possibility to experiment in a safe and non-disturbing way with an existing or non-existing traffic system. As all models, traffic simulation models must be calibrated and validated in order to generate trustworthy results. This is often a very time-consuming task and sometimes limits the models cost-efficiency.

### 2.1 Classification of traffic simulation models

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

Microscopic models represent the traffic stream at a very 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 et al., 2002), VISSIM (PTV, 2003), Paramics (Quadstone, 2004a, Quadstone, 2004b), MITSIMLab (Toledo et al., 2003), and CORSIM (FHWA, 1996).

Mesosopic 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, for example, flow, speed and density. Examples of mesoscopic simulation models are DYNASMART (Jayakrishnan et al., 1994) and CONTRAM (Taylor, 2003).

Macroscopic models use a low level of detail, both regarding the representation of the traffic stream and interactions. Instead of modeling individual vehicles, the

macro models use aggregated variables as flow, speed and density to characterize the traffic stream. Macro models commonly use speed-flow relationships and conservation equations to model how traffic propagate thru the modeled network. Examples of macroscopic simulation models are METANET/METACOR (Papageorgiou et al., 1989, Salem et al., 1994) and the Cell Transmission model (Daganzo, 1994, Daganzo, 1995).

## 2.2 Microscopic traffic simulation

Microscopic traffic simulation models, hereby called micro or 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 sub-models, hereby called *behavioral models*, that each handles specific interactions. The most essential behavioral model is the car-following model, which handles the longitudinal interaction between two preceding vehicles. Other important behavioral models include models for lane-changing, gap-acceptance, overtaking, ramp merging, and speed adaptation. The sub-models needed depend on which type of road that the model should be able to simulate. Lane-changing models are for instance only necessary when simulating urban or freeway environments and are not needed in models for two lane highways without a barrier between oncoming lanes. The most common behavioral models will be presented in more detail in Section 2.3.

Most micro models are able to simulate urban or freeway networks. The most well known models for these environments are also the ones presented in Section 2.1 (AIMSUN, VISSIM, Paramics, MITSIMLab, and CORSIM). Only a couple of 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 et al., 1986). The VTISim model is currently being further developed in the Rural Road Traffic Simulator (RuTSim) model (Tapani, 2005).

In order to model that behavior and preferences varies among drivers, each vehicle driver unit is assigned different driver characteristics parameters. These parameters 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. We can for example assume that desired speeds on freeways follows a normal distribution with mean 111 km/h and a standard deviation of 11 km/h.

Micro models are generally time-discrete, but some event based models has also been developed, see for instance Brodin and Carlsson (1986). The basic principle of a time discrete model is that time is divided into small time steps, commonly between 0.1 and 1 second. 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 perform capacity and level-of-service evaluations of different road designs and management strategies. During the last decade, micro models have also in greater extent been used to evaluate different ITS-applications for example Intelligent



Speed Adaptation (Liu et al., 2000) or Adaptive Cruise Control systems (Champion et al., 2001). Research has also been made within in 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 et al. (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 are therefore generally performed at a macroscopic level. The different behavioral model has to various extents been calibrated and validated at a micro level. However, very 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 well performing, traffic simulation models must be based on high-quality behavioral models. To generate realistic behavior is of course the most important property of a good behavioral model, but not the only desirable property. A very 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 utilized parameters easily can be interpreted as known vehicle or driver factors. This simplifies the calibration work and allows the user to in a more straightforward and easy way experiment with different parameter settings regarding for example the variation in behavior among drivers.

Different road environments require different kinds of behavioral models. A traffic simulation model for urban roads must include different types of behavioral models compared to a simulation model for rural environments. Common for all environments is however the need of a car-following model. A car-following model controls drivers' acceleration behavior with respect to the preceding vehicle in the same lane. It deduce when a vehicle is free or following a preceding vehicle and what action to take in each case. Another behavioral model 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 consider the whole overtaking procedure is needed. Such a model cannot only deal with the lane change to the oncoming lane. It also has to consider the actual passing procedure when traveling in the oncoming lane and the lane change back to the 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 of accepting or rejecting an available gap, for example if a vehicle that wants to change lane accept 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 weaving decisions.

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 driver's behavior with respect to the preceding vehicle in the same lane. A vehicle is classified as *following* when it is constrained by a preceding vehicle, and driving at the desired speed will lead to a collision. When a vehicle is not constrained by another vehicle it is considered *free* and travels, in general, at its desired speed. The follower's actions is commonly specified through the follower's acceleration, although some models, for example the car-following model presented in Gipps (1981), specify the follower's actions through the follower's speed. Some car-following models only describe drivers' behavior when 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 is in 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. Vehicles in the free regime are unconstrained and try to achieve their desired speed, whereas vehicles in the following regime adjust their speed with respect to the vehicle in front. Vehicles in the emergency deceleration regime decelerate to avoid a collision. The following notation will be used throughout this section to describe the car-following models, see also Figure 2.1:

$a_n$	Acceleration, vehicle $n$ , [ $\text{m/s}^2$ ]
$x_n$	Position, vehicle $n$ , [ $\text{m}$ ]
$v_n$	Speed, vehicle $n$ , [ $\text{m/s}$ ]
$\Delta x$	$x_{n-1} - x_n$ , space headway, [ $\text{m}$ ]
$\Delta v$	$v_n - v_{n-1}$ , difference in speed, [ $\text{m/s}$ ]
$v_n^{\text{desired}}$	Desired speed, vehicle $n$ , [ $\text{m/s}$ ]
$L_{n-1}$	Length, vehicle $n-1$ , [ $\text{m}$ ]
$s_{n-1}$	Effective length ( $L_{n-1} + \text{minimum gap between stationary vehicles}$ ), vehicle $n-1$ , [ $\text{m}$ ]
$T$	Reaction time, [ $\text{s}$ ]

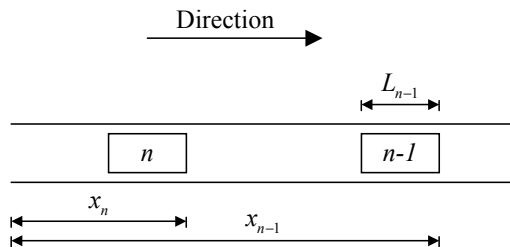


Figure 2.1 Car-following notation.

## Classification of car-following models

Car-following models are commonly divided into classes or types depending on the utilized logic. The Gazis-Herman-Rothery (GHR) family of models is probably the most studied model class. 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 is in this case 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 follower and leader, and the space headway (Brackstone et al., 1998). That is, the acceleration of the follower at time  $t$  is calculated as

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

where  $\alpha > 0$ ,  $\beta$  and  $\gamma$  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 for instance used in MITSIM (Yang et al., 1996) to calculate the acceleration in the following regime, and is formulated as

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

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

The *safety distance* or *collision avoidance* models constitute another type of car-following model. 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 et al., 2001), is a simple example of a safety distance model. The safe distance is however 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 presented in Gipps (1981). In this model the follower choose the minimum speed of the one constrained by the own vehicle and the one constrained by the leader vehicle, that is the minimum of

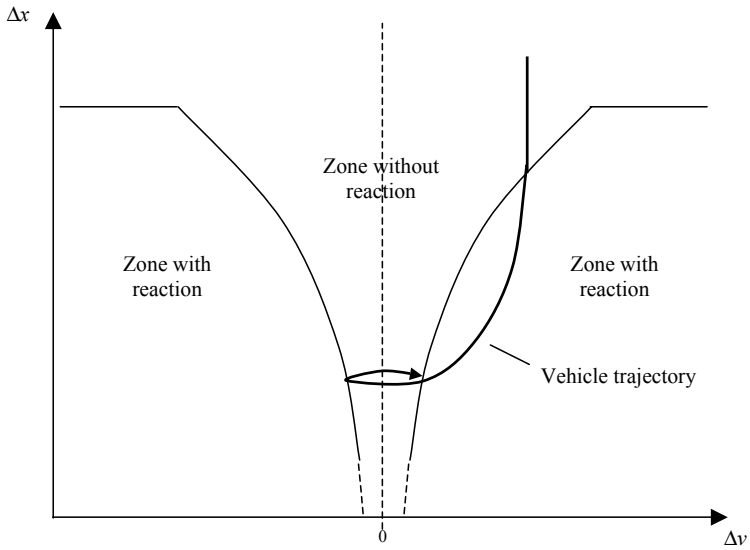
$$v_n^a(t+T) = v_n(t) + 2.5 \cdot a_n^m \cdot T \cdot \left(1 - \frac{v_n(t)}{v_n^{desired}}\right) \cdot \sqrt{0.025 + \frac{v_n(t)}{v_n^{desired}}} \quad (2.3)$$

and

$$v_n^b(t+T) = d_n^m T + \sqrt{(d_n^m T)^2 - d_n^m \left[2(\Delta x(t) - s_{n-1}) - v_n(t)T - \frac{v_{n-1}(t)^2}{\hat{d}_{n-1}}\right]} \quad (2.4)$$

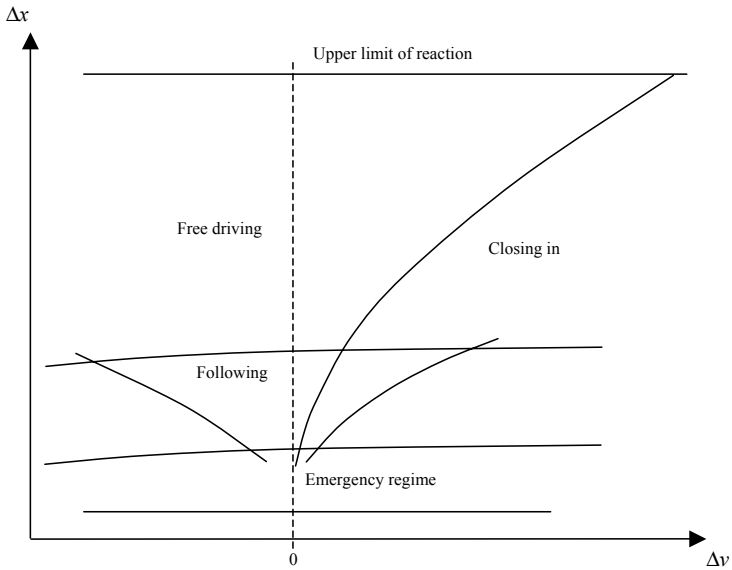
Here  $a_n^m$  and  $d_n^m$  is the maximum desired acceleration and deceleration for vehicle  $n$ , respectively, and  $\hat{d}_{n-1}$  is an estimation of the maximum deceleration desired by vehicle  $n-1$ . The safe speed with respect to the leader (equation (2.4)) is derived from the Newtonian equations of motion. The equation calculates the maximum speed that the follower can drive at and still be able to, after some reaction time, decelerate down to zero speed and avoid a collision if the leader decelerates down to zero speed.

In 1963 a new approach for car-following modeling were presented, (Brackstone et al., 1998). Models using this approach are classified as *psycho-physical* or *action point models*. The GHR models assume that the follower reacts to arbitrarily small changes in the relative speed. GHR models also assume that the follower reacts to actions of its leader even though the distance to the leader is very large and that the follower's response disappears as soon as the relative speed is zero. This can be corrected by either extending the GHR-model with additional regimes, e.g. free driving and emergency deceleration, or using a psycho-physical model. Psycho-physical models use thresholds or *action points* where the driver changes his or 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.

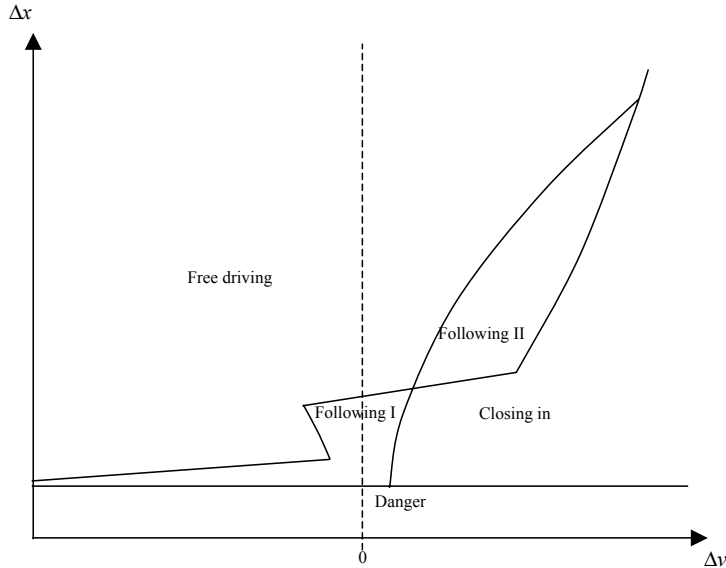


**Figure 2.2** A psycho-physical car-following model (Source: (Leutzbach, 1988)).

Representative examples of psycho-physical car-following models are the ones presented in Wiedemann and Reiter (1992), see Figure 2.3, and Fritzsche (1994), see Figure 2.4.

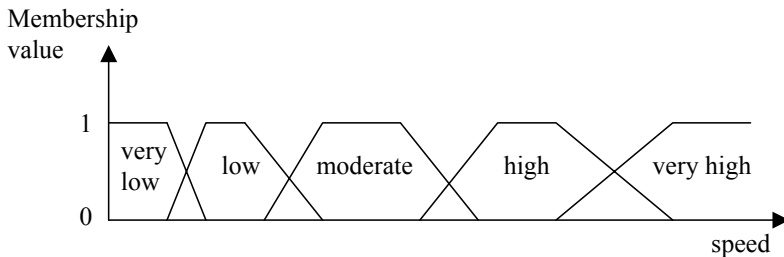


**Figure 2.3** The different thresholds and regimes in the Wiedemann car-following model.



**Figure 2.4** The different thresholds and regimes in the Fritzsche car-following model.

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. Human beings cannot observe exact values of for instance speed or relative distance, but they can give estimations like “above normal speed”, “fast”, “close”, etc. In the earlier described models drivers are assumed to know their exact speed and distance to other vehicles etc. In order to get a more human-like modeling, fuzzy logic models assume that drivers only are able to conclude, for example, if the speed of the front vehicle is very low, low, moderate, high, or very high. 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 linguist values has to be specified, see Figure 2.5 for an example.



**Figure 2.5** Example of membership functions for driving speed

The strength with fuzzy logic is that the fuzzy sets easily can be combined with logical rules to 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, with varying approaches, have been developed since the 1950’s. Despite the number of already developed models, 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 speed and position changes.

Traffic simulation 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. The simulation output of interest in such applications are in other words macroscopic measures, hence the utilized car-following models should at least generate representative macroscopic results. Leutzbach (1988) presents a macroscopic verification of GHR-models. Through integration of the car-following equation it is possible to obtain a relation 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 arrives at the well recognized Greenshields relationship (see for example May (1990)):

$$q = v \cdot k = v_{desired} \cdot \left(1 - \frac{k}{k_{max}}\right) \cdot k, \quad (2.5)$$

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 is however not possible for an arbitrary car-following model. It is for example not possible to integrate a psycho-physical model, since such models don’t express the follower’s acceleration in mathematically closed form. Macroscopic relationships can however always be generated by running several simulations with different flows.

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

The magnitude of drivers’ reactions also influences the result. How the output is affected is not as obvious as in the reaction time case. High acceleration rates should lead to that vehicles reach their new constraint speed faster, which would

decrease the vehicles travel time delay. High deceleration rates should also lead to less travel time delay, thus the vehicles can start their decelerations later. High acceleration and retardation rates may however result in oscillating vehicle trajectories at congested situations and thereby decrease the average speed.

Car-following models utilized in applications where microscopic output data is required must of course generate driving behavior as close as possible to real driving behavior. This is the case in simulation of surrounding traffic for a driving simulator or simulation used to estimate exhaust pollution, which requires detailed information about the vehicles' driving course of events. One should however bear in mind that the calibration of models used to produce microscopic output is considerably more expensive than the calibration of models used to estimate macroscopic traffic measures.

There are many possible pitfalls in the modeling of car-following behavior. Firstly, driver parameters such as reaction time and reaction magnitude vary among drivers. The behavior may also differ between different countries or territories, due to different formal and informal driving and traffic rules. Drivers in the USA may, for example, not drive in the same way as European or Asian drivers. Car-following models that is used to model traffic in different countries must therefore offer the possibility to use different parameter settings. The differences between countries may however be so big that the same car-following model cannot be used even with different parameter values to describe the behavior in two countries with very different traffic conditions.

Further more, 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 at congested and non-congested situations, (Brackstone et al., 1998). The reaction time may, for example, vary for one driver depending on traffic situation. Drivers may be more alert at congested situations and thereby have a shorter reaction time than in non-congested situations.

Modeling of congested situations and the transition from normal non-congested traffic to a congested state also place additional requirements on the car-following modeling. If the model is to give a correct description of the jam build up and the capacity drop in these situations the car-following model must yield higher queue inflows than queue discharge rates, (Hoogendoorn et al., 2001).

### **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 very important both in urban and freeway environments. When deciding whether to change lane, a driver need to consider several aspects. Gipps (1986) proposed that a lane-changing decision is the result of answering the questions

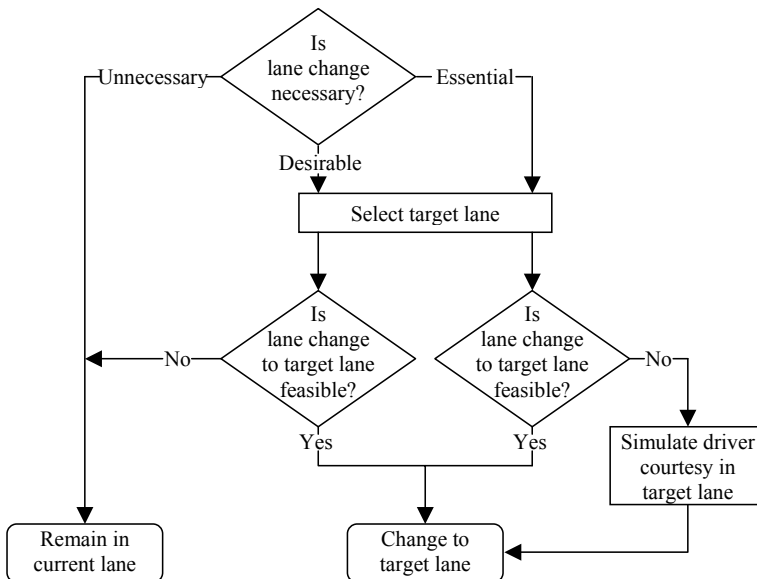
- Is it necessary to change lanes?
- Is it desirable to change lanes?
- Is it possible to change lanes?

Gipps (1986) presented a framework for the structure of lane-changing decisions in form of a decision tree. The proposed decision tree considered, in addition to



the list above, 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 such as (Barceló et al., 2002, Hidas, 2002, Yang, 1997) are based on the three basic steps proposed in Gipps (1986).

In the Gipps (1986) model all lane changes are impossible if the available gap in the target lane is smaller than a given limit. This is a reasonable approach in cases where 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 helps the trapped vehicle by decreasing its speed and creating a large enough gap for the trapped vehicle to enter. This has for instance been pointed out in Hidas (2002). Hidas (2002) describes a further developed variant of the model presented in 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).

An enhanced variant of this model has later been presented in Hidas (2005). In the Hidas (2002) structure 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 has been presented in Yang and Koutsopoulos (1996). This model classifies a lane change as either mandatory or discretionary. Mandatory lane changes corresponds to the essential statement in Hidas (2002), that is lane changes necessary in order to pass lane blockage, reach an intended turn, avoid restricted lanes, etc. Discretionary lane changes refers to lane changes in order to gain speed advantages, avoid lanes close to on-ramps, etc, which can be compared to the desirable path in the Hidas (2002) structure. In both structures, the differences between mandatory and discretionary lane changes is in the gap-acceptance behavior and the possibility

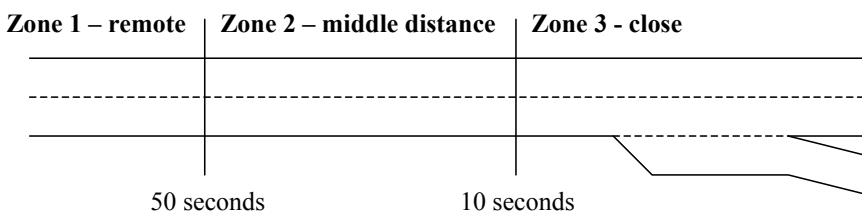
that vehicles in the target lane may renounce their right of way in favor for a vehicle performing a mandatory lane change.

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 regarding their lane-changing behavior. Toledo et al. (2005) presented a model in which a driver chooses a target lane, not necessary an adjacent lane, that is most beneficial for the driver. In this way the driver will strive for reaching the most beneficial lane, which may need several lane changes to reach. 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, due to for example 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 discussing the drivers desire to change lane.

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 one adjacent lane. Instead, the simulated drivers base their lane changes on the situations in all lanes. The model does not only consider the traffic situation in the closest area around the driver but do also account for the situation further away. The area around a driver is divided into several, in the paper 20, different areas. 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).

### Modeling the urgency to change lane

The urgency or necessity to change lane depends very much on the distance to an obstacle or an intended turn. This can and has been modeled in a couple of 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 headways were proposed, (Gipps, 1986). This zone division has later been adopted and further developed in both 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 in zone 1 are

considered far away from its intended turning or any obstacle and change lane if it desire. A vehicle in zone 2 is closer to its intended turn and is assumed to be a little bit more restrictive in its lane changing decisions. Vehicles in zone 2 do often not change to lanes further away from the lane suitable for the next turning. In zone 3, all lane-changing decisions exclusively focus on getting into the suitable lane. A vehicle in zone 3 that do not travel in the suitable lane for its intended turning will get more aggressive and start to accept smaller gaps. This will be discussed further on under the sub-section Gap-acceptance.

Yang (1997) proposed another way of modeling the drivers urgency 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 were used, in which the probability to tag a vehicle as mandatory mainly depends on the distance to the intended turning or obstacle. This strategy has also been adopted in Wright (2000), but the exponential distribution were replaced with a linear relationship in order to save computational time.

### Modeling drivers' desire to change lane

The drivers desire to change lane can be modeled in several ways, for example by using

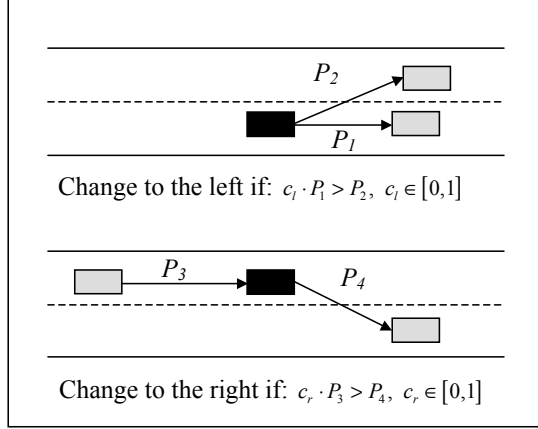
- A car-following model
- A pressure function
- Discrete choice theory
- Fuzzy logic

In the model proposed in Gipps (1986) a car-following model, more precisely the model presented in Gipps (1981) (see equation (2.3) and (2.4)), was used to calculate which lane that has the least effect on the drivers 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. As default values 1 m/s and -0.1 m/s were used for lane changes towards the centre 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 then the preceding vehicle in the current lane.

A similar variant of using the car-following model to evaluate which lane that is most preferable has been presented in Kosonen (1999). 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 is defined as

$$P = \frac{(v_{des} - v_{obs})^2}{2 \cdot s}, \quad (2.6)$$

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 decision according to the logic described in Figure 2.8.



**Figure 2.8** The lane-changing logic proposed by Kosonen (1999).  $P$  is calculated according to equation (2.6). The parameters  $c_l$  and  $c_r$  are calibration parameters, which controls the willingness to change to the left and right, respectively.

The logic is combined with a minimum time before a new lane change constraint in order to avoid frequent lane-changing behavior. For lane changes to the left it is also combined with a minimum difference in desired speed condition, similar to the one used in Gipps (1986).

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

$$U_{\text{int}}^{TL} = \beta_i^{TL} X_{\text{int}}^{TL} + \alpha_i^{TL} v_n + \varepsilon_{\text{int}}^{TL} \quad \forall i \in \{\text{lane 1, lane 2, ...}\}, \quad (2.7)$$

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

$$P(TL_{nt} = i | v_n) = \frac{\exp(V_{\text{int}}^{TL} | v_n)}{\sum_{j \in TL} \exp(V_{\text{int}}^{TL} | v_n)}, \quad \forall i \in TL = \{\text{lane 1, lane 2, ...}\}, \quad (2.8)$$

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

Drivers' willingness or desire to change lane can also be modeled by using fuzzy logic techniques, see Section 2.3.1. Wu et al. (2000) describes a lane-changing model that used the fuzzy sets in Table 2.1 and Table 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 offside/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 nearside/right, (Wu et al., 2000).

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

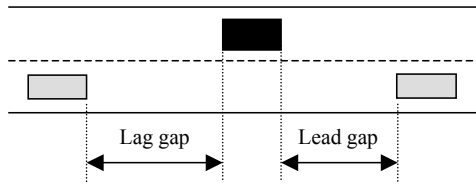
A typical lane-changing rule for changing to the left is according to Wu et al. (2000):

*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 or perhaps also necessary it might not be possible or safe to conduct it. In order to evaluate if 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 that drivers accept and which they don't. 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 hard to observe, in principle only accepted gaps and to some extent rejected gaps can be measured. Thus, it is hard 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 for instance used in the model presented in Kosonen (1999). Even though critical gaps are hard to observe some models has 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 in Gipps (1986) and Hidas (2002) are based on a similar but to some extent different approach. Instead of looking at the available and critical gap, a critical deceleration rate is used. In Gipps (1986) a car-following model, namely the model in Gipps (1981), were used to calculate the deceleration rate needed to change lane into the available gap. This deceleration rate was compared to an acceptable deceleration rate. If the deceleration rate needed was unacceptable by 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 changing lane. When getting closer to an obstacle or an intended turn, i.e. being in zone 2 or 3 in Figure 2.7, drivers are more urgent to get to the target lane. Drivers in these situations generally accept smaller gaps or, following the approach in Gipps (1986) and in Hidas (2002), higher deceleration rates. In Yang and Koutsopoulos (1996) this is modeled by letting the critical gap linearly decrease from a standard critical value to a minimum value with the distance to the critical point for the lane change. The model in Gipps (1986) uses 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 only consider the actual lane change to the oncoming lane. Instead a model that considers the whole overtaking process is needed. As lane-changing decisions, overtaking decisions can be divided into several sub-models or questions. An

overtaking decision can for instance be the answer of the following questions, (Brodin et al., 1986):

- Is the overtaking distance free from overtaking restrictions?
- Is the available gap long enough?
- Is the driver-vehicle unit able to perform the overtaking?
- Is the driver willing to start an overtaking at the available gap?

Drivers generally do not start an overtaking on places with 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. Drivers generally do not start an overtaking if the available gap at the time of the overtaking decision is shorter than the estimated overtaking distance. Another limitation for performing an overtaking can be the overtaking vehicle's performance, for example maximum acceleration or speed. Even though a vehicle might be able to perform an overtaking, the driver will probably not execute it if the overtaking distance will be unreasonable long, for example more than one kilometer. Even if the driver is able to perform the overtaking it is not sure that he or she is willing to execute it at the available overtaking gap. Drivers' willingness to accept an overtaking opportunity varies quite a lot. One driver may reject a gap whether another accepts the same gap, and one driver that accepts a gap at one point in time can reject an equal gap at another time.

The drivers' 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, for example as in the model presented in Ahmad and Papelis (2000). However, drivers' willingness to accept an available gap varies both among drivers and over time for a specific driver. Overtaking models therefore often need more advanced gap-acceptance models compared with the lane-changing case. These 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 previously 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 lies between drivers. That is, each driver is assumed to have a critical gap, such that the driver would accept every gap that is longer and reject gaps that is shorter than the driver's critical gap at all times. According to McLean (1989) there are at least two studies that states that the variance over time for a specific driver is larger than the among driver variance with respect to overtaking decisions. In the first study (Bottom et al., 1978) it was found that more than 85 % of the total variance in gap-acceptance is over time variation for a specific driver, which lead to the conclusion that an inconsistent model would be a more preferable 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. By using statistical estimation techniques this study 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-

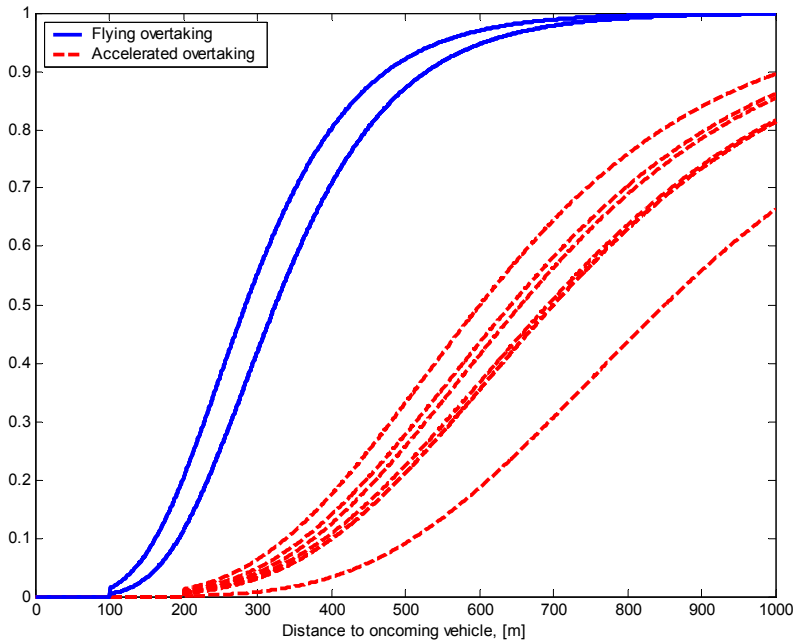
acceptance is of course to use a model that includes both over time and among driver variance. However, a big problem, pointed out in Daganzo (1981), is that it's very difficult to estimate appropriate distributions for such an approach, (McLean, 1989).

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

- Type of overtaken vehicle: A driver behave 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 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 perform a flying overtake, i.e. start to overtake when it catches up with a preceding vehicle, a driver behave differently compared to situations where the driver first has to accelerate in order to perform the overtaking.
- Type of gap limitation: Drivers' willingness to start an overtaking also varies depending on if an oncoming vehicle or a natural sight obstruction limits the available gap. Drivers are for instance generally more willing to accept a gap limited by a natural sight obstruction than equal gaps limited by oncoming vehicles.

Using these descriptors, the probability of accepting a certain overtaking gap does not only depend on the size of the gap but also on the other descriptors. This leads to a probability function for every combination of descriptors. A quite large data material is needed to estimate all these functions. A couple of studies and estimations of the overtaking probability has been performed, 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 presented in Carlsson (1993).





**Figure 2.10** Probability functions for overtaking decisions, combinations of descriptors with oncoming vehicle in sight, (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 at the same available gap.

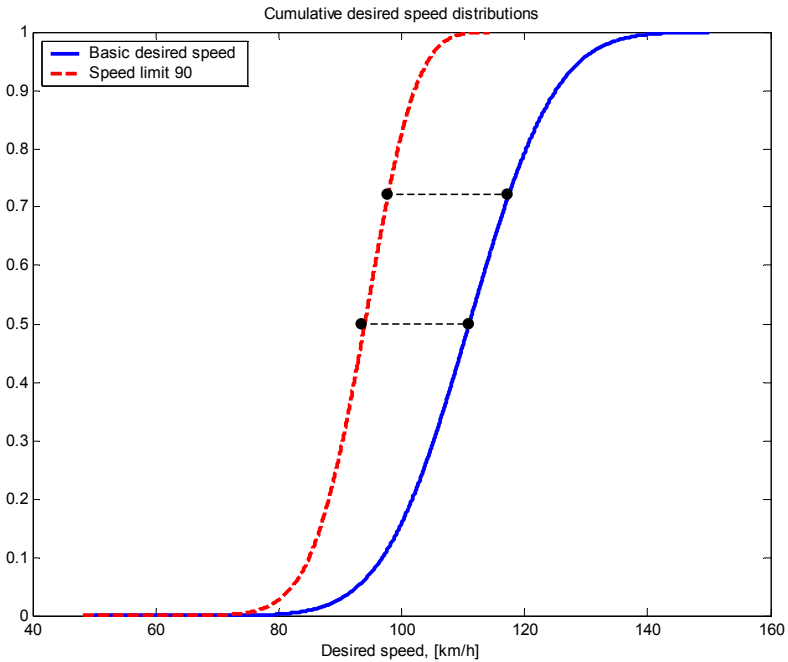
### 2.3.4 Speed adaptation models

Most micro 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, drivers' desired speed mainly depends on the posted speed limit. However, on rural roads, like two-lane highways the desired speed also varies with for example road width and curvature. In order to model that drivers' desired speed varies depending on the road design some kind of speed adaptation model is needed.

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 in which it is possible to catch variation in desired speed for different 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 posted speed limit. This approach was for example used in Yang (1997) and Ahmed (1999). In Barceló and Casas (2002) a similar variant is used, in which driver's desired speeds are deduced by multiplying the posted 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. The desired speed can for instance depend on the road width or the curvature. Brodin and Carlsson (1986) include a presentation of a speed adaptation model in which a drivers 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, a driver's desired speed is in the model not only the result of a shift of the distribution curve, as in the models presented in Yang (1997), Ahmed (1999), and Barceló and Casas (2002). The desired speed distribution curve is also rotated around its median. 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, see the example in Figure 2.11.



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

How much the curve is rotated depends on which factors that addressed the reduction. Different rotation parameters are used for adaptation caused by the road width, the speed limit, and the horizontal curvature.

### 3 Surrounding traffic in driving simulators

It is well known that the surrounding road environment influences drivers and their behavior. The road environment for instance affects a driver's 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 consciousness. 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. However, the need of a realistic representation of the environment sometimes stands in contradiction to the design of useful driving simulator experiments, i.e. experiments from which useful conclusions can be drawn. The task is to find a compromise that fulfills the realism and validity demands without limiting the range of applications too much.

This chapter will first give an introduction to driving simulator experiments and scenarios. Section 3.2 then presents benefits, difficulties, advantages and disadvantages of using stochastic traffic simulation to simulate surrounding vehicles in driving simulators. The next section (3.3) outline special demands on traffic simulation when used to simulate ambient vehicles in driving simulators, including differences and similarities compared to traditional applications of traffic simulation. The chapter ends with Section 3.4 that consists of a survey of related research within the area of simulation of ambient vehicles in driving simulators.

#### 3.1 Driving simulator experiments

Driving simulators offers the possibility to conduct many different kinds of experiments. It is for example possible to test different road-, vehicle- or driver place designs. Driving simulators are also commonly used for human-machine-interaction studies, including interactions with different ITS, ADAS, and IVIS. One of the strengths with driving simulator experiments is the possibility to study situations or conditions that rarely occur in reality. It is also possible to study situations or conditions that is too risky or unethical to study in real traffic, for example fatigue or drunk drivers. Another strength is the possibility of systematical variation of test parameters in order to distinguish differences or correlations between different variables.

##### 3.1.1 Experiments, scenarios, and scenes

A driving simulator *scenario* is a specification of the road and traffic environment along the road. This includes specification of how the road and the environment looks like, e.g. specification of road geometry, road surface, weather conditions, and surroundings 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, which starts when a certain condition is met and ends when another condition is met, (van Wolfelaar, 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 that will be present, what is going to happen, and in which order things is going to happen. An example of a scene, 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 enter 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 remains at the bus stop. But if the driver yields for the bus, the bus accelerates 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 held high in order to prevent the subject from overtaking. To sum up, a scenario is a specification of the road environment and a number of scenes, including information about when and where the scenes will take place.

So far we have only been discussing scenarios and scenes. What is then a driving simulator experiment? The experimental design includes the specification of how many participants that should be involved in the experiment and which scenarios that they should drive. The experimental design also includes the specification of which independent variables to use. The independent variables can for example be an 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 a ADAS is to let half of the participants drive with an ADAS and 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 drives 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 regarding one independent variable and a within group design regarding another independent variable.

### **3.1.2 Design issues**

Designing useful and well working driving simulator experiments and scenarios 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 very much on the application. Some tries have however 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 simulator scenarios are often very rigorously specified and controlled. Everything that is going to happen, excluding the simulator driver's actions, is specified in beforehand in such a way that every subject experiences the same situations. This makes it possible to draw statistically conclusions from an experiment using quite few participants.

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 then probably better to perform various experiments. For example, instead of conducting one experiment with the variables: mobile phone or not, handheld or handsfree, and rural or urban environment, is it 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 looking at the effects of using mobile phones or not in different road environments.

Driving simulator experiments can be divided into two different types of experiments: those that include critical situations or events and those that do not. Critical situations are often used in order to perform accelerated testing. Some traffic situations or events occur seldom, many simulator hours is thus needed to study driver's behavior in such situations if we wait until they arise by themselves. One of the strengths with driving simulators is that it is possible to shorten the time between these situations.

## **3.2 Using stochastic traffic in driving simulator scenarios**

The realism in the simulation of ambient traffic certainly affects the validity of a driving simulator. However, 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 within and between drivers.
- **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 as normal, fatigued, aggressive, and drunk.

Excluding the virtual personalities requirement, a traffic simulation model should be able to reproduce drivers' behavior in a realistic way and also to catch how the behavior varies 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 unintelligent to the same extent as in reality. A realistic variation in driver behavior is normally achieved by using stochastic microscopic traffic simulation. However, a stochastic simulation approach does not only affect the realism in driving simulators experiments.

### **3.2.1 The stochastic traffic – Driving simulator dilemma**

Ambient vehicles in driving simulators have traditionally been modeled using deterministic models. The main reason for this could be summarized with something called *The Stochastic Traffic – Driving Simulator Dilemma*. A certain number of observations (participants) are needed to be able to draw statistic significant conclusions from an experiment and the number of participants needed highly depends on the variation in the participants test conditions. This stands in contradiction to the aim of minimizing the number of participants due to economic reasons. Thus, the aim is to keep both the variation in test conditions

and the number of participants needed as low as possible. The dilemma lies in the modeling of the ambient vehicles. Drivers do not always behave the same. Driving behavior varies, both between drivers and within a driver. This is usually modeled by using behavioral models that includes stochastic parts; either by including stochastic functions in the actual behavioral models or using stochastic functions when assigning different driving characteristics, see Chapter 2. Using stochastic simulation of ambient vehicles will lead to that the participants will experience different situations at a micro level, depending on how they drive. The meaning of the Stochastic traffic – Driving simulator dilemma is, consequently, that stochastic simulation of ambient vehicles will increase the realism in the driving simulator but it will at the same time increase the variation in test conditions, at least at the micro-level, between the participants. The test conditions will still be comparable at a more aggregated level, i.e. the participants will experience the same traffic conditions, regarding intensity and composition, etc. Whether equal conditions at a higher level is sufficient or not varies between different driving simulator experiments. Equal conditions at a micro level can be very important in some driving simulator experiments and less crucial in others. The objective is to find a workable compromise between realism and reproducibility, i.e. to design experiments so that they generate both valid and useful results.

### **3.2.2 Stochastic traffic simulation and critical events**

In some driving simulator experiments are the participants exposed to one or several situations or events that may be critical, this can for example be an animal that runs out on 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. The basic idea is that at certain points in time or space a predetermined situation or event will occur. When the event or situation occur the vehicles' types, positions, and speeds must agree with those specified in the scenario. If not using stochastic simulation of the ambient vehicles, scenario scenes can be totally specified and controlled before running the scenario. This can of course be tricky but the advantage is that every vehicle movement, except the simulator vehicle, is known in beforehand. The introduction of stochastic traffic makes the generation of specific scenes even more difficult. Due to the stochastic simulation it is impossible to know which vehicles that will be in the area around the driving simulator when it gets close to the time and position of a specified event. The situation must therefore be created "on-line" rather than in advance.

Alloyer et al. (1997) proposed a framework for dealing with on-line creation of scenes. Following the theatrical terminology used in Alloyer et al. (1997), the specification of a scene is divided into three parts: the set, the cast of principal actors, and the script of actions (Alloyer et al., 1997). The set is a description of the physical surroundings at the place where the scene will take place. It also includes a specification of which actors that will be present in the scene. The casting is the procedure of choosing suitable traffic elements, vehicles, pedestrians, etc, for the different "roles". The script is finally the specification of all actions that are going to take place in the scene. When not using stochastic simulation of ambient traffic all three parts can be done in advance. When using stochastic simulation of traffic, the set and the script can and should still be

specified in beforehand while the casting has to be done on-line, i.e. during the simulation. The on-line casting includes several steps:

- Choosing suitable vehicles to be included in the scene, i.e., vehicles of suitable vehicle type and with suitable position and speed.
- Moving the chosen vehicles into the given positions and to the given speeds.
- Moving “non-scene” vehicles out of sight from the driving simulator vehicle.

The difficulty of choosing suitable vehicles depends on the current traffic situation and the scene complexity. Choosing suitable vehicles in the oncoming direction is rather easy and can be done by rearranging the oncoming vehicles out of sight of the simulator vehicle. Choosing suitable vehicles in the same direction as the driving simulator vehicle is more complicated. The chosen vehicles must be of the correct type and their speed, as observed by the simulator driver, cannot differ too much from the one they will obtain in the scene.

The sequence of the available vehicles often differs from the given one, which implies that the vehicles must be rearranged in some way to obtain the right vehicle type in the right place. The correct order must be created as unnoticeably as possible for the simulator driver. The vehicles should therefore be chosen so that the number of overtakings needed to get the ambient vehicles into the correct positions is kept as low as possible. When there are no suitable vehicles, new vehicles have to be generated.

Moving the vehicles into the right positions and speeds is the most difficult and critical part. This must be done without giving the simulator driver any hints on the forthcoming event. The first step is to rearrange the vehicles into the correct order. As much as possible of the necessary rearranging should be performed out of sight of the simulator vehicle. If overtakings within sight of the simulator vehicle are necessary, they can be arranged by creating suitable gaps in the oncoming vehicle stream. Depending on road type, intersection, ramps or traffic lights are probably more useful means than overtakings for adding or removing vehicles to or from the traffic stream in a non-noticeable way. A method for on-line creation of scenes should therefore try to use intersections and ramps in the first place and overtakings in the second place.

The vehicles must finally be moved to the right position and speed, according to the scene specification. This can be done by increasing or decreasing their speed, depending on whether the distance to simulator vehicles should be increased or decreased.

### **3.3 Demands on traffic simulation when used in driving simulators**

Microscopic simulation of traffic is a growing research area and there are today several commercial and non-commercial models available. However, these models cannot directly be used to simulate surrounding vehicles in a driving simulator. There are a couple of aspects that makes simulation of ambient traffic for a driving simulator different from the ordinary use of traffic simulation.

Firstly, simulation of ambient vehicles for a driving simulator involves higher demands regarding the microscopic behavioral modeling compared to “ordinary”

applications of traffic simulation. Traffic simulation is usually used to generate aggregated macroscopic output data 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 reasonable good agreement at the micro level, e.g. reasonable realistic behavioral models. Traffic simulation models often include assumptions and simplifications that do not affect the model validity at the macro level but sometimes affect the validity at the micro level. One typical example is the modeling of lane-changing movements. In most simulation models vehicles change lanes instantaneously. This is not very realistic from a micro-perspective but do not affect macro measurements appreciably. When simulating ambient vehicles for a driving simulator this is much more important, since in this case it is the microscopic behavior that is the essential output of the model. 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 that are not specified in the scenario or caused by the simulator driver.

Secondly, applications of traffic simulation normally deal with 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 ambient 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, which implies that the geographic places at which vehicles should be generated also moves with the speed of the simulator. 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 is generated behind the simulator vehicle and which is driving slower than the driving simulator will never catch up with either the simulator vehicle or the back edge of the window. It is therefore necessary to use an algorithm that only generates faster vehicles behind the simulator vehicle and slower in front, but that still generates the correct frequency of fast and slow vehicles, respectively. This approach of only simulating vehicles within a certain window around the simulator vehicle has for example been used 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 vehicles around the simulator vehicle. Vehicles further away from the simulator 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 to only use 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 within the research area of combining micro-, meso-, and macro simulation models.

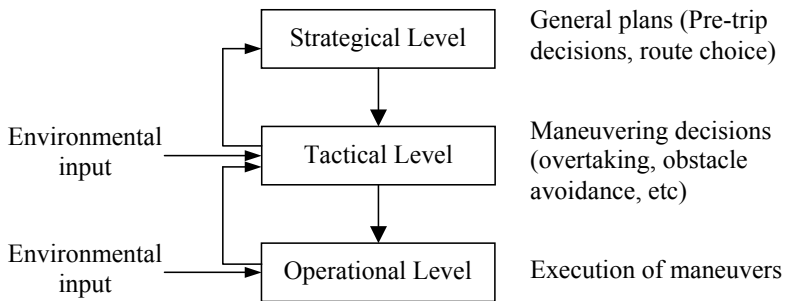
### **3.4 Related research**

Some research has been carried out within the area of simulating ambient vehicles for driving simulators. As seen in the previous section a couple of models



(Bonakdarian et al., 1998, Espié, 1995) has used the approach of only simulating vehicles in the closest neighborhood of the simulator vehicle. Other models for this application probably use similar approaches even though such information not seems to be available.

Most presented models have adopted the framework for describing the driving task proposed in Michon (1985). This framework divides the driving task into three levels: Strategic, Tactical, and Operational, see Figure 3.1.



**Figure 3.1** A hierarchical structure for the driving task, (Michon, 1985).

The strategic level includes “long-term” planning decisions as route or modal choices. The tactical level consists of maneuvering decisions as 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 in for example Champion et al. (1999) and Wright et al. (2002)

Most developed models focus on freeway or urban roads, see for example Ahmad et al. (2001), Al-Shihabi et al. (2002), Champion et al. (1999), Champion et al. (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<sup>®</sup>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) states that the traffic simulation model used in the National Advanced Driving Simulator (NADS), located at the University of Iowa, is able to simulate vehicles on such rural roads. This model includes a very simple overtaking model, which for instance use 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 obey 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 ordinary traffic simulation models. Another important vehicle generation issue regards 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. The different generation issues and proposals for dealing with these issues will be presented later on in Section 4.2.

Research within the area of simulation of vehicles for driving simulator has to a large extent been focused on decision making modeling concepts or techniques. Three commonly used techniques are: Rule based models, State Machines, and Mathematical or probabilistic models. Other used techniques are for instance the eco-resolution principle (El hadouaj et al., 2002, Espié et al., 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 whether 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.

There are also some tries with connecting an “ordinary” traffic simulation model with a driving simulator, see for example Bang et al. (2004), Jenkins (2004), and Kuwahara et al. (2004).

### 3.4.1 Rule-based models

Rule based models, also known as *knowledge-based systems*, *expert systems* or *production systems*, use a set of rules on the form if (*condition*) then (*action*) to model for example driver behavior (Wright, 2000). Each driver’s behavior is deduced by running through the set of rules and checking each one of them. 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 it desires it accelerate in order to obtain its desired speed. This type of models is deterministic and will lead to that every driver will react in the same way. In reality driver’s behavior differs both between drivers and within drivers. To overcome this a probability value is usually 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 very common conflict will be that the driver is driving slower than 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. The decelerate-to-front-vehicle-speed rule has for example higher priority than the increase-speed-to-obtain-desired-speed rule. Another way to solve the conflicts is

to make use of the rules' probability values. One way is to use a weighted average of the outcome of the different rules. This can however lead to, for example, unintelligent speed choices.

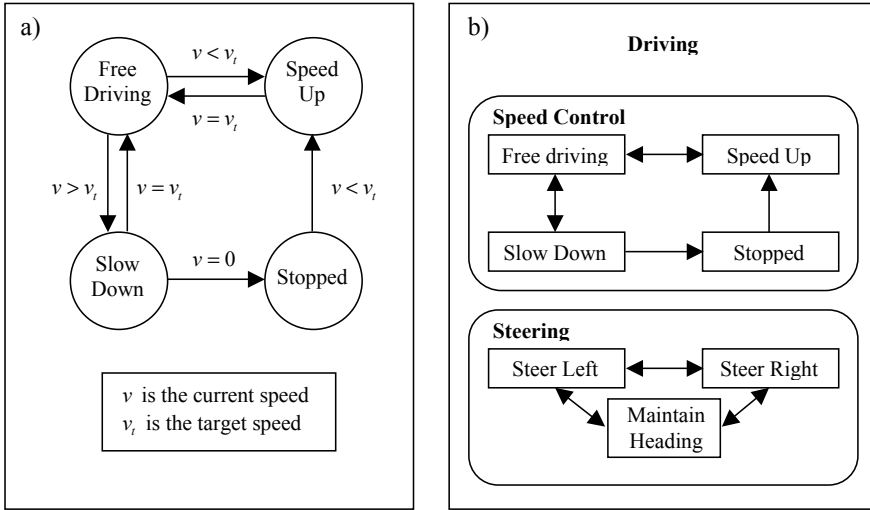
The main advantage of rule-based systems is that they are very simple and flexible. A rule-based model can easily be modified by adding, changing, or deleting rules. However, modeling advanced behaviors often require a great number of rules, which can make rule-based models hard to visualize and debug (Wright, 2000). Michon (1985) includes a simple estimation of how many rules that is 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 has for example been used in Boer 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 fuzzy rule based car-following model. Such an approach has for instance been proposed in Al-Shihabi and Mourant (2002).

### **3.4.2 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 it very hard to use them for modeling of system that requires simultaneous attention and actions (Cremer et al., 1995). Thus, state machines are not very suitable for modeling of complex systems as for example driver behavior. To overcome these drawbacks Cremer et al. (1995) among others 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, HCSM contain multiple, concurrently executing child state machines (Cremer et al., 1995). For example could a HCSM for car driving 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, intersections navigation, overtaking, oncoming avoidance, etc. The introduction of the concurrency characteristic makes it possible to have several active states simultaneously. This also leads to that concurrent states can generate conflicting outputs. Thus, as for more advanced rule-based system, high-quality conflict resolution principles is 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 simple assumed to be solved at the lower child HCSM level.



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

HCSMs overcome many of the shortcomings of the simple state machine but HCSMs are still highly deterministic. The deterministic approach can be useful for generating replicable driving simulator scenarios but it limits the possibility of creating realistic driver behavior since real driver behavior varies both among drivers and over time.

HCSM has for example been used in the autonomous driver behavioral models used in the simulators HANK (Cremer et al., 1997) and NADS (Ahmad et al., 2001) located at the University of Iowa.

### 3.4.3 The eco-resolution principle

Researchers at the French research institute INRETS has developed a model called ARCHISIM that can run as a “ordinary” traffic simulation model or host a driving simulator (El hadouaj et al., 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 other actors. In 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

(Source: El hadouaj and Espié (2002))

The driver first identifies possible interactions with other actors and the infrastructure. The interactions can be both observed and anticipated interactions. Then she 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 road. In cases where the interaction duration is estimated as short the driver chooses to adapt to the situation and thereby stay in the current lane. It is only in the case of long duration and the possibility of suppressing the interaction that the driver takes action. The basic principle is to minimize interactions both at a short and a long-term perspective. In the example of lane driving the ARCHISIM model use 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 simulation model

This chapter presents the proposed simulation model. The chapter starts with a presentation of the simulation framework, which include presentation of how vehicles and drivers are represented and updated. Section 4.2 then describes the algorithms used to generate new vehicles. The chapter ends with a description of the utilized behavioral models in Section 4.3. This section also includes a presentation of the outcome of the calibration of the different behavioral model parameters.

### 4.1 The simulation framework

The simulation model is based on established techniques for time-driven micro-simulation of road traffic. The model simulates surrounding traffic corresponding to a given target traffic flow and composition. The model uses the simulator vehicle's speed, position, etc. as input and generates the corresponding information about the ambient vehicles as output. Realistic driver behavior is generated by using behavioral models for car-following, speed adaptation, overtaking, etc. In these respects the model is similar to ordinary traffic simulation models, like *AIMSUN* (Barceló et al., 2002), *MITSIMLab* (Toledo et al., 2003), and *VISSIM* (PTV, 2003). The main difference is that in this case only the closest neighborhood of the simulator vehicle is simulated. Vehicles traveling slower or faster than the simulator will increase the distance to the simulator vehicle and they will be deleted from the model when they pass out of this closest neighborhood.

#### 4.1.1 Representation of vehicles and drivers

As in most micro simulation models vehicles and drivers are treated as vehicle-driver units. These vehicle-driver units are described by a set of driver or vehicle characteristics. Both the vehicle and the driver characteristics vary between different vehicle types. At the moment the model includes the vehicle types: Cars, Buses, Trucks, Trucks with trailer with 3-4 axes, and Trucks with trailer with 5 or more axes. However, buses and trucks without trailers are assumed to have equal characteristics.

##### Vehicle parameters

The characteristics used to describe a vehicle are length, width and the power/weight ratio, also called p-value. The vehicles' length and width are totally controlled by the visual profile that the vehicles are given in the simulator's visual system. The power/weight ratio is the ratio between a vehicle's power, available at the wheels, and its mass. For all vehicle types except cars, the power/weight ratio describes the vehicles' acceleration capacity. For cars the p-value instead describes the acceleration behavior at normal conditions. For cars a higher p-value can be used in special situations, for example in overtaking situations, in which car drivers tend to use higher acceleration rates. The power/weight ratio is assumed to be normal distributed among vehicles of a certain vehicle type. The typical average power/weight ratio for cars is for example 19 W/kg. See Appendix A for a complete listing of parameter values.

## Driver parameters

The characteristics used to describe the driver part of the vehicle-driver units are: basic desired speed and desired time gap. The basic desired speed is the speed that a driver wants to travel at on a dry, straight, and empty road. This basic desired speed is reduced to a desired speed for each road section according to a speed adaptation model, see Section 4.3.1. The basic desired speed is assumed to be normal distributed between drivers driving a certain vehicle type. The basic desired speed for car drivers are for instance assumed to be  $N \sim (111, 11.5)$  (units in km/h). When assigning a desired speed to a vehicle the driven vehicle's acceleration capacity is checked. The vehicle has to be powerful enough to be driven in the desired speed. If that is not the case the vehicle-driver unit is assigned a new power/weight ratio.

The desired time gap is the time gap that a driver desire when following another vehicle. This parameter is for instance used in the car-following model, see further description in Section 4.3.2. The desired time gap is assumed to be lognormal distributed among drivers driving a certain vehicle type. Standard values for all vehicle and driver parameters are presented in Appendix A.

## Brake lights and turning signals

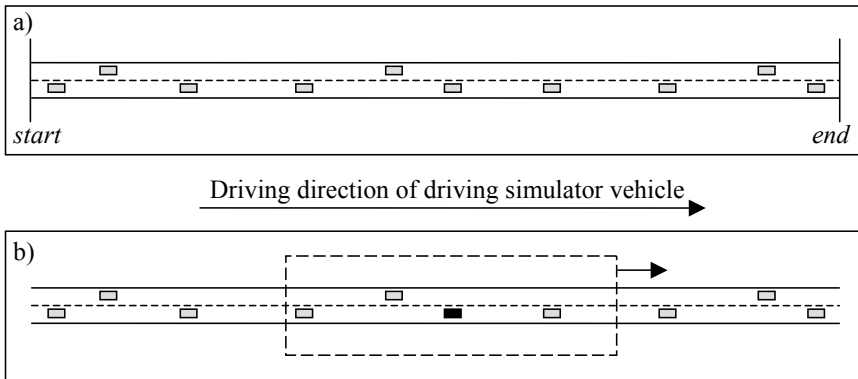
In ordinary traffic simulation there is no need for simulating occurrences like the use of turn signals or brake lights since all vehicle actions are known within the model. However, when simulating traffic for a driving simulator it is important to model both turn signals and brake lights, otherwise such signals will not be visible for the simulator driver. It is also important to model the variation in the use of, for example, turn signals. The use of turn signals varies both between drivers and traffic situation. Drivers' turn signal usage for example differs between lane changes and intersections turns. Traffic flow may also influence the use. The need to tell other vehicles about one's intentions is significantly lower at night, when there are almost no ambient vehicles, than during rush hour.

Brake lights have in this work been assumed to be on when using deceleration rates higher than an engine deceleration rate, assumed to be  $0.5 \text{ m/s}^2$ . Drivers are assumed to use the turning lights with some probability, which differs between lane changes to the right and left and between freeways and rural roads. When driving on freeways, drivers are for instance assumed to use the left turn signal more often than the right one.

### 4.1.2 The moving window

The simulation of the surrounding traffic should run in real time in order to make a realistic impression for the simulator driver. This implies that the simulation model must have a high efficiency level. The model therefore follows the approach of only simulating vehicles within a certain area around the driving simulator vehicle. This area moves with the same speed as the simulator vehicle and can be interpreted as a moving window, which is centered on the simulator vehicle, see Figure 4.1 for an illustration.

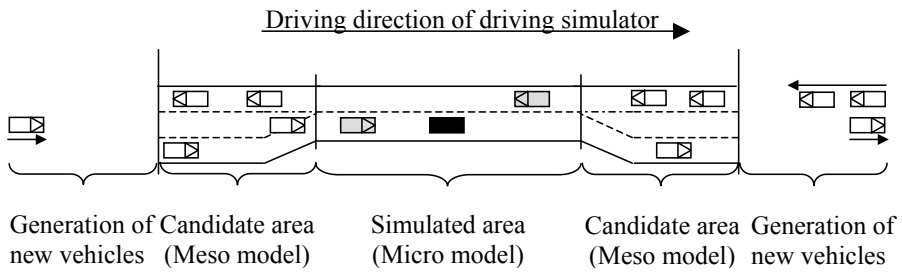




**Figure 4.1:** a) Illustration of traditional traffic simulation  
 b) Illustration of traffic simulation for a driving simulator using the moving window. The black vehicle is the driving simulator.

The basic idea of the moving window is to avoid simulating vehicles several miles ahead or behind the simulator vehicle, which is not very efficient. Vehicles that far away do not affect the driving simulator. However, the window cannot be too small. Firstly, the size of the window is constrained by the sight distance. The window must at least be as wide as the sight distance, so that vehicles do not “pop up” in front of the simulator vehicle. Secondly, the window must be large enough to make the traffic realistic and to allow for speed changes of the simulator vehicle. A too narrow window can for instance lead to situations in which vehicles that for the moment travel faster than the simulator vehicle pass out of the system and will not reappear when the simulator driver increase the speed. A too narrow window can also make it hard to model how traffic conditions moves along the traffic stream, for example queue spillback from a merging area. Notice that the moving window does not control which vehicles that are visualized on the screen in the driving simulator, this is instead controlled by the scenario module. The moving window is generally wider than the area within vehicles are shown on the screens in the simulator.

In order to get a wide enough window but at the same time limit the computational efforts, the window is divided into one inner and two outer regions, see Figure 4.2. It is important that the vehicles in the closest neighborhood of the simulator vehicle behave like real drivers. Vehicles traveling in the inner region are therefore simulated according to advanced behavioral models for car-following, overtaking and speed adaptation, etc. The inner area is therefore called the *simulated area*. The behavior of vehicles traveling further away from the simulator is less important. These vehicles, traveling in the outer regions, are simulated according to a simple mesoscopic model that is less time-consuming. When getting closer to the simulated area, these vehicles become candidates to move into the simulated area. The outer regions are therefore called *candidate areas* and vehicles traveling in these areas are consequently called *candidate vehicles*. At the end of the candidate areas vehicles that travels out of the system is removed from the model and new vehicles are generated, see Section 4.2.



**Figure 4.2** The different areas. The black vehicle is the driving simulator, the grey vehicles are simulated vehicles and the white vehicles are candidate vehicles.

### 4.1.3 The simulated area

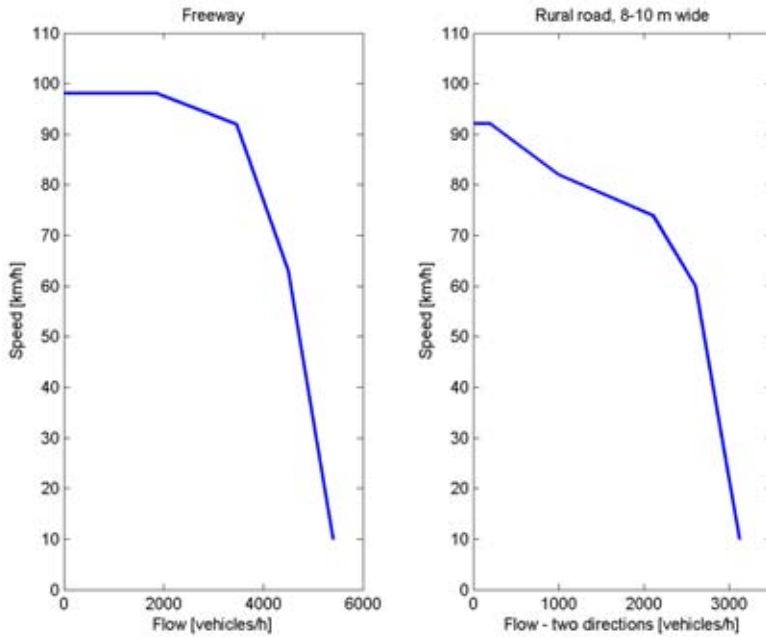
Vehicles traveling in the simulated area, the inner region, are simulated according to established techniques for time-driven micro simulation of traffic. The vehicles are updated frequently. Different behavioral models are used to create real driving behavior. The behavioral models used in this simulation model are presented in Section 4.3. The utilized behavioral models are to a large extent based on behavioral models from the TPMA (Traffic Performance on Major Arterials) model (Davidsson et al., 2002) and the VTISim model (Brodin et al., 1986).

### 4.1.4 The candidate areas

The candidate areas are in principle only necessary for traffic traveling in the same direction as the driving simulator vehicle. Oncoming vehicles far away in front of the simulator are assumed to not affect the driving simulator driver. Oncoming vehicles far behind the simulator may only affect the simulator in rare circumstances, for example by incidents that create congestion in the oncoming lane on rural roads. Thus the candidate areas are in principle redundant in the oncoming direction. Vehicles in the oncoming direction can either be generated at the front edge of the window or at the edge between the candidate area in front of the simulator vehicle and the simulated area. However, it is essential to simulate oncoming vehicles in the whole simulated area on rural roads since the oncoming vehicles have a great impact on the queue discharging rates in the driving simulator direction. When using the candidate areas in the oncoming direction, the oncoming vehicles are assumed to drive at the platoon leader's desired speed in the candidate area.

Candidate vehicles in the same direction as the simulator vehicle are updated according to a simple mesoscopic model. Initially the candidate vehicles were assumed to drive at their desired speed, (Janson Olstam, 2003, Janson Olstam et al., 2003). This worked properly for low traffic flows on freeways. However, at rural road and at higher flows on freeways the candidate vehicles traveled too fast, which resulted in a quite empty candidate area in front of the simulator and congestion in the candidate area behind the simulator vehicle. Instead of assuming that the candidate vehicles drive at their desired speed a speed-flow curve is used to calculate the candidate vehicles' speeds. The utilized speed-flow relationships are taken from representative relationships for Swedish roads presented in SRA

(2001), see examples in Figure 4.3. These speed-flow relationships vary with road type, vehicle type, speed limit, number of lanes, road width, and sight class. However, in the model not all dependent variables are used. The speed-flow relationship for cars is for instance used for all vehicle types and on rural roads the relationships for the best sight class (class 1) is used irrespective of the sight class of the simulated road. The relationships in the model depend on the road type, road width and the speed limit.



**Figure 4.3** Examples of speed-flow relationships for a freeway with speed limit 90 km/h and a 8-10 m wide rural road with speed limit 90 km/h (SRA, 2001).

The candidate vehicles' actual speeds are based on the vehicles' desired speeds and the average speed taken from the relevant speed-flow function. This is the way in which delay due to surrounding traffic is modeled in the candidate area. Two different methods to calculate a vehicle's speed have been tested. In the first one, the speed of vehicle  $n$  is calculated as

$$v_n = f(q) + (v_n^{des} - f(0)), \quad (4.1)$$

where  $v_n^{des}$  is the desired speed of vehicle  $n$ ,  $q$  is the traffic flow, and  $f(q)$  is the average travel speed at a traffic flow of  $q$  vehicles/h. This method assumes that a vehicle will be able to drive as much faster or slower than the average speed as it does at free flow conditions. The second method instead use the methodology of not only shifting the speed distribution curve but also rotating it around its median, similar to the speed adaptation model in Brodin and Carlsson (1986), see

Section 2.3.4. Following this approach the speed of vehicle  $n$  is instead calculated as

$$v_n = \left( f(q)^Q + \left( (v_n^{des})^Q - f(0)^Q \right) \right)^{1/Q}, \quad (4.2)$$

where  $Q$  is a parameter that controls the rotation of the speed distribution curve. When using this method, vehicles traveling fast will be more affected than vehicles that drive slow. Vehicles that drive faster than the average speed at free flow conditions will still do this at the traffic flow  $q$ , but the difference between the vehicle's speed and the average speed will be smaller. The parameter  $Q$  has initially been set to  $-0.2$ , which is the value used for speed adaptation to speed limits in the model presented in Brodin and Carlsson (1986). Both models seem to perform well, but further evaluation is needed before a recommendation can be made.

Apart from this reduction of speed corresponding to the speed-flow function, the candidate vehicles travel unconstrained with regard to surrounding traffic. When a candidate vehicle catches up with another candidate vehicle it can always overtake the preceding vehicle without any loss in time. In principle every vehicle is driving in a separate lane, which is illustrated by the multiple lanes in the simulator direction in Figure 4.2.

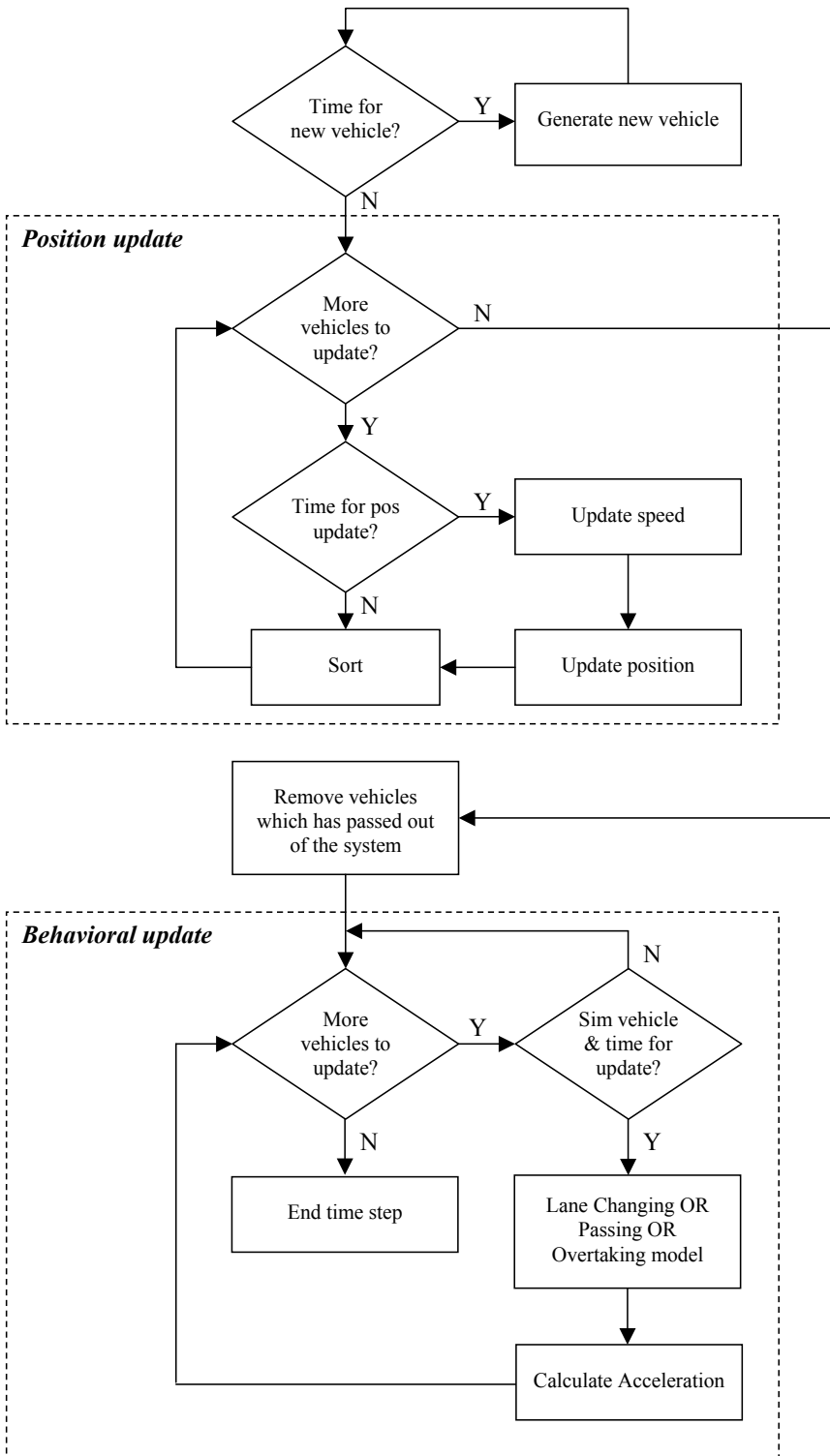
A candidate vehicle that reaches either boundary of the simulated area is only allowed to travel into the simulated area if there is a sufficient distance to the first vehicle in the simulated area. The logic for checking if there is a sufficient space differs depending on if the vehicle comes from the candidate area behind or in front of the simulator vehicle.

For vehicles that want to enter the simulated area from the candidate area behind the simulator, the car-following model is used to deduce whether it can do so or not. The vehicle is allowed to enter the simulated area if it can do so without decelerating, thus when the car-following model returns a non-negative acceleration. If this is not the case, the vehicle adopts the acceleration given by the car-following model and is then placed at the edge between the candidate area and the simulated area. The vehicle gets a new opportunity to pass into the simulated area in the next time step. While waiting on a sufficient gap the candidate vehicle adjusts its speed in order to avoid high decelerations when entering the simulated area. There is also a minimum gap criterion saying that the gap to the front vehicle must at least be larger than a minimum distance between stationary vehicles parameter. In the freeway environment cars are also given the possibility of entering the simulated area in the left lane. The same logic is used in order to deduce whether they are allowed to enter the left lane in the simulated area.

For vehicles in the candidate area in front of the simulator vehicle a similar but somewhat different approach is used. The simulated vehicle closest to the candidate area treats the first vehicle in the candidate area as any other simulated vehicle. Thus it uses the car-following model to adjust the speed and the lane-changing or overtaking model in order to decide whether it should try to overtake the candidate vehicle. This is similar to the approach used in the other candidate area, but instead of applying the car-following model on the candidate vehicle it is here applied on the following vehicle in the simulated area.

#### **4.1.5 Vehicle update technique**

The simulation model follows a traditional time-discrete update approach. The update procedure, described in Figure 4.4, has been divided into two parts. In the first part the speed and position is updated for all vehicles and in the second part the behavior of the simulated vehicles is updated, i.e. acceleration, lane-changing and overtaking decisions, etc. The separation of the position and behavior updating makes it possible to avoid that information of already updated vehicles is used when updating the behavior of the rest of the vehicles.



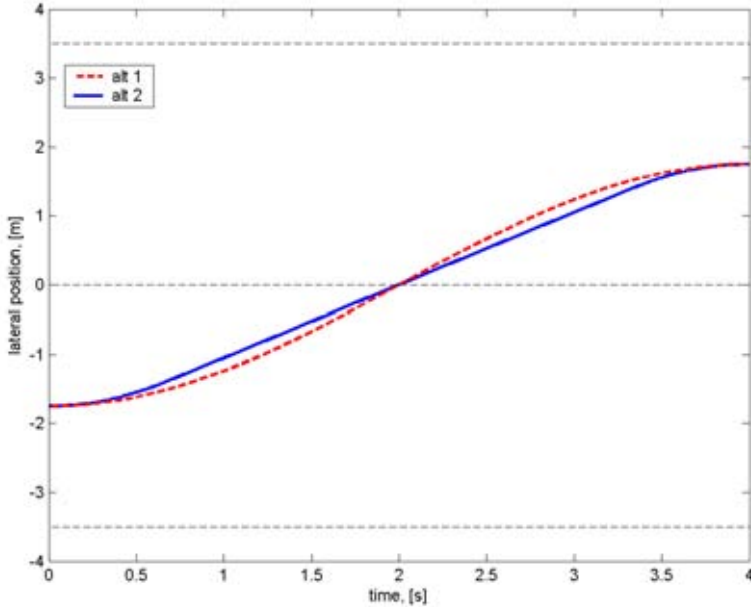
**Figure 4.4** Flow chart over the vehicle update procedure.

The speed and position of the vehicles is calculated using the Newtonian equations of motion, assuming that the acceleration and the speed are constant during the time step. The speed and position for the next time step is then calculated as

$$\begin{aligned} v_n(t) &= v_n(t - T) + T \cdot a_n(t - T) \\ x_n(t) &= x_n(t - T) + T \cdot v_n(t - T), \end{aligned} \tag{4.3}$$

where  $v_n(t)$  and  $x_n(t)$  is the speed and position of vehicle  $n$  at time  $t$ , and  $T$  is the duration of a time step. For candidate vehicles the acceleration  $a_n$  is zero and the speed  $v_n$  is instead calculated from either equation (4.1) or (4.2). The time step  $T$  varies depending on in which area the vehicle is. Simulated vehicles are updated with a time step of 100 milliseconds. However, vehicles within sight of the simulator driver are updated more often in order to get a clear picture on the simulator screen. Candidate vehicles are updated less seldom, currently one time per second.

So far, we have only treated the update of the longitudinal speed and position. The vehicle's lateral position is assumed only to change as a result of a change of lane. When driving in a lane the vehicles are assumed to drive in the middle of the lane. During a change of lane two different approaches for modeling the lateral position has been tested. In the first one the vehicles lane-changing movements is assumed to follow a sine-curve, see alternative 1 in Figure 4.5. In the second alternative the movements follows a function that uses a second grade polynomial in the beginning and in the end of the movement and a linear relationship in between. Both approaches looks quite realistic on freeways, were the lane-changing movements are made during quite a long time, about 4-6 seconds according to measurements presented in Liu and Salvucci (2002). However, on rural roads "lane changing" movements are sometimes executed during a much shorter time, for instance at evasive maneuvers or when aborting an overtaking. During the user evaluation, see Section 6.3, it was observed that none of the two functions seem to represent lateral movements at quick lane changes correctly. Another drawback is that these functions assume that all started lane changes are completed. The functions cannot model the lateral movements when a driver decides to abort an ongoing lane change. In order to overcome these drawbacks a more advanced steering model is needed, perhaps a model similar to the one presented in Boer et al. (2001) or a control theory based model.



*Figure 4.5* The two different functions for lateral lane-changing movements. The dashed grey lines symbolize the lane lines.

## 4.2 Vehicle generation

Vehicles traveling much slower or faster than the simulator will travel out of the simulated area, into the candidate areas and finally out of the system. Thus, the system will become empty if no new vehicles are generated. Since our model does not include intersections or ramps, all new vehicles are generated at the edges of the window, see Figure 4.2. As the edges consequently move with the speed of the simulator vehicle, new vehicles cannot be generated in the same way as in ordinary traffic simulation models, where new vehicles are generated at the geographical places that define an origin in the simulated network.

Oncoming vehicles can, however, be generated almost in the same way as in ordinary simulation models. The difference is, that the arrival time for an entering vehicle do not only depends on the own speed and headway but also of the speed of the simulator vehicle.

### 4.2.1 Generation algorithm

In driving direction of the simulator vehicle, new vehicles are generated both behind and in front of the simulator. The generation process differs from generation approaches used in ordinary simulation models. For instance, when generating new vehicles at the edge behind the simulator vehicle it is only interesting to generate vehicles traveling faster than the simulator vehicle. Vehicles driving slower than the simulator vehicle will never catch up with the edge between the candidate area and the simulated area. The opposite holds for the edge in front of the simulator vehicle, where there is no need to generate vehicles that drive faster than the simulator vehicle.



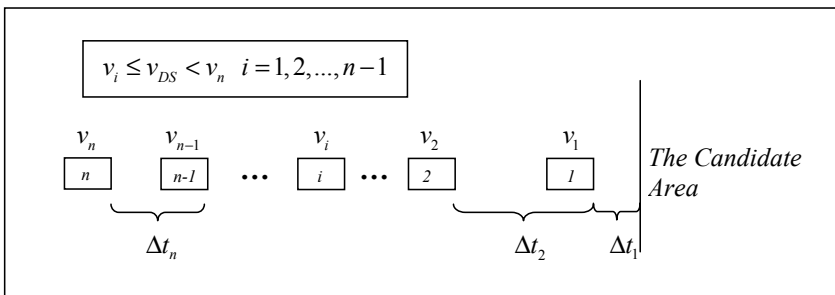
If only generating faster vehicles behind and slower vehicles in front of the simulator vehicle, the calculation of the vehicles arrival times cannot be done in the usual way. In ordinary traffic simulation models, vehicles arrival time is drawn from a time headway distribution. The average time headway between arriving vehicles is calculated as the inverse of the traffic flow. If the arrival time between faster vehicles generated behind the simulator vehicle were calculated like this, the average distance between them would be equal to the average distance between vehicles. Since the vehicles generated behind the simulator vehicle is a sub-group of the total population of vehicles, the actual average distance between vehicles in this sub-group has to be longer than the average distance between vehicles. If this is ignored new vehicles will be generated with a higher frequency compared to reality, which results in a traffic composition that differs from the specified one. In order to deal with this problem a new generation algorithm has been developed. This algorithm generates a new vehicle and calculates a reasonable time to arrival for the generated vehicle. Below follows a description of the algorithm used for generation of new vehicle behind the simulator vehicle, see also the illustration in Figure 4.6.

0. Set  $i = 1$ .
1. Generate a new vehicle with a desired speed,  $v_i^{des}$ , and time headway,  $\Delta t_i$ , to the vehicle in front.
2. Calculate the vehicle's speed,  $v_i$ , given its desired speed and the traffic flow, according to either equation (4.1) or (4.2).
3. If the speed is lower than the simulator vehicle's present speed: increase  $i$  and go to step 1, otherwise let  $n = i$
4. Calculate the time to arrival as

$$\Delta T = \frac{\sum_{i=1}^n (\Delta t_i \cdot v_i)}{v_n - v_{DS}}, \text{ where}$$

$v_{DS}$  is the present speed of the simulator vehicle, [m/s]

5. Discard all vehicles except the last generated.



**Figure 4.6** Illustration of the algorithm for generation of new vehicles at the edge behind the driving simulator.

During the iterations the algorithm will generate a number of slower vehicles and one faster vehicle, but in the end only one faster vehicle will be generated since every slower vehicle is discarded. In order to limit the computational effort and to avoid that the algorithm gets “stuck” trying to generate faster vehicles when the simulator vehicle is driving very fast, new vehicles are only generated behind the simulator vehicle when it is traveling slower than the highest speed in the current desired speed distribution. For the same reason has the number of tries at each time step been restricted, currently to 10 presumptive new vehicles per time step, i.e.  $n \leq 10$ .

In order to avoid too long time to arrivals, the speed of the generated vehicle,  $v_n$ , must differ by at least 5 % from the simulator vehicle’s speed,  $v_{DS}$ . If the speed lies in this range, that is  $v_{DS} < v_n \leq 1.05 \cdot v_{DS}$ , a speed equal to  $1.05 \cdot v_{DS}$  is used in the calculations of the arrival time.

At the edge in front of the simulator, new vehicles are generated according to a corresponding algorithm. But the stop criterion is then a speed lower than the simulator’s present speed.

#### 4.2.2 Generation of new vehicles on freeways

The time headways  $\Delta t_i$  correspond to a one-time picture of a traffic situation and they may therefore differ from the vehicles’ desired time headways, presented in Section 4.1.1. The time headways  $\Delta t_i$  are instead drawn from a time headway distribution, which differ between the freeway and the rural road environment. The time headway distributions will be described in this and the following sections.

##### Time headway distribution

For the freeway environment the time headway distribution presented in Blad (2002) is used for generating the time headways  $\Delta t_i$ . This time headway function is also used in the TPMA-model. This time headway distribution can be expressed as

$$f(x) = 0.1 \cdot p_1^2 \cdot \ln\left(\frac{1 + e^{(x-p_2)}}{1 + e^{-10p_2}}\right) \cdot \frac{(1 + e^{-10p_2})^{0.1p_1}}{(1 + e^{10(x-p_2)})^{(0.1p_1+1)}} \cdot e^{10(x-p_2)}, \quad (4.4)$$

where  $x$  is the time headway and  $p_1$  and  $p_2$  is parameters that depends on the traffic flow  $Q$  according to

$$\begin{bmatrix} p_1 \\ p_2 \end{bmatrix} = \begin{bmatrix} -7.991 \cdot 10^{-3} + 7.737 \cdot 10^{-4}Q - 3.099 \cdot 10^{-7}Q^2 + 1.089 \cdot 10^{-10}Q^3 \\ -2.807 \cdot 10^{-1} + 6.485 \cdot 10^{-3}Q - 9.794 \cdot 10^{-6}Q^2 + 3.479 \cdot 10^{-9}Q^3 \end{bmatrix} \quad (4.5)$$

and

$$\begin{bmatrix} p_1 \\ p_2 \end{bmatrix} = \begin{bmatrix} -7.628 \cdot 10^{-2} + 9.527 \cdot 10^{-4}Q - 1.500 \cdot 10^{-7}Q^2 + 3.991 \cdot 10^{-11}Q^3 \\ 3.890 - 5.273 \cdot 10^{-3}Q + 2.885 \cdot 10^{-6}Q^2 - 5.432 \cdot 10^{-10}Q^3 \end{bmatrix}, \quad (4.6)$$

for the right and left lane, respectively. The values of the parameters  $p_1$  and  $p_2$  has also been taken from Blad (2002). For lane flows larger than 1800 vehicles/h the function (4.4) is adjusted to

$$f_{stretch}(x) = \frac{f\left(\frac{x}{corr(Q)}\right)}{corr(Q)}, \quad (4.7)$$

in order to fit real data in a better way.  $corr(Q)$  is a correction factor calculated according to

$$corr(Q) = 1.347 \cdot 10^1 - 1.314 \cdot 10^{-2}Q + 4.285 \cdot 10^{-6}Q^2 - 4.653 \cdot 10^{-10}Q^3 \quad (4.8)$$

and

$$corr(Q) = 7.910 - 8.780 \cdot 10^{-3}Q + 3.535 \cdot 10^{-6}Q^2 - 4.404 \cdot 10^{-10}Q^3, \quad (4.9)$$

for the right and left lane, respectively.

### Calculation of lane flows

In order to use the time headway distribution functions presented above, a model for estimating how the traffic flow splits on the two lanes is needed. We use the model presented in Blad (2002) for this purpose. In this model, which was originally presented in Carlsson and Cedersund (2000), the right lane flow,  $Q_{right}$  is calculated according to

$$Q_{right} = k \cdot (1 - e^{-l \cdot Q}), \quad (4.10)$$

where  $k$  and  $l$  is calculated as

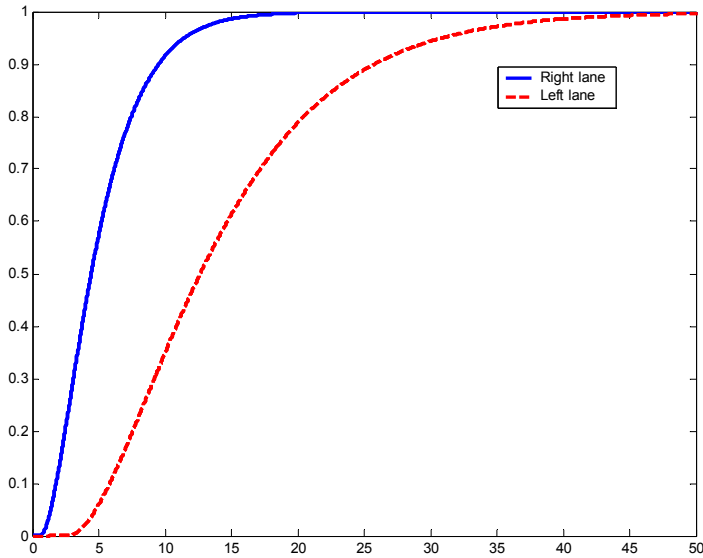
$$k = 2600 \cdot (1 - 0.34 \cdot \alpha - 0.90 \cdot \beta) \quad (4.11)$$

and

$$l = \frac{(3.1 + 4 \cdot (\alpha + \beta))}{10000}, \quad (4.12)$$

respectively. The parameter  $\alpha$  is the proportion of trucks and buses and  $\beta$  is the proportion of trucks with trailer. The left lane flow is then calculated as the

difference between the total flow and the right lane flow. Figure 4.7 shows the resulting time headway distributions at a total flow of 1000 vehicles/h.



**Figure 4.7** Time headway distributions for the right and left lane on a two-lane freeway at a total traffic flow of 1 000 vehicles/h.

### Generation of oncoming vehicles

Oncoming vehicles on freeways do not interact with the driving simulator. These vehicles could therefore be visualized by a playback loop of a recorded, measured or simulated vehicle stream. In this work we have chosen to simulate also the oncoming vehicle on freeways since this was the easiest solution with respect to programming effort. It is probably more efficient to use a playback loop.

On freeways the oncoming vehicles are generated at the edge between the simulated area and the candidate area in front of the simulator vehicle. The time between arrivals of new vehicles is calculated using equation (4.4)-(4.12) and the vehicles desired speed and the present speed of the simulator vehicle. The oncoming vehicles are assumed to drive at their desired speed when they enter the model. This assumption and the fact that no correlation is made between desired speed and headway requires a quite long warm-up simulation stretch. The reason for this is that vehicles may be generated very close to each other and with large speed differences, which can lead to strong decelerations and oscillations in the vehicle stream. This loading problematic has been totally ignored in this work by the same reason as mentioned above. Noticeable is however that no strange or unrealistic behavior was observed in the oncoming direction on freeways during the user evaluation, see Section 6.3. This indicates that this method probably is good enough for this application.

In order to limit the simulation effort, the oncoming vehicles is removed from the model has soon as they surely no longer is visible in the mirrors of the simulator vehicle. A distance of 2 km has been assumed to be enough.

### 4.2.3 Generation of new vehicle and vehicle platoons on rural roads

Due to limited passing and overtaking possibilities on rural roads, vehicles often end up in platoons. A simulation model for rural road traffic must therefore generate realistic vehicle platoons rather than only generating individual vehicles. A platoon generation model has therefore been used for the generation of vehicles in the oncoming direction. The generation of realistic vehicle streams in the simulator vehicle direction is performed in another way. Generating vehicle platoons in this direction would demand a more complicated model for updating the candidate vehicles. Such a model must handle both vehicles from the simulated area and newly generated vehicles traveling in platoons. Instead of generating platoons, single vehicles are generated. Vehicle platoons then arise by themselves, for example when slower vehicles enter the simulated area from the candidate area in front of the simulator vehicle.

#### Generation of vehicles in the simulator direction

Vehicles in the simulator vehicle direction are generated according to the algorithm presented in Section 4.2.1. The time headways  $\Delta t_i$  are assumed to be exponential distributed with mean equal to the inverted traffic flow and they are restricted downwards by a minimum value for free time gaps, currently set to 6 seconds.

#### Generation of oncoming vehicles

We use the platoon generation model used in the VTISim model (Brodin et al., 1986) for generating realistic vehicle platoons in the oncoming direction. In this model the queuing model presented in Miller (1967) is used to estimate the mean platoon length as

$$\hat{\mu} = \begin{cases} 0.58 + 1.58 \cdot Z & Z > 1 \\ 1 + 1.16 \cdot Z & Z \leq 1, \end{cases} \quad (4.13)$$

where  $Z$  is calculated as

$$Z = \begin{cases} 0.1 \cdot \frac{q_f}{\lambda} & \lambda > 0 \\ 20 & \lambda \leq 0. \end{cases} \quad (4.14)$$

The parameter  $\lambda$  describes the overtaking possibilities on the current road and is calculated as.

$$\lambda = A \cdot q_o^{-0.66} \left( 1 - \frac{q_f \cdot \bar{\mu}_c}{3600} \right) \ln(2 - p_{hv}), \quad (4.15)$$

where  $A$  is a road standard measure,  $q_f$  is the flow in the studied direction,  $q_o$  is the flow in the oncoming direction,  $\bar{\mu}_c$  is the mean time gap between constrained vehicles for the current composition of vehicle types, and  $p_{hw}$  is the proportion of heavy vehicles. Since the road standard differs between roads, the road standard measure  $A$  has to be calibrated for every new road that is going to be simulated. The calibration parameter  $\bar{\mu}_c$  is calculated as

$$\bar{\mu}_c = \sum_{i \in I} p_i \mu_i, \quad (4.16)$$

where  $I$  is the set of all vehicle types,  $p_i$  is the proportion of vehicle type  $i$ , and  $\mu_i$  are calibration parameters currently set to 1.2 s for cars, 1.5 s for trucks and buses, 1.75 s for trucks with trailer (3-4 axes), and 2.25 s for trucks with trailer (5 or more axes).

Given the mean platoon length  $\hat{\mu}$  the proportion of free and constrained vehicles can be calculated as  $\hat{\mu}^{-1}$  and  $1 - \hat{\mu}^{-1}$ , respectively. The platoons are generated by first generating one free vehicle and then generating constrained vehicles until a new free vehicle is generated. The order of vehicles in the platoon is then rearranged so that the slowest vehicle becomes the lead vehicle. Time headways between vehicle platoons, i.e. time headways for platoon leaders, are assumed to be exponential distributed according to the function

$$h(t) = \begin{cases} e^{-\frac{t-t_{\min}}{\bar{t}_f - t_{\min}}} & t \geq t_{\min} \\ 0 & t < t_{\min}, \end{cases} \quad (4.17)$$

where  $\bar{t}_f$  is the mean free time headway and  $t_{\min}$  is a minimum time headway for free vehicles parameter, currently set to 6 seconds. Time headways between constrained vehicles are assumed to follow a lognormal distribution with mean  $\bar{t}_c$ . Vehicles driving in a platoon are assumed to drive at their desired time headway, whereby vehicles desired time gaps, see Section 4.1.1, is related to this constrained time headway. The mean constrained time headway  $\bar{t}_c$  is given by the vehicle-driver settings and the mean free time headway  $\bar{t}_f$  is calculated as

$$\bar{t}_f = 3600 \frac{\hat{\mu}}{q} - (1 - \hat{\mu}) \cdot \bar{t}_c, \quad (4.18)$$

where  $q$  is the traffic flow in the current direction and  $\hat{\mu}$  is calculated according to equation (4.13).

#### 4.2.4 Initialization of the simulation

There is not only important to generate new vehicles during the simulation. In order to create a realistic initial traffic situation a warm up simulation has to be

conducted. During the warm-up simulation new vehicles is generated using approaches utilized in ordinary applications of traffic simulation. On rural roads, the same platoon generation algorithm as used in the oncoming direction during the real simulation is used also in the driving simulator direction.

When running the warm-up simulation an end condition is needed. The end condition is normally a user specified warm-up run time. However, in this work this is replaced by a criterion on the number of vehicles passing the front of the window. The minimum number of vehicles has been set to the number of vehicles that passes out of the window during the average time it takes to travel the distance, and is calculated as

$$n_{\min} = q \frac{d}{\bar{v}_{des}}, \quad (4.19)$$

where  $q$  is the traffic flow,  $d$  is the total width of the moving window, and  $\bar{v}_{des}$  is the average desired speed for the current traffic composition. This condition is combined with a condition saying that the actual flow is at most allowed to differ 5 % from the specified flow.

### 4.3 Behavioral models

The behavioral models used in this work are to a large extent based on behavioral models from the TPMA-model (Davidsson et al., 2002, Kosonen, 1999) and the VTISim model (Brodin et al., 1986). These two simulation models are quite detailed documented and they have been well calibrated and validated for Swedish roads. However, some adjustments have been necessary to do and some of the behavioral models therefore differ from the original formulation. This section presents the utilized behavioral models for speed adaptation, car-following, lane-changing, overtaking, passing, and oncoming avoidance. The speed adaptation model is based on the VTISim model, but adjustments and recalibration have been done for freeways. The Car-following model is a fusion of the car-following logic in the TPMA model, the free acceleration model in the VTISim model, and a new deceleration model. The lane-changing model is totally based on the TPMA model with some minor adjustments. The overtaking model is based on the VTISim model but has been complemented with a sub-model that describes drivers' behavior during an overtaking including abortions of overtakings. The passing model is based on the VTISim model and the oncoming avoidance model is completely new. Except the presentation of the models, this section also discusses and presents the utilized parameter values.

#### 4.3.1 Speed adaptation

Drivers' desired speed varies along a road depending on the speed limit and the road profile. Every driver is assigned a basic desired speed, which is the speed they want to travel at under perfect conditions, see Section 4.1.1. The driver's desired speed on a specific road section is calculated according to the speed adaptation model presented in Brodin and Carlsson (1986) and later in Tapani (2005). The basic desired speed is reduced with respect to road width, curvature, and speed limit. However, on freeways only the speed limit is assumed to affect

the desired speed. In the model the median basic desired speed  $v_0$  is first reduced with respect to road width to a speed  $v_1$  according to

$$v_1 = \begin{cases} v_0 & \text{if } w \geq 8 \\ v_{1m} & \text{if } 7.5 \leq w < 8 \\ \left( \frac{1}{v_{1m}} + \frac{a}{w - 2.5} - \frac{a}{5} \right)^{-1} & \text{if } w < 7.5, \end{cases} \quad (4.20)$$

where,  $v_{1m}$  is a calibration constant equal to 27.75 m/s,  $w$  is the road width, and  $a$  is a calibration constant set to 0.042. The speed  $v_1$  is then reduced with respect to curvature to a speed  $v_2$  according to

$$v_2 = \begin{cases} v_1 & \text{if } r > 1000 \\ \left( \sqrt{v_1^{-2} + b \cdot (r^{-1} - 0.001)} \right)^{-1} & \text{if } r \leq 1000, \end{cases} \quad (4.21)$$

where  $r$  is the mean curve radius in meters and  $b$  is a calibration constant equal to 0.15. Freeways are always assumed to have curve radiuses larger than 1 000 meters. The speed  $v_2$  is finally reduced with respect to the current speed limit to a speed  $v_3$  according to

$$v_3 = \frac{v_2}{1 + c \cdot d^2}, \quad (4.22)$$

where  $z$  is the ratio between the speed limit and  $v_2$ ,  $d$  is a calibration constant equal to 0.05, and  $c$  is a calibration constant that depend on the speed limit and type of road. For rural roads the parameter  $c$  is calculated according to

$$c = 1.3 - |v_g - 90| \cdot 0.015, \quad (4.23)$$

where  $v_g$  is the speed limit. For freeways the parameter  $c$  has been recalibrated (Janson Olstam et al., 2003) and is now calculated according to

$$c = \begin{cases} 1.3 - |v_g - 70| \cdot 0.015 & \text{if } v_g < 110 \\ 0 & \text{otherwise} . \end{cases} \quad (4.24)$$



As seen in equation (4.24) drivers are assumed to drive at their basic desired speed when driving on freeways with speed limits of 110 km/h or higher.

The desired speed  $v_{3n}$  for a certain vehicle  $n$  at a certain part of a road is finally calculated as

$$v_{3n} = \left( v_{0n}^Q - (1 - \alpha) \cdot (v_0^Q - v_1^Q) \right)^{1/Q}, \quad (4.25)$$

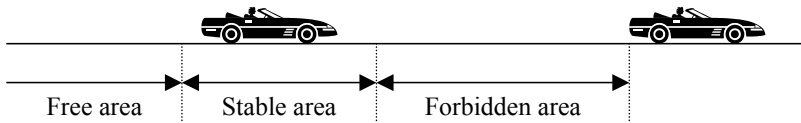
where  $0 \leq \alpha \leq 1$  is a vehicle type dependent parameter. Current values on  $\alpha$  are 0 for cars, 0.3 for trucks and buses, and 0.5 for trucks with trailer. The parameter  $Q$  is a dispersion measure calculated according to

$$Q = \frac{q_1(v_0 - v_1) - 2q_2(v_1 - v_2) - 2.5q_3(v_2 - v_3)}{(v_0 - v_1) - 2(v_1 - v_2) - 2.5(v_2 - v_3)}, \quad (4.26)$$

where  $q_1$ ,  $q_2$ , and  $q_3$  are calibration constants equal to 0.6, -0.8, and -0.2, respectively. As seen by equation (4.25), the desired speed is not only the result of a shift of the basic desired speed distribution but also of a rotation around its median. Values of  $Q < 1$  results in an anti-clockwise rotation around the median. This implies that fast vehicles will be more affected than slow vehicles. For  $Q = 1$  the desired speed distribution is the result of a parallel shift of the basic desired speed distribution.

### 4.3.2 Car-following

The car-following model is based on the car-following model presented in Kosonen (1999) and in Davidsson et al. (2002). The car-following model is probably best classified as a safety distance model. Three different regimes are used, namely *Free*, *Stable*, and *Forbidden*, see Figure 4.8.



**Figure 4.8** The three different regimes in the car-following model

The different regimes are defined by headways. The forbidden area is defined by a headway that depends on the speed of both the follower and the leader. It consists of an estimation of the brake distance needed for a deceleration from the follower's speed down to the leader's speed with a normal deceleration rate. In this work the forbidden headway is calculated as

$$d_f(v_n, v_{n-1}) = \begin{cases} v_n \cdot t_{\min} + L_n + \frac{v_n^2 - v_{n-1}^2}{2 \cdot a_{avg}} + s_{stop} & v_n \geq v_{n-1} \\ v_n \cdot t_{\min} + L_n + s_{stop} & v_n < v_{n-1}, \end{cases} \quad (4.27)$$

where  $v_n$  and  $v_{n-1}$  are the speed of the follower and the leader, respectively,  $t_{\min}$  is a minimum time gap,  $L_n$  is the length of the follower vehicle, and  $a_{avg}$  is an average normal deceleration rate parameter, currently set to  $2 \text{ m/s}^2$ . The last term,  $s_{stop}$ , is the minimum distance between stationary vehicles.

The stable area is defined as the area enclosed by the forbidden area and the free area. The width of the stable area,  $W_{stable}$ , is calculated as

$$W_{stable} = \begin{cases} \max \{ d_f(v_n + 2.5, v_{n-1}) - d_f(v_n, v_{n-1}), v_n T_s, W_m \} & v_n \geq v_{n-1} \\ 0 & v_n < v_{n-1}, \end{cases} \quad (4.28)$$

where  $T_s$  is the minimum stable time headway,  $W_m$  is the minimum stable space headway, and  $d_f$  is the function presented in equation (4.27).

When traveling at greater headways than the sum of the forbidden headway and the width of the stable area, the vehicle is classified as free and accelerates or decelerates in order to obtain its desired speed. In the original TPMA version vehicles accelerate and decelerate by increasing or decreasing their speed with a discrete speed step of  $2.5 \text{ km/h}$ . This is however not very realistic from a micro perspective. In this work the acceleration is instead calculated by a continuous function. When the speed is lower than the desired speed the acceleration model presented in Brodin and Carlsson (1986) is used, which is

$$a_n = \frac{p_n}{v_n} - (C_A)_n \cdot v_n^2 - (C_{R_1})_n - (C_{R_2})_n \cdot v_n - g \cdot i(x_n), \quad (4.29)$$

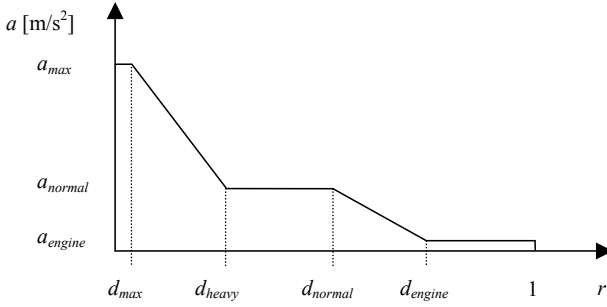
where  $p_n$  is the power/weight ratio for vehicle  $n$ ,  $C_A$ ,  $C_{R_1}$ , and  $C_{R_2}$  are vehicle type dependent air and rolling resistance coefficients, and  $g$  is the gravitational acceleration constant. The function  $i(x_n)$  represents the road incline at the position  $x_n$  of vehicle  $n$ .

When the speed of a free vehicle instead is higher than desired the vehicle uses a deceleration rate given as

$$a_n = \begin{cases} -(C_A)_n \cdot v_n^2 - (C_{R_1})_n - (C_{R_2})_n \cdot v_n - g \cdot i(x_n) & i(x_n) \geq 0 \\ -(C_A)_n \cdot v_n^2 - (C_{R_1})_n - (C_{R_2})_n \cdot v_n & i(x_n) < 0, \end{cases} \quad (4.30)$$

in order to reach the desired speed. In the stable area the driver is assumed to keep a constant speed, i.e. no acceleration or deceleration. If the vehicle travels faster

than its leader and passes the forbidden time headway, the vehicle enters the forbidden area and has to decelerate in order to avoid a collision and to reenter the stable area. The deceleration rate depends on the ratio,  $r$ , between the actual space headway and the forbidden headway (equation (4.27)). The basic idea is that the deceleration rate increases with decreasing ratio. The deceleration is at the moment calculated according to the piecewise linear function presented in Figure 4.9.

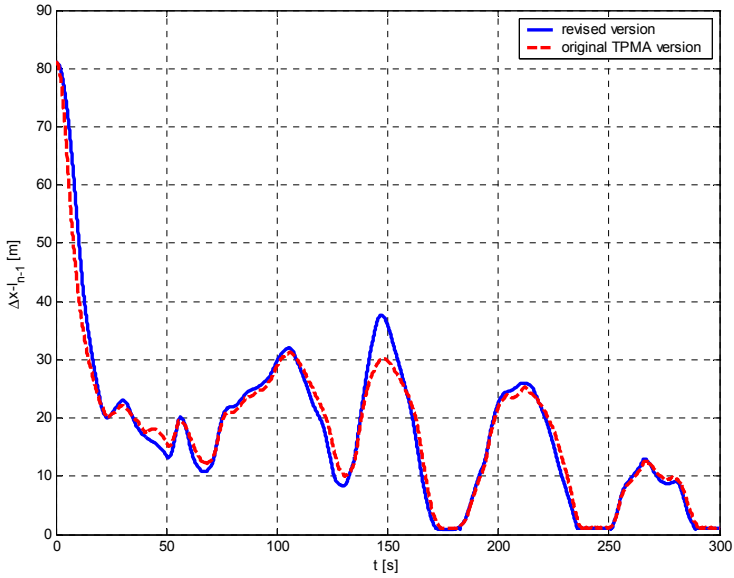


**Figure 4.9** Deceleration function.

The parameter  $a_{engine}$  represent the engine deceleration rate, currently set to 0.5  $m/s^2$ ,  $a_{normal}$  is the highest deceleration rate used under normal conditions, currently set to 3  $m/s^2$ , and  $a_{max}$  is the maximal deceleration rate under any circumstances, currently set to 9  $m/s^2$ . The maximum deceleration rate is set very high in order to always avoid collisions. The parameters  $d_{max}$ ,  $d_{heavy}$ ,  $d_{normal}$ , and  $d_{engine}$  are calibration constants currently set to 0.15, 0.3, 0.6, and 0.75, respectively. In cases where the follower is in the forbidden area but the leader drives faster than the follower the follower always use the engine deceleration rate in order to reenter the stable area.

This car-following model does not model driver reaction times explicit, but the stable area is a kind of implicit modeling of reaction time. That is, vehicles will not start to brake before they have passed the stable area. However, in an acceleration situation drivers are assumed to react immediately, that is  $W_{stable} = 0$  in these situations, see equation (4.28).

The car-following model is based on the calibrated TPMA model, but our model has only undergone minor calibration and validation work showing that it generates similar results as the original model, see for example Figure 4.10.



**Figure 4.10** Relative position between a leader and a follower when applying the original and the revised TPMA car-following model.

The car-following model described here is used both for freeway and rural road environments. However, there is an ongoing work to develop a new more flexible car-following model for rural roads, see Lundgren and Tapani (2005). This car-following model will probably replace the car-following model presented here, at least in the model for rural environments.

### 4.3.3 Lane-changing

The lane-changing model is based on the TPMA lane-changing model presented in Davidsson et al. (2002) and in Kosonen (1999). This model uses the pressure function presented in equation (2.6) and the logic presented in Figure 2.8 to model drivers willingness to change lane. In the original model drivers are not willing to change lane if the drivers speed is not less than its desired speed. This implies that drivers when catching up with a preceding vehicle first have to decelerate before they start any lane change to the left. This has in this work been replaced by a minimum difference conditions between the drivers desired speed and the speed of the front vehicle, resulting in the conditions

$$\begin{aligned}
 & \text{IF}(v_{n-1} < v_n^{des} - \Delta v_{\min} \text{ AND } c_l \cdot P_{fr} > P_{fl} \text{ AND } t_{lane} > t_{\min}) \text{ THEN} \\
 & \quad \text{desirable to change to the left} \\
 & \text{IF}(c_r \cdot P_{bl} > P_{fr} \text{ AND } t_{lane} > t_{\min}) \text{ THEN} \\
 & \quad \text{desirable to change to the right}
 \end{aligned}$$

where  $P_{fr}$ ,  $P_{fl}$ , and  $P_{bl}$  are the pressure, according to equation (2.6), to the front right, to the front left, and from the back left vehicle, respectively. The parameter  $t_{lane}$  is the time since the vehicle entered the current lane, and  $t_{\min}$  is the

minimum time before performing a new lane change, currently set to 10 s. Different values have been tested on the lane-changing parameters  $c_l$  and  $c_r$ , and in the end the parameters have been set to the values presented in Gutowski (2002), which is  $c_r = 0.86$  and  $c_l = 0.56$ . There is also an additional constraint for changes to the left saying that a vehicle do not change if it would have changed to the right if it were traveling in the target lane.

The gap-acceptance part of the lane-changing model also follows the approach used in the TPMA model. Different critical gaps are used for lane changes to the right and left and for lead and lag gaps. The critical gaps are calculated as

$$t_{cr} = t_n^{des} \cdot \gamma, \quad (4.31)$$

where  $t_n^{des}$  is the desired time gap for vehicle  $n$ , which is the vehicle that wants to change lane. The parameter  $\gamma$  is a calibration parameter that varies with direction of the lane change and between lead- and lag gaps. The parameter  $\gamma$  has been set to the values presented in Table 4.1, which follows recommended values presented in Hillo and Kosonen (2002).

**Table 4.1** Used values on the critical gap parameter  $\gamma$ .

	Lag gaps	Lead gaps
Change to the right	0.5	0.5
Change to the left	0.4	0.4

#### 4.3.4 Overtaking

The overtaking model consists of two parts. The first one is the modeling of overtaking decisions, i.e. the decision of whether or not to start an overtaking at the current situation. The second part is the modeling of drivers' behavior during the overtaking, evaluating if the overtaking should be completed or aborted.

##### The overtaking decision model

The overtaking model used is the one originally presented in Brodin and Carlsson (1986). The model work as follows. When a vehicle catches up a preceding vehicle, it has the possibility to execute a flying overtaking. If a flying overtaking is not possible, the vehicle has to slow down and adjust its speed to the preceding vehicle, according to the car-following model. The following vehicle can later, when an opportunity arises, execute an accelerated overtaking. Flying overtaking is only possible at the point where the vehicle catches up with the preceding vehicle and accelerated overtaking is only possible when the vehicle is in the following state. The following vehicle can only start an accelerated overtaking when passing either a sight maximum or when meeting an oncoming vehicle. Drivers that has overtook a vehicle which is driving in a platoon get an opportunity to continue in the oncoming lane and overtake also the vehicle ahead, a so called multiple overtaking. A vehicle only accepts an overtaking opportunity if the following four conditions are fulfilled.

1. *No overtaking restrictions*

The road must be free of overtaking restrictions from the vehicle's position and 300 meter ahead. Restrictions further away are assumed not to affect the overtaking decision.

2. *Enough space*

The estimated overtaking distance has to be shorter than the available gap. There must also be a sufficient space in the oncoming lane.

3. *Ability to execute an overtaking*

The estimated overtaking distance must be shorter than 1000 meters. This constraint is used to avoid extreme long overtaking distances. An accelerated overtaking is only executed if the vehicle's desired speed is higher than the preceding vehicle's desired speed. The difference must at least be 0.5 m/s.

4. *Willingness to execute an overtaking*

An overtaking is only performed if the driver accepts the available gap. The probability that a driver accepts a gap is determined by a stochastic probability function.

The estimated overtaking distance is calculated differently for flying and accelerated overtakings. At a flying overtake the driver estimates the overtaking distance as

$$d_O = \Delta d + \Delta d \cdot \frac{v_{n-1}}{(v_n - v_{n-1})}, \quad (4.32)$$

where  $\Delta d$  is the distance which the overtaking vehicle must travel relative the overtaken vehicle. At an accelerated overtake the driver instead estimates the overtaking distance as

$$d_O = \Delta d + v_{n-1} \cdot \sqrt{2 \cdot \frac{\Delta d}{a_n}}, \quad (4.33)$$

where  $a_n$  is the acceleration of vehicle  $n$  calculated according to equation (4.29).

The probability that a driver will execute an overtaking is a function of the available overtaking gap. The probability is determined by the following stochastic probability function

$$P(d_{gap}) = e^{-A \cdot e^{-k d_{gap}}} \quad (4.34)$$

where  $d_{gap}$  is the available gap in meters, that is

$$\min\{\text{distance to oncoming vehicle, distance to natural sight obstruction}\},$$

and  $A$  and  $k$  are constants that depend on: type of overtaking, type of sight limitation, type and speed of the vehicle being overtaken, and the road width. Calibrated values for Swedish road conditions has been presented in Carlsson (1993) and is also presented in Appendix B.

In order to avoid that vehicles in a platoon overtake each other too frequent the probability to start an overtaking when driving in a platoon is reduced with respect to the vehicle's place in the current vehicle platoon. The probability for vehicles in a platoon to start an overtaking is therefore finally given by

$$P_{red} = \kappa^{(N-1)} \cdot P(d_{gap}), \quad (4.35)$$

where  $N$  is the number of vehicles ahead in the platoon,  $\kappa$  is a calibration parameter, currently set to 0.6, and  $P(d_{gap})$  is the overtaking probability calculated according to equation (4.34). The probability is however not reduced in decisions situations of multiple overtakings, i.e. overtakings of one more vehicle precisely after ending an overtaking. The overtaking probability for roads with wide shoulders, defined as roads with shoulder width larger than 2.25 meters, is very high, even at short distances. This is due to the fact that vehicles on this kind of roads execute overtakings even if they will not be able to finish them before they meet an oncoming vehicle. The overtaking driver assumes that the oncoming vehicle will pass out into the shoulder in order to let the overtaking driver use the oncoming lane. This is also the way that this is handled in the model. On roads with wide shoulders a vehicle also have the possibility to go out in the shoulder in order to let faster vehicle pass in the normal lane. This is modeled in the passing model described in Section 4.3.5.

The overtaking decision model is an inconsistent driver model, i.e. overtaking decisions do not depend on previously overtaking decisions. Every overtaking decision is made independently. See the discussion on inconsistent versus consistent overtaking models in Section 2.3.3.

When decided to start an overtaking the driver starts to accelerate and changes to the oncoming lane after a short delay, currently set to 2 seconds.

### Behavior while overtaking

During an overtaking drivers' speed choices and acceleration behavior differs compared to normal driving. Drivers tend to be willing to drive faster than their desired speed during overtakings. This is modeled by giving all drivers an increment in desired speed during overtakings, currently set to 10 km/h. Another difference compared to normal driving is that drivers, especially car drivers, accelerate faster in overtaking situations. Car drivers therefore get an increase in their power/weight ratio, used in the free acceleration model in equation (4.29). The power/weight ratio is currently increased to at least 30 W/kg or with a maximum increment of 6 W/kg.

When overtaking, the overtaking vehicle must continuously reevaluate the distance to the vehicle in the oncoming lane and the distance left of the overtaking. This was not included in the model presented in Brodin and Carlsson (1986). The model has therefore been complemented with a new sub-model for this task. This new model states that a driver has to take action if the time to collision,  $TTC$ , with the oncoming vehicle is less than the estimated time left of the overtaking. The time left on the overtaking is estimated as

$$t_{left} = -\frac{v_n - v_{n-1}}{a_n} + \sqrt{\left(\frac{v_n - v_{n-1}}{a_n}\right)^2 + 2\frac{\Delta d}{a_n}} + 0.5 \cdot t_{change}, \quad (4.36)$$

where  $\Delta d = x_{n-1} - x_n + l_n + d_{\min}$ .  $d_{\min}$  is the critical lag gap for lane changes to the right and  $t_{change}$  is the time it takes to perform the lane change back to the normal lane. The vehicle is assumed to have passed the line between the oncoming and the normal lane after half the lane change time. The acceleration  $a_n$  is calculated according to equation (4.29). The time left of the overtaking,  $t_{left}$ , was initially directly compared to the time to collision. However, after noticing quite dangerous overtaking behavior during the user evaluation, see Section 6.3, a safety margin was added. This safety margin has temporarily been set to 1 seconds for all vehicles, but the parameter must of course be further calibrated.

In situations where  $TTC < t_{left}$  and the driver has not yet passed the lead vehicle,  $x_n < x_{n-1}$ , the driver is assumed to abort the overtaking. The driver then falls back and merges into the normal lane behind the lead vehicle. If the vehicle is side-by-side or has passed the lead vehicle, the driver instead increases the desired speed to a level needed to end the overtaking without colliding with the oncoming vehicle. That is the new temporarily desired speed is calculated as

$$v_n^{des*} = \frac{d_{left}}{(TTC - t_{safety})} + v_{n-1}, \quad (4.37)$$

where  $d_{left}$  is the minimum distance left of the overtaking,  $TTC$  is the time to collision, and  $t_{safety}$  is the added safety margin. If the vehicle's power/weight ratio is too low in order to be able to accelerate to the new desired speed, checked via equation (4.29), the vehicle is temporarily assigned a new power/weight value. However, if the power/weight ratio needed to drive at the new desired speed exceeds the maximum power/weight ratio for the current vehicle type, the driver abort the overtaking and falls back in order to merge into the normal lane behind the overtaken vehicle.

### 4.3.5 Passing

At roads with wide shoulders drivers can change "lane" to the shoulder to let other vehicle pass in the normal lane. The shoulder is classified as wide if the shoulder width exceeds 2.25 meter. Not all drivers pass out into the shoulder and some drivers do it sometimes and sometimes not. The passing model used is also an inconsistent model based on the model presented in Brodin and Carlsson (1986). Every time a vehicle catches up a preceding vehicle and wide shoulders are available, the preceding vehicle passes out into the shoulder according to a certain probability, at present set to 0.85. If there is an extra lane, as an auxiliary lane vehicles always go to the rightmost lane in order to let other vehicle pass.

### 4.3.6 Oncoming avoidance

Vehicles traveling on rural roads not only have to consider oncoming traffic when overtaking another vehicle, but also when oncoming vehicles overtake. On roads with wide shoulders, the natural reaction is to drive out into the shoulder if an



oncoming overtaking vehicle is getting too close. On other roads vehicles decelerate and signal with the horn or using the high beam. If the situation becomes really critical, they try to drive out to the shoulder or the ditch in a last attempt to avoid a collision. In our model drivers are assumed to go out into the shoulder on roads with wide shoulders if  $TTC < 2 \cdot t_{change} + t_{safety}$ , where  $t_{change}$  is the time for a lane change and  $t_{safety}$  is the added safety margin parameter. On roads without wide shoulders the driver instead signalizes with the high beam in these situations. However, if the  $TTC < 1.5 \cdot t_{change}$ , the driver brakes and moves as far out in the shoulder as he or she can in order to avoid a collision and lets the oncoming overtaking vehicle safely end the overtaking.



## 5 Integration with the VTI Driving simulator III

The developed simulation model has been integrated and tested within one of the driving simulators at VTI. This chapter will present how the integrated system works, starting with a short introduction of the VTI driving simulator III, followed by a description of the integrated system, and ending with how the simulation model communicates with the driving simulator system.

### 5.1 The VTI Driving simulator III

VTI has been developing and working with driving simulators since the 1970's. The VTI driving simulator III is the third generation of high-fidelity driving simulators developed at VTI. The simulator, see Figure 5.1, consists of a cut-off vehicle cab, a vehicle model, a motion system, a PC-based visual system, and a PC-based audio system. The visual system consists of three screens in front of the simulator, with a horizontal view of 120° and a vertical view of 30°, and three rear mirrors. The motion systems consist of a linear, a pitch, and a rolling motion. The simulator also has a vibration table that can simulate the contact with the road surface. Technical specifications of the driving simulator are available at the VTI webpage ([www.vti.se](http://www.vti.se)).

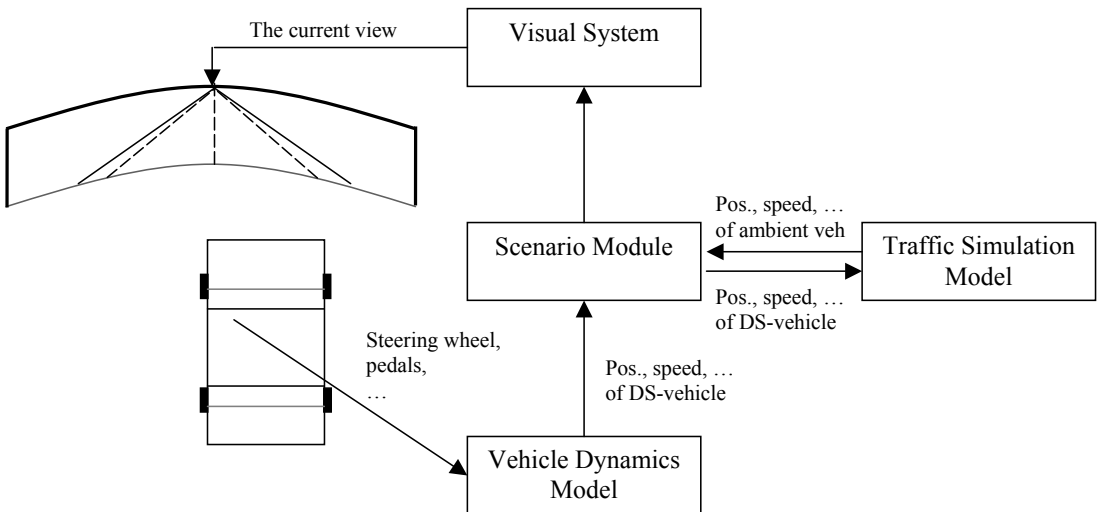


*Figure 5.1 The motion system of the VTI Driving simulator III (Source: Swedish National Road and Transport Research Institute (VTI) (2004))*

### 5.2 The integrated system

Figure 5.2 shows a schematic picture over the integration of the simulation model and the driving simulator. The normal flow through the system is that the vehicle

model calculates the simulator vehicle's state variables, i.e. acceleration, position, lateral position, etc., that corresponds to the subject's use of the steering wheel and the pedals. This information is sent to the scenario module that controls the movements of other moving objects, such as vehicles, animals, pedestrians, etc. Information about all moving objects, including the simulator vehicle, is sent to the visual system that calculates the current views, which finally is showed for the driver on the different screens in the simulator.



*Figure 5.2 Schematic picture over the integrated system*

In the integrated system the simulation of all autonomous vehicles is done in the traffic simulation model. The scenario module sends information about the driving simulator vehicle and any other non-autonomous vehicles or objects. The scenario module still controls the simulation loop and the simulation of a specific vehicle can be moved from the autonomous simulation in the traffic simulation model to a strictly controlled simulation in the scenario module. This framework makes it possible to combine autonomous vehicles with vehicles with predetermined behavior. The area of combining traffic simulation and scenarios that include vehicles predetermined behavior is discussed in Section 3.2.2. The scope of this thesis do not include any further investigation on how traffic simulation and critical events could and should be combined in order to deal with realism and reproducibility in the best possible way.

Except the possibility to move the control of a vehicle between the scenario module and the simulation model, the possibility to deny simulated vehicles to overtake the driving simulator or to overtake any vehicle at all has been implemented. This makes it for example possible to simulate a realistic oncoming traffic stream in which no overtakings are executed within sight of the simulator vehicle.

### 5.3 Communication with the scenario module

In the current integration configuration the traffic simulation model runs on a separate computer, which communicates with the scenario module via an ethernet network. However, the plan is to integrate the traffic simulation model into the

scenario module and thereby get rid of the ethernet communication. This has not yet been possible to do due to ongoing work with the scenario module computer.

The current ethernet communication set up uses two different kinds of protocols. In order to be sure that commands like start, stop and freeze of the simulation reaches the simulation model; these commands are sent via a TCP/IP connection. The TCP protocol checks whether the IP-packages arrive at their destination and return feedback information to the sender. Thanks to this handshaking the sender know if the information has reached the receiver, the scenario module for example knows if the simulation model has received an initialization or a start command. Information about the state variables is instead sent via a UDP/IP connection. This protocol is more convenient to use when sending real time data since no handshaking is used. This makes the connection faster but more unreliable since the sender does not know which IP-packages that reach the receiver. The sender cannot even be sure of that the packages reach the receiver in the same order that they were sent in. The solution to the increased unreliability is to increase the send frequency. Then it does not matter if one package does not reach the receiver or if the packages arrive in the wrong order. The receiver can discard any old package that arrives late and do not suffer from "losing" a package since it quickly gets a new package with up to date information.

In order to minimize the time delay between actions in the simulator and the visualization of those actions, information in the main driving simulator loop is sent with a very high frequency, namely 200 Hz. The scenario module must always have up to date information about the simulated vehicles. This implies that the scenario module either must be able to handle a missing package from the traffic simulation model or that the send frequency from the simulation model to the scenario module must even be higher than the frequency in the main loop. Irrespective of which approach that is used the update of the vehicles' positions and their behavior must be run on different computer processor threads since the position and speed must be updated with the main loop frequency while running the behavioral update with this frequency is a waist of computer power. The high frequency position update can either be ran in the traffic simulation module or in the scenario module. We have chosen the latter approach in which the scenario module keeps the simulated vehicles' positions and speeds up to date by extrapolating the latest information received from the traffic simulation model.

One problem when running the simulation model and the scenario module on different computers is the synchronization of clocks. The used clock in the scenario module and the traffic simulation model must be very well synchronized in order for the extrapolation of the vehicles' position to be correct. This has been a problem in this work because the scenario module and the simulation model have been running on different operating systems. The traffic simulation model has been running on a Windows machine, on which it has been hard to find a clock with enough accuracy and that does not drift. This has resulted in that when driving close to a simulated vehicle this vehicle seems to jump a little back and forth. There is therefore an ongoing work of compiling the traffic simulation model to also be able to run in the operating system Linux in order to totally integrate the simulation model and the scenario module. This would solve the synchronization problem and would also lead to that the ethernet communication is unnecessary, which is quite nice since the ethernet communication has been a very common source of error during the integration work.



## 6 Validation

The primary outputs of the developed model are the behavior of the simulated vehicles, thus the primary output is at a microscopic level. It is therefore important to also validate this model at a microscopic level. If the model is valid at the microscopic level it will also generate valid results at a macroscopic level, noticeable is that the opposite does not always hold. However, how validation of the developed model on a micro level could and should be done is not obvious. This chapter therefore starts with a discussion of different ways and methods for validating the model. The chapter then continues with a description of the two used validation approaches. The chapter ends with a discussion and some additional observations made during tests in the driving simulator.

### 6.1 How should the model be validated?

The most important thing in this application is that the simulator drivers observe the surrounding vehicles and their behavior as realistic. If this is not the case the simulator driver may behave differently compared to in a real car. One problem is nevertheless that it is hard to define realistic. A second problem is that it is hard to state how realistic the behavior has to be in order for the model to be valid. The goal is, of course, a model where the simulator driver cannot conclude whether an ambient vehicle is driven by another human or by a computer. However, the creation of a model that fulfills such a criterion is probably a utopia.

It is also important to remember that the model should not only generate valid results, it must also generate “safe” behavior. It is very important that the surrounding vehicles do not cause dangerous situations or collisions. Even though this happens sometimes in the real world, this cannot be tolerated in a driving simulator. The simulator driver should only be exposed to critical situations or events specified in the scenario module. Exceptions may, of course, be made for situations caused by extremely risky maneuvers made by the simulator driver.

Some of the things that influence a simulator driver’s opinion of how realistic the surrounding vehicles behave can be measured and compared to real data. One example is the outputs generated by the behavioral models, which can be compared to measurements from real drivers. Data for such validation studies can for example be obtained from measurements with instrumented vehicles or driving simulators. One approach is to measure the positions, speeds, and acceleration of two subsequent vehicles and then applying a car-following model to this data. It is then possible to compare acceleration rates given by the car-following model and the measured ones. It can also be interesting to study the agreement of relative speed and position. One big problem is that it is difficult and expensive to get enough and usable data for such comparisons. No such studies have been possible to conduct within the frames of this project and the aim has therefore been to use already calibrated and validated behavioral models. However, several of the used behavioral models have been adjusted and may perhaps need to be revalidated. The outputs from the behavioral models have in this work only been visually validated, that is by studying two- and three-dimensional visualizations of the simulation.

Another important part that can be measured and that is connected to the observed realism is the number of vehicles that catches up with the driving simulator and the number of vehicles that the simulator driver catches up with. When driving at a certain speed you may not be able to say whether the number of

vehicles that overtake you is comparable to when driving on a real road, but you certainly react if the proportion between vehicles that catches up with you and that you catches up with is not realistic. For example, if you according to your own opinion drive faster than the average driver you expect to catch up with more vehicles than catches up with you. These numbers of catch-ups can easily be measured when running the simulation model and be compared to real data. This kind of validation has been performed within this work and the results is presented in Section 6.2.

Another approach that can be used for validation is to let participants drive on a specific road both in reality and in the driving simulator. If the model is valid participants speed choices, headways, overtaking and lane-changing behavior should not differ between driving in the simulator and in a real car. This approach is not directly useful for validating the simulation model it is rather a method for validating the whole driving simulator system. If differences are observed it can be hard to distinguish whether they are due to the traffic simulation model or other parts of the simulator system.

Since the most important thing is that participants observe the surrounding vehicles as realistic, a reasonable approach could be to use simulator drivers' opinions in the validation. The human mind is a very useful tool that can be used both for detecting unrealistic behavior and to get statements on how realistic the behavior of the simulated vehicles is. Their statements will of course be highly subjective, but this can be overcome by letting several persons give their opinion. We have in this work tried to validate the simulation model based on such approach by conducting a small driving simulator experiment in which the participants were asked to give comments about the simulated vehicles' behavior. The design and results of this user evaluation study is presented in Section 6.3.

## 6.2 Numbers of active and passive overtakings

The first approach used in the validation work of the developed model was to study the numbers of active and passive overtakings. Active overtaking refers to the cases when the simulator driver overtakes other vehicles and passive overtakings refer to cases when other vehicles overtake the driver of the simulator. Participants may not be able to observe whether number of active and passive is correct or not, but they probably will react if the proportion between active and passive overtakings is wrong.

There is unfortunately no real data available on the number of active and passing overtakings. Data from the simulation model has instead been compared to an analytical expression for calculating the number of vehicles that a specific vehicle catches up with and the number of vehicles that catches up with this vehicle. The analytical expression was originally derived and presented in Carlsson (1995), in which it was used to estimate the number of active and passive overtakings of a vehicle used in a floating car study.

Let us first assume that the observed road section has the length  $L$  and that the studied vehicle travel with the speed  $v_0$  km/h. The travel time for the studied vehicle over the stretch  $L$  is then  $L/v_0$ . Let us now look at another vehicle that arrives later to the starting point of the stretch, traveling at the speed  $v$  km/h. In order for the second vehicle to catch up with the first vehicle before the stretch ends, the catch up must happen no longer than  $L \cdot (1/v_0 - 1/v)$  hours after the



first vehicle entered the stretch. During this time period  $q \cdot L \cdot (1/v_0 - 1/v)$  numbers of vehicles will arrive to the stretch, where  $q$  is the flow in the studied direction. In order to calculate how many vehicles that drives at the speed  $v$  and arrives during this time interval the time mean speed distribution  $f_t(v)$  must be known. The number of passive and active catch-ups can then finally be calculated according to

$$U_p = qL \int_{v_0}^{\infty} \left( \frac{1}{v_0} - \frac{1}{v} \right) f_t(v) dv \quad (6.1)$$

and

$$U_a = qL \int_0^{v_0} \left( \frac{1}{v} - \frac{1}{v_0} \right) f_t(v) dv, \quad (6.2)$$

respectively. One of the underlying assumptions for equation (6.1) and (6.2) is that every vehicle can overtake each other without any time delay. The equations can thus be expected to give upper limits on the number of active and passive catch-ups.

### 6.2.1 Simulation design

Data from the simulation model was taken from simulations of a straight and plain road during a time period of 2.5 hour. During the simulation also the driving simulator vehicle was simulated according to the simulation model, thus the simulator vehicle was not driven by a human being. The driving simulator driver's desired speed was varied between the different simulation replications. Three different basic desired speeds were used, namely 25.8, 30.8, and 35.8 m/s.

In the rural environment the sight distance was assumed to be infinitely long, thus available overtaking gaps were always restricted by oncoming vehicles. The simulated road was 9 meters wide and had a speed limit of 90 km/h, i.e. a quite normal Swedish rural road. Three different flow levels were used in this environment, namely 200, 400, and 600 vehicles/hour/direction.

For the freeway environment, a straight and plain road with speed limit 110 km/h were simulated. Also here three different flow levels were used: 500, 1000, and 1500 vehicles/h. For both environments the flow rates were chosen in such a way that they both cover low and high traffic conditions on Swedish roads.

In all simulations the share of heavy vehicles were set to 12 % (4 % trucks, 4 % buses, and 2 % of each of the two truck types with trailer), which corresponds to normal traffic conditions on Swedish roads. For every combination of basic desired speed and flow 10 replications were run, giving a total number of 90 replications for each road environment.

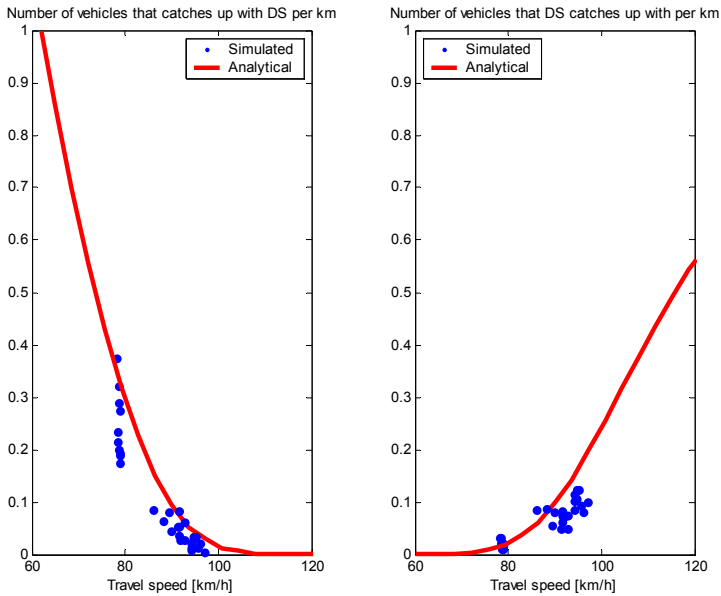
In the rural environment, active and passive catch-ups were calculated by first noting the number of active and passive overtakings during the simulation. The number of catch-ups can then be obtained by adding the queue length in front and behind the simulator vehicle, respectively, in the last time step. In the freeway

environment the number of passive catch-ups were measured as the number of vehicles that passed the driving simulator vehicle in the left lane. This number was reduced for the number of vehicles that the simulator vehicle temporarily passed on the right side. The number of active catch-ups was measured in the opposite way.

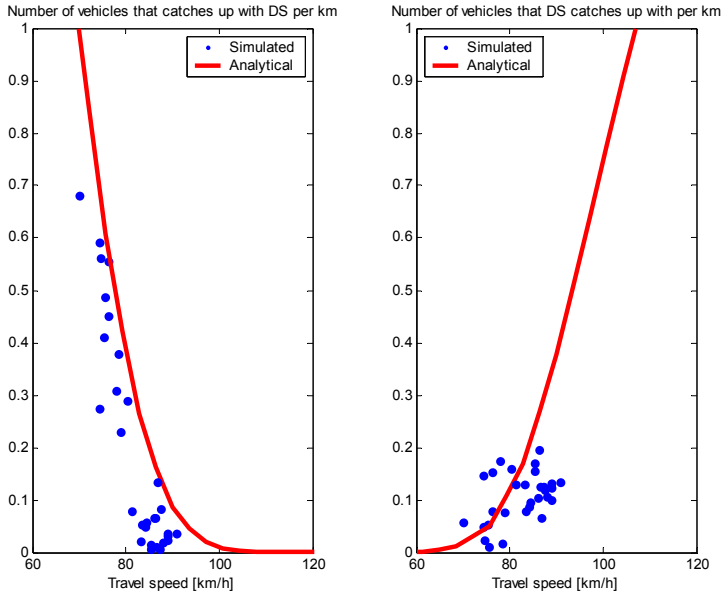
The time mean speed distribution,  $f_t(v)$ , used in equation (6.1) and (6.2) for calculating the expected number of active and passive catch-ups was generated by running the simulation model with the driving simulator standing beside the road. The time mean speed distribution was assumed to follow a normal distribution. Mean and standard deviation values to the distribution were calculated from point measurement from 10 such simulation runs. The time mean speed distribution  $f_t(v)$  varies with the traffic flow and the procedure above was therefore repeated for each studied flow.

### 6.2.2 Results

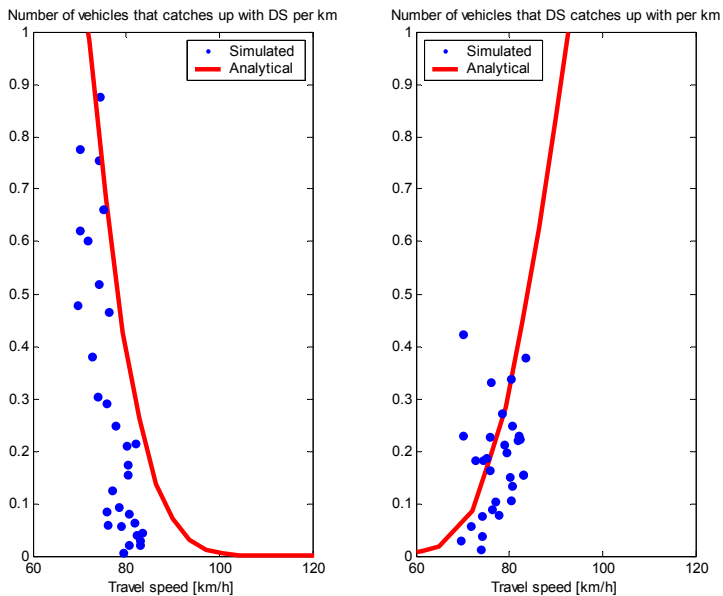
The results from the rural road environment are presented in Figure 6.1 - Figure 6.3. As can be seen in the figures, the simulated values correspond quite well to the analytical calculation of the expected number of active and passive catch-ups. The simulated values are generally a little lower than the corresponding values from the analytical expression. However, this is reasonable since the analytical expression is based on the assumption that a vehicle that catches up with another vehicle can overtake this vehicle directly without any delay.



**Figure 6.1** Simulated and calculated number of passive (left figure) and active (right figure) catch ups per km of the driving simulator vehicle (DS) on a straight and plain rural road with oncoming traffic, at 200 vehicles/h and  $f_t(v) \sim N(90.9, 9.7)$ .

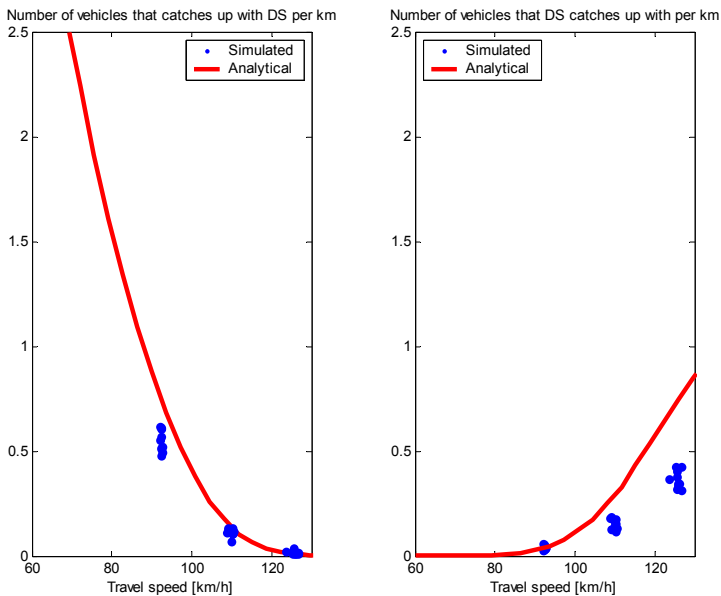


**Figure 6.2** Simulated and calculated number of passive (left figure) and active (right figure) catch ups per km of the driving simulator vehicle (DS) on a straight and plain rural road with oncoming traffic, at 400 vehicles/h and  $f_i(v) \sim N(85.6, 9.5)$ .

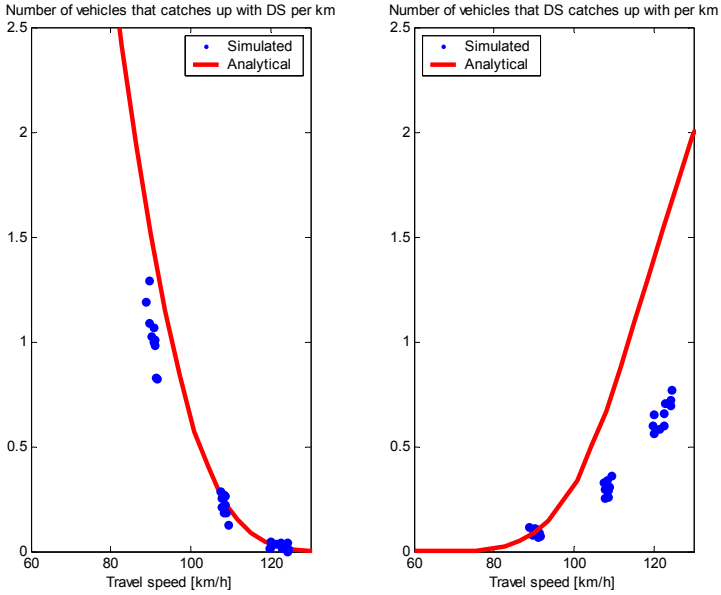


**Figure 6.3** Simulated and calculated number of passive (left figure) and active (right figure) catch ups per km of the driving simulator vehicle (DS) on a straight and plain rural road with oncoming traffic, at 600 vehicles/h and  $f_i(v) \sim N(81.8, 9.5)$ .

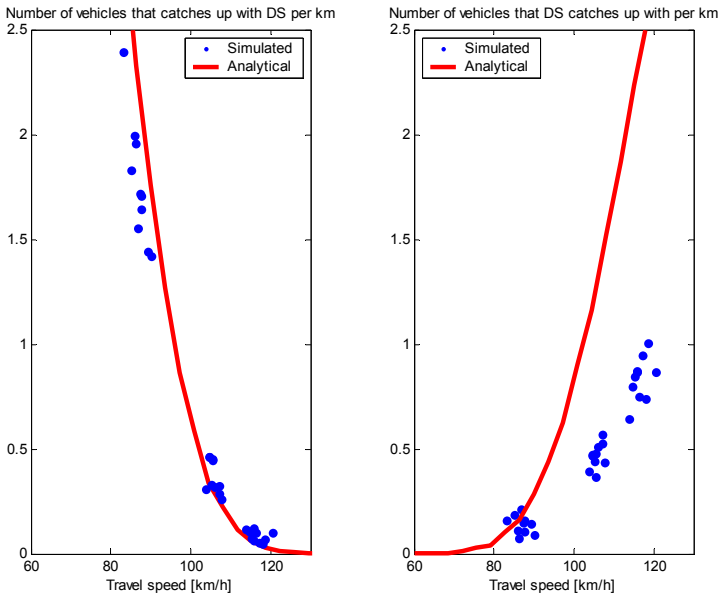
Figure 6.4 - Figure 6.6 shows the results from the freeway simulations. The results for the freeway environment should show a better agreement since the assumption of overtaking without delay is almost true, at least for moderate flows. The simulated number of passive catch-ups shows a good agreement with the analytical expression, whereas the number of active catch-ups does not show the same good agreement; see the left and right figures respectively. The agreement is good for low travel speeds, but the difference between the analytical expression and the simulated values for active catch-ups increase with increasing travel speed, see the right figures. The difference also seems to increase with increasing flow, for instance bigger differences in Figure 6.5 than in Figure 6.4. Some of this increased difference with the increased flow can be explained by the fact that the assumption of overtaking without delay gets less valid.



**Figure 6.4** Simulated and calculated number of passive (left figure) and active (right figure) catch ups per km of the driving simulator vehicle (DS) on a straight and plain freeway, at 500 vehicles/h and  $f_t(v) \sim N(107.6, 12)$ .



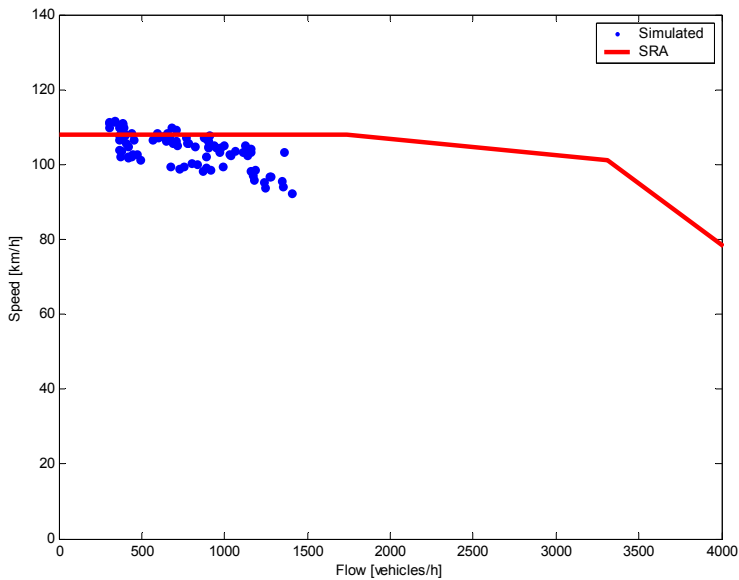
**Figure 6.5** Simulated and calculated number of passive (left figure) and active (right figure) catch ups per km of the driving simulator vehicle (DS) on a straight and plain freeway, at 1000 vehicles/h and  $f_t(v) \sim N(104.6, 11.9)$ .



**Figure 6.6** Simulated and calculated number of passive (left figure) and active (right figure) catch ups per km of the driving simulator vehicle (DS) on a straight and plain freeway, at 1500 vehicles/h and  $f_t(v) \sim N(100.2, 11.9)$ .

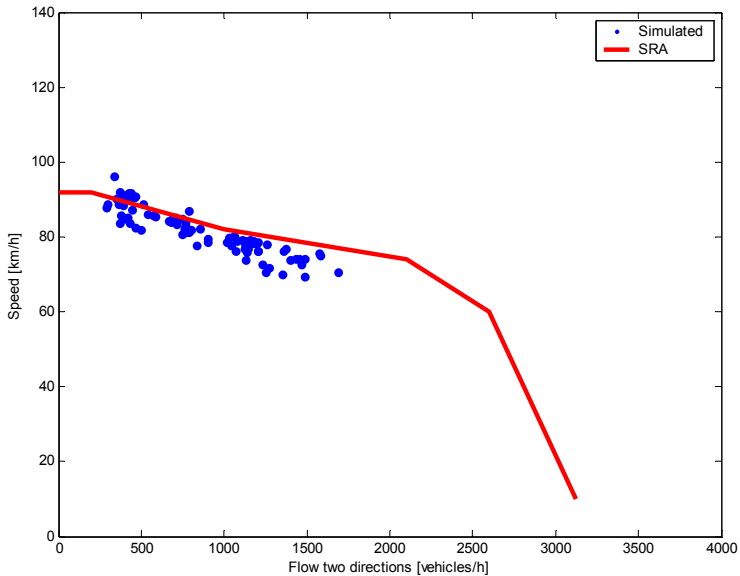
The differences in the number of active catch-ups do not seem to be present for the rural environment and the problem is therefore probably freeway-specific. The unsolved question is whether the problem is due to errors in the model or in the implementation it. One also has to bear in mind that the analytical expression only is an estimation of the number of catch-ups and that it can be the expected number that is the failing part.

One indication for that the mismatch is due to errors in the simulation model is that the simulated mean speed seems to fall faster with increasing flow compared to reality. Figure 6.7 shows speed-flow data from the freeway simulations above and representative data for an average Swedish freeway taken from SRA (2001). As can be seen in the figure, the simulated space mean speed start to decrease much earlier than it should. It seems like the simulated vehicles are constrained more than they should be. Different values on the lane-changing parameters and the desired time gaps have been tested in order to get less speed decreasing interactions, without getting any better results. It seems like further calibration and validation of the freeway model is needed.



**Figure 6.7** Comparison of simulated freeway speed-flow data and speed-flow relationships presented in SRA (2001).

In Figure 6.8 speed-flow data from the rural road simulations is presented. Even if the simulated speed seems to be a little low the agreement is much better than for the freeway. Once again this supports the theory that the problem is in the modeling of freeways.



**Figure 6.8** Comparison of simulated rural road speed-flow data and speed-flow relationships presented in SRA (2001).

### 6.3 User evaluation

The most important validation criterion is probably that the traffic “feels” or is observed as realistic. Noticeable is that even if the generated driver behavior corresponds to measurements from real driving, it is still important that the participants observe the simulated vehicles and their behavior as realistic. If this is not the case, the surrounding traffic may influence the participants so that they drive differently compared to how they drive on a real road. In order to validate if the simulated vehicles’ behavior is observed as realistic, a driving simulator experiment with 10 participants has been conducted. In difference with the simulation runs described in Section 6.2, in which also the driving simulator vehicle was simulated, the driving simulator vehicle was in this experiment driven by human drivers. The experiment was conducted in the VTI Driving simulator III, see Section 5.1. The purpose with the experiment was also to identify needs for further development and enhancement.

#### 6.3.1 Experimental design

The group of participants consisted of 3 women and 7 men. The age varied from 27 to 76 years with a concentration between 40 and 60. The mean age was 50.9 years and the standard deviation was 15.4. None of the participants had ever been driving in a driving simulator before. The normal driving mileage varied from 2000 km to 20 000 km per year, with a mean of 13 300 km/year and a standard deviation of 6 300 km/year. See Table E.1 in Appendix E for a complete list of the participants’ background information.

In order to get to know the simulator, the participants first drove 5 minutes on a rural two-lane highway and then 5 minutes on a freeway. During this warm-up

drive, the road was empty with respect to other vehicles. The participants then drove 15 minutes on each of the two road types, now with surrounding traffic simulated by the presented model. The participants got the instruction to drive as they normally do in each of the two road environments. After the totally 40 minutes of driving the participants were asked to fill in the questionnaire and to answer the interview questions.

All participants drove the both road environments in the same order. A better approach would have been to let half of the participants drive in the inverted order. Such an approach minimizes the risk of order-effects, i.e. the risk that the result from the second environment has been affected by the participants' experiences from the first environment.

### 6.3.2 Scenario design

The rural road scenario consisted of an approximately 9 km long stretch of the Swedish national road Rv34, starting in Målilla and ending in Hultsfred. The road has no barrier between oncoming lanes, i.e. the oncoming lane is used when executing overtakings. There are lots of horizontal curves along the stretch and the sight distances are rather short, see the screen shot in Figure 6.9. The road is 9 meters wide with a carriageway of 7 meters. All intersections along the stretch were removed in the scenario. The posted speed limit was 90 km/h along the whole stretch. There were no programmed critical events during the drive.



*Figure 6.9* Screen shot from the rural environment

The freeway scenario consisted of a stretch of the European road E4 between Linköping and Norrköping. The posted speed limit was 110 km/h along the whole stretch. The freeway has two lanes in each direction. All on and off ramps along the stretch were removed in the scenario. The roads Rv34 and E4 were chosen



because they are good representatives of Swedish rural roads and freeways, respectively.

The input traffic conditions were identical for both environments and directions, with exception to the traffic flow that varied between the two road types. The traffic flow was set to 300 vehicles/hour/direction on the rural road and to 1300 vehicles/hour on the freeway. The flows correspond to Swedish rush-hour traffic conditions on each of the two road types. The composition of different vehicle types was set to: 90 % cars, 5 % buses, and 5 % trucks. However, no visual representation of trucks was available at the moment so trucks were instead visualized as either buses or vans. The vehicle-driver parameters in Appendix A were used in the simulation of both environments.

In the rural environment the simulator vehicle started in a parking slot and on the freeway it started in the shoulder. In the rural scenario the road was free from other vehicles within an area starting 600 meters behind the simulator vehicle and ending 100 meters in front. On the freeway the corresponding free area was 800 meters behind and 100 meters in front.

### **6.3.3 Evaluation design**

A very important part is the formulation of the questions that the participants should answer. The formulation and design of a question can affect the answers. It is both important which questions that is asked and how these are formulated. Another thing that may affect the answers is if the questions are asked and answered orally or in written language. In this experiment the participants were both asked to fill a questionnaire and to answer a couple of interview questions. The questionnaire was answered in written language and the interview questions were answered in oral language.

The questionnaire included questions that were answered by using a linear rating scale. There are several different linear and non-linear rating scales that can be used in order to get subjective measurements. In our experiment a quite simple and standard linear scale with a range from 1 to 7 has been used. A similar scale was used in the user validation of the model presented in Wright (2000). An English translation of the questionnaire is presented in Appendix C. The questionnaire was originally written in Swedish, and can be obtained from the author on request. The first question in the questionnaire deals with the realism regarding such things as the feeling when steering, accelerating, and braking, etc. This question was only used to avoid getting comments on this kind of issues in the questions that deal with the surrounding traffic. Three questions for each road environment were then asked. In the first one, participants were asked to judge to what extent the other drivers behave like real drivers. In the other two questions, participants were asked to compare the speed and headway choices of the simulated and real drivers.

The reason for also using interview questions is that orally asked and answered questions was assumed to be a better approach to capture comments on strange or unrealistic situations or behavior. The interview questions, also originally in Swedish, is presented in Appendix D. The participants were asked if they had observed any strange or unrealistic situations and if so if they think that the observed situations could happen in reality or not. The participants were also asked questions about the simulated vehicles' behavior in connection with that the subject or a simulated vehicle performed overtakings or lane-changes.

### 6.3.4 Results and analyses of the questionnaire

The participants were asked to answer the questions in the questionnaire using a grading scale between 1 and 7. The answers from the questionnaire are presented in Appendix E. The answers from question 2 – 7 will be further discussed in the following sub-sections.

#### Question 2

Question 2 dealt with to what extent the participants think that simulated drivers in the rural road environment behave like real drivers. The grading scale went from to “*to a little extent*” (1) up to “*to a large extent*” (7). As can be seen in Table E.3 the result is quite good, with a range from 3 to 7 and with the mean of 5.4. The following comments were received:

- “*The other vehicles drove relatively aggressive.*”
- “*Many strange overtakings or tries to overtake.*”
- “*Some quite extreme situations.*”

These comments agree with the author’s observation during the experiment. Some of the simulated drivers started some very risky overtakings and ended or abandon some overtakings late.

#### Question 3

In question 3 participants were asked if the simulated drivers drove slower, as fast as, or faster than vehicles on a real rural road. A seven-grade scale was used, in which 1 meant *much slower* and 7 *much faster*. The answers varied from 3 to 5 with an average of 3.6, see Table E.3. The opinion that the simulated driver drove a little slower than real drivers is also clear when looking at the comments from some of the participants.

- “*It felt like all vehicles drove in 80 km/h, larger variation in reality. The vehicles that overtake me did not overtake the other vehicles in the platoon that I was traveling in.*”
- “*It felt ok, but differences between fast and slow vehicles are bigger in real life.*”
- “*The vehicle platoons traveled a little slow.*”
- “*They seemed to drive slower than in reality. It may depend on the platoons. There are more vehicles driving fast on a real road.*”

#### Question 4

Question 4 dealt with the headways that vehicles’ that followed behind the simulator vehicle drove at. Participants were asked if the other vehicles drove closer, as far away as, or further away than vehicles on a real rural road. The scale started at *much closer* (1) and ended with *much further away* (7). The answers varied between 3 and 5 with a mean of 3.9. Thus, the participants did not seem to have observed any differences compared to real environments. However, as seen in the comments below and as also observed by the author, the mirrors did not display a proper image during the rural road driving. This made it difficult to

anticipate distances to vehicles behind and thereby difficult to answer this question.

- *“I did not think about it, so I guess it was normal.”*
- *“Hard to make any judgment since the mirrors was not as real mirrors.”*

#### Question 5

Question 5 is equal to question 2 but instead deal with the freeway environment. The answers varied between 3 and 7, with a mean of 5.4, see Table E.4. So as for the rural environment, the participants seem to a quite large extent think that the simulated vehicles behave realistic. The following comments were received.

- *“My only comment is that no one overtook me.”*
- *“Quite calm traffic rhythm in the simulator environment, Harder to predict other driver’s behavior in reality.”*
- *“It looks like this in dense traffic, heavy vehicles often overtake.”*

#### Question 6

Question 6 dealt with the difference in speed between the simulated drivers and real drivers on a freeway, that is question 3 but for the freeway environment. The answers varied between 2 and 6 with a mean of 3.8. As in the rural environment, it seems like the participants think that the simulated drivers drove a little bit slower than vehicles in reality. This is also seen in the comments below.

- *“There is a larger difference between slow and fast vehicles in reality.”*
- *“The buses drove a little faster.”*
- *“More vehicles drive faster in reality. It seemed like no one drove faster than 125 km/h.”*

#### Question 7

Question 7 dealt with the distances to vehicles following the simulator during the freeway driving. As can be seen in Table E.4, the participants’ opinions seem to be that the vehicles drove a little bit closer than in reality. The answers varied between 2 and 5 with an average of 3.6. The author has observed that vehicles seems to be much closer when looking in the mirror in the driving simulator compared to what they actually are. This could be one possible explanation.

### 6.3.5 Results and analyses of the interview questions

The interview questions were used to get information about strange or unrealistic situations or behavior. An English translation of the originally questions in Swedish is available in Appendix D.

The first question was if the subject had noticed any strange or unrealistic situations or behavior. Three of the participants said that they haven’t experienced any such situation and that they think that all situations during the simulation could occur in the real world. The remaining 7 participants described the situations presented in Table 6.1 (rural environment) and Table 6.2 (freeway environment). They were also asked whether the situations that they describe could occur in real life, see the rightmost column in each table.

**Table 6.1** Strange or unrealistic situations observed by the participants during the rural road driving.

Road type	Description	Could occur in reality
Rural	The blue van was a plug. It should have moved out into the shoulder or stopped at a parking lot.	Yes
Rural	More vans than in reality.	No
Rural	An oncoming vehicle moved suddenly from the shoulder back to its normal lane. Felt like it was going to change to my lane.	No
Rural	Oncoming vehicles did not use the high beam or horn when vehicles from the own direction did not end risky overtakings. Instead they went out into the shoulder directly.	No
Rural	I overtook a blue van that after a while overtook me.	Yes
Rural	Overtaking vehicles used more of the oncoming lane than in reality. They were driving in the oncoming lane. In reality they often only move so that the left side of the car is in the oncoming lane.	No
Rural	There were some very aggressive drivers taking risky overtakings.	Yes
Rural	Very long platoons	Yes
Rural	One oncoming vehicle seemed to collide with a vehicle in the own direction.	No
Rural	A red Volvo crossed an overtake restriction line and started an overtaking and then ended it. The subject could not see any reason why the vehicle ended the overtaking. The subject did not see any oncoming vehicle.	No
Rural	Oncoming vehicles moved quickly into the shoulder when performing evasive maneuvers.	Yes
Rural	Several strange attempts to start overtakings. Can happen in reality but not that often,	No

In principle all situations that the participants think were strange or unrealistic and which they do not think could happen in reality has in one or another way to do with an overtaking situation. Firstly, some of the participants felt that the other drivers were more aggressive than real drivers, taking risky overtakings and completing overtakings with very short safety margins. Similar comments were given in the questionnaire; see the results and discussion from question 2 in Section 6.3.4. Secondly, vehicles that made evasive maneuvers, e.g. moving into the shoulder in order to avoid a collision with oncoming overtaking vehicles, moved very quickly and strange to and from the shoulder. This resulted in that some of the participants felt like the oncoming vehicle were moving into the subject's lane when the oncoming vehicles moved back from the shoulder to the normal lane.

Another common comment was that there were more vans than on a real road. This was due to a programming mistake. All types of personal cars were assumed to be equally probable. The few number of visual profiles for personal cars in

combination with this bad assumption resulted in a much larger share of vans than in reality. This is simply corrected by also setting the probability of each type of personal car.

The problem with the large portion of vans is the same in the freeway environment as in the rural environment, which is also pointed out in the answers for the freeway environment presented in Table 6.2.

**Table 6.2** *Strange or unrealistic situations observed by the participants during the freeway driving.*

Road type	Description	Could occur in reality
Freeway	More vans than in reality.	No
Freeway	I waited for one vehicle to pass in the left lane in order to change to the left lane myself. But instead of passing the vehicle decreased the speed.	Yes
Freeway	Quite long platoons in the left lane. More flexible queue discharging in reality.	No
Freeway	A car traveling in the left lane that had recently passed another vehicle in the right lane did not change back to the right lane even if the road was free for some distance ahead. It changed first after awhile.	Yes
Freeway	The other vehicles drove slowly.	No
Freeway	Some vehicles passed other vehicles very slowly. The subject does not think that one behave like that on a freeway, you accelerate in order to pass faster.	No
Freeway	One bus drove for a very long time in the left lane.	Yes
Freeway	There was a van that almost passed me on the right side.	Yes

The comments for the freeway environment are more disparate than for the rural environment. No especially strange or unrealistic situations seemed to occur during the experiment. One subject felt that there were longer queues in the left lane than normally while another driver said, in the questionnaire, that the traffic rhythm was more relaxed in the simulator. Some of the participants commented that some vehicles drove a long time in the left lane before they changed back to the right lane. But they also said that this is the case sometimes in real traffic.

The participants were also asked for their opinion about other drivers behavior in the following specific situations: the subject changed lane, other vehicles changed lanes, subject overtook, other vehicles overtook, and other situations. The comments are very similar to the ones above, aggressive driving on the rural road, all vehicles did not go back to the right lane on the freeway, vehicles moved quickly when changing lane on the rural road, etc. There were also one comment about that no vehicles tried to pass platoons by overtaking one vehicle at the time and improve their position in the platoon and finally pass the whole platoon.

In the last interview question the participants were informed that there are two driving simulators located at VTI. The participants were told that it was possible to let a human drive the other simulator and thereby one of the other cars during the experiment. The question was if the subject thought that a human being was

driving any of the other vehicles. However, this was not the case. The idea with this question was to try to validate the model by using the criterion for an optimal model, thus that one cannot distinguish between a simulated and a real driver. Three of the participants thought that a human could have been driving one of the other vehicles and two of them pointed out which vehicle they thought was the one driven by a human. The other seven participants thought that all of the other vehicles were simulated. The most common reasons to why the participants answered *no* were that the participants assumed that every vehicle was simulated and that no vehicles stood out from the rest. It is probably impossible to create a model that totally fulfills the optimal validation criterion.

## 6.4 Discussion

The overall impression of the results from Section 6.2 and 6.3 is that the model to a large extent is able to simulate surrounding vehicles in a driving simulator in a realistic way. The results also indicate that some parts of the model have to be enhanced. The reasons for some of the observed errors or problems and possible measures for solving them will be discussed below.

The aggressive behavior that was observed on rural roads is probably due to the following reasons. In the model for overtaking abandoning no safety margin was used in the calculation of the estimated time left on the overtaking, resulting in that the estimated time left on the overtaking was compared directly to the time to collision. Adding a safety margin would solve the main problems with drivers that ending overtakings in a very risky way or drivers that abandon overtakings very late. Later conducted tests indicate that this seem to work. The added safety margin most however be carefully calibrated so that abortion rates comply with the reality. A too long safety margin will lead to that very few of the overtakings started will be completed.

Another reason for the aggressive overtaking behavior on rural roads can be that the simulated drivers underestimate the time left on the overtaking. In the calculation of the estimated time left on the overtaking the acceleration is assumed to be constant. Since the acceleration rate decrease with the speed, see equation (4.29), the time left on the overtaking will be slightly underestimated.

A probable reason for that some of the participants think that the simulated drivers sometimes started overtakings at risky places, e.g. places with limited sight, is that it can be quite hard for the subject to distinguish objects far away on the simulator screen while the simulated vehicles have “perfect” vision. The best way to solve this is probably to limit the simulated vehicles’ sight so that it better correspond to the sight distances experienced by the simulator driver.

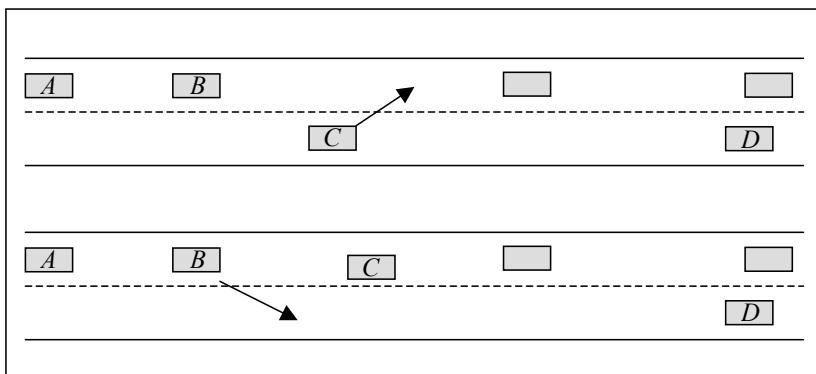
The traffic flow on the rural road used in the user evaluation was relatively high. The curvy road and the limited sight distances did not make it easy to overtake. The participants therefore caught up with platoons of about 5 – 10 vehicles. In the first platoon that most participants caught up with, the queue leader traveled around 80 km/h. A couple of the participants executed overtakings in order to pass the platoon. However, most of the participants felt that overtaking on this road in combination with the current traffic conditions were too risky and did therefore not start any overtakings. These participants got stuck in the platoon, which may be one possible explanation to that they felt that the other drivers drove slower than on a real rural road.

An ever more possible explanation to that the participants felt like the simulated vehicles drove slower than in reality is that the speedometer in the simulator shows the actual speed. In most real cars the speedometer show a speed somewhat higher than the actual speed. This difference in speed can sometimes be up to 5 - 8 km/h. The result is that the participants drives faster in the simulator than they think that they normally do, which leads to that the surrounding vehicles seems to drive slower than in real life. This can easily be fixed by adjusting the speed in the speedometer so that better correspond to a real vehicle.

#### 6.4.1 Some additional observations

During test driving in the VTI driving simulator III it has been observed that the simulated drivers' behavior on rural roads wider than 11 meter is very risky. In reality it is usual that vehicles on this kind of roads pass or overtake other vehicles even if there are oncoming vehicles in sight. This behavior of course generates risky situations also in real life. However, these situations are not solved in the same smooth way in the model as in real life. The modeling of how drivers solve the risky situations in connection with passings and overtakings therefore must be enhanced. Such further development has been given a low priority and has been put into the future enhancements plans on the basis of that these kind of rural roads are getting less common in Sweden. Most of these wide two-lane highways are redesigned to so called 2+1 roads, i.e. roads were the number of lanes alternates between 1 and 2 lanes in each direction.

It has also been observed that the lane-changing model in some situations generates somewhat strange behavior. One example is the situation illustrated in Figure 6.10, in which  $v_A^{des} > v_B^{des} > v_C^{des} > v_D^{des}$ . Vehicle *B* is traveling in the left lane in order to pass vehicle *C*. Then vehicle *C* changes to the left lane in order to pass vehicle *D*. When *C* has changed to the left lane, vehicle *B* changes to the right lane because the pressure to the front right vehicle is now much lower due to the increased distance to the front right vehicle. Vehicle *B* then gets stuck in the right lane until vehicle *A* and maybe other vehicles has passed.



**Figure 6.10** Illustration of strange lane-changing behavior.

The current lane-changing model does not seem to be able to model drivers tactical lane choices good enough. It is probably necessary to either enhance the

current model or change to a model that deals with this in a more appropriate way. Suitable models can maybe be the ones presented in Toledo et al. (2005) and El hadouaj et al. (2000).



## 7 Conclusions and future research

In this thesis a model for generating and simulating surrounding vehicles in a driving simulator is presented. The model is able to simulate rural roads with oncoming traffic and freeways without intersections and ramps. It is based on established techniques for time-driven microscopic simulation of traffic using behavioral models based on the VTISim (Brodin et al., 1986) and the TPMA (Davidsson et al., 2002) models. The presented simulation model includes a more complete model for overtakings on rural roads than the one used in VTISim. The enhanced model deals with drivers' behavior during overtakings, including abortions of overtakings, in a more realistic way.

The model has been integrated and tested within the VTI Driving simulator III. The performed user evaluation showed that the participants to a quite large extent observe the simulated vehicles and their behavior as realistic. Observations and comments from the experiment also indicate that further work is needed. Some of the observed drawbacks have been taken care of, but others have to be dealt with in later work. The model has also been validated on the number of active and passive catch-ups. The agreement is good for active and passive catch-ups on rural roads and for passive catch-ups on freeways. However, there is a miss-match in the number of active catch-ups on freeways. The reason for this miss-match has not yet been found.

The presented model does not only increase the realism in driving simulator scenarios but it also widens the range of driving simulator applications. This model makes it possible to for example conduct the following type of experiments:

- Studies on how the traffic load affects drivers.
- Demonstration of new or changed road designs.
- Studies in which the effect of what is being studied may vary with traffic intensity. This could for example be in cases where the drivers' concentration on the driving task is reduced due to alcohol, fatigue, or by using technical equipments as mobile phones or navigation systems.
- Evaluation on how different road designs affect drivers' acceleration, lane-changing, or overtaking behavior.

As indicated in the last paragraph a combination of a traffic simulation model and a driving simulator also creates great possibilities to further develop or enhance 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, for example, car-following, lane-changing, and overtaking behavior in order to create more realistic behavioral models.

The combination of a driving simulator and a traffic simulation model can also constitute a powerful tool for investigating the effects of, for example, different ADAS. The driving simulator can be used to study how an ADAS influence drivers' behavior. This behavior can then be implemented in the traffic simulation model. By running a new experiment in the driving simulator it is possible to check if the behavior is consistent when also other vehicles have the ADAS. Finally the overall effect on the traffic system can be studied by running the traffic simulation model alone. The ongoing research on using traffic safety indicators in combination with traffic simulation, see for example Gettman and Head (2003),

Archer (2005), and Lundgren and Tapani (2005), also makes it possible to study the overall safety impact of an ADAS.

The presented model is only able to simulate road links, thus roads without intersections and ramps. In order to be really usable the model must also include modeling of on and off ramps on freeways. This implies detailed modeling of lane-changing and acceleration behavior in merging situations. One problem here can be that some merging models use priority rules like closest to the merging point goes first. Such approaches cannot be used in this kind of applications since driving simulator driver may not follow this behavior. It is better to use a similar approach as used in the ramp merging model presented in Kuwahara and Sarvi (2004). In this model the vehicles on the ramp adjust their speeds in order to find a suitable gap and the vehicles in the main stream adjust their speeds and headways in order to let the ramp vehicles merge into the main stream. Another approach may be to use the approach of cooperative lane-changing presented in Hidas (2005). To achieve a more complete modeling of rural roads the model has to 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.

The developed model can only be used in driving simulator scenarios that do not include critical events. However, many driving simulators scenarios include critical events and an important research need is therefore to be able to create scenarios that combine stochastic simulation of vehicles and critical events. The basic idea is to use the simulation model to simulate the vehicles during the time between the predetermined critical situations. When getting closer to the point in time or space where the critical event is going to take place the simulation of the surrounding vehicles turn from stochastic to totally controlled according to the definition in the scenario. The tricky part is to create the specified situation from an unknown initial state and without giving the subject any clue about what is going to happen. In order to be able to do such transitions from stochastic simulation to a specified situation the simulation model must first be enhanced to include intersection and ramps. The reason for this is that intersections and ramps will be very useful means for adding or removing wanted or unwanted vehicles to the traffic stream. Without intersections and ramps the task of creating the specified situation in an unnoticeable way will probably be impossible.

Other useful enhancements would be to improve the model with the ability to simulate different weather and road conditions. When running experiments on winter roads for example not only the driving simulator vehicle but also the ambient traffic must be affected by the changed road conditions. Otherwise the surrounding vehicles will drive as if the winter conditions did not exist, thus probably faster and without getting into skids.

## 8 References

- Ahmad, O. and Y. Papelis (2000). "An autonomous driver model for the overtaking maneuver for use in microscopic traffic simulation". In Proceedings of: *Driving Simulator Conference, DSC'00*, Paris, France.
- Ahmad, O. and Y. Papelis (2001). "A Comprehensive Microscopic Autonomous Driver Model for Use in High-Fidelity Driving Simulation Environments". In Proceedings of: *81st Annual Meeting of the Transportation Research Board*, Washington, USA.
- Ahmed, K. I. (1999). *Modeling Drivers' Acceleration and Lane Changing Behavior*. Doctorial thesis at Department of Civil and Environmental Engineering, Massachusetts Institute of technology, Cambridge.
- Alloyer, O., E. Bonakdarian, J. Cremer, J. Kearney and P. Willemsen (1997). "Embedding Scenarios in Ambient Traffic". In Proceedings of: *Driving Simulator Conference, DSC'97*, Lyon, France.
- Al-Shihabi, T. and R. R. Mourant (2002). "Toward More Realistic Driving Behavior Models for Autonomous Vehicles in Driving Simulators". In Proceedings of: *82nd Annual Meeting of the Transportation Research Board*, Washington, D.C., USA.
- Archer, J. (2005). *Indicators for traffic safety assessment and prediction and their application in micro-simulation modelling: A study of urban and suburban intersections*. Doctorial thesis at Department of Infrastructure, Royal Institute of Technology, Stockholm, Sweden. ISBN: 91-7323-119-3.
- Bailey, A. C., A. H. Jamson, A. M. Parkes and S. Wriugh (1999). "Recent and future development of the leeds driving simulator". In Proceedings of: *Driving Simulator Conference, DSC'99*, Paris.
- Bang, B. and T. Moen (2004). *Integrating a driving simulator and a microscopic traffic simulation model*. Trondheim, Norway, SINTEF (unpublished paper).
- Barceló, J. and J. Casas (2002). "Dynamic network simulation with AIMSUN". In Proceedings of: *International Symposium on Transport Simulation*, Yokohama. [http://www.aimsun.com/Yokohama\\_revised.pdf](http://www.aimsun.com/Yokohama_revised.pdf)
- Blad, P. (2002). "Part E: Traffic Generators". In: *TPMA - Model-1 final report*. F. Davidsson, I. Kosonen and A. Gutowski. Stockholm, Sweden, Centre for Traffic Research (CTR): pp.
- Boer, E. R., A. Liu and D. Salvuvvi, D. (2001). "Toward an Integrated Model of Driver Behavior in a Cognitive Architecture." *Transportation Research Record* Vol. 1779: 9-16.
- Bolling, A., R. Ceci, A. Kircher, T. Malmström, L. Nilsson, C. Patten, J. Törnros and K. Vogel (2004), *Mobile telephone - simulator study*. VTI meddelande 969A. Swedish National Road and Transport Research Institute, VTI, Linköping. [http://62.119.60.67/templates/Report\\_2797.aspx?reportid=3544](http://62.119.60.67/templates/Report_2797.aspx?reportid=3544), Accessed February 8, 2005.
- Bonakdarian, E., J. Cremer, J. Kearney and P. Willemsen (1998). "Generation of Ambient Traffic for Real-Time Driving Simulation". In Proceedings of: *IMAGE Conference*, Scottsdale, Arizona, USA.
- Bottom, C. G. and R. Ashworth (1978). "Factors affecting the variability of driver gap-acceptance behaviour." *Ergonomics* Vol. 21(9): 721-734.

- Brackstone, M. and M. McDonald (1998). "Car-following: a historical review." *Transportation Research F* Vol. 2: 181-196.
- Brodin, A. and A. Carlsson (1986), *The VTI traffic simulation model - A description of the model and programme system*. VTI meddelande 321A. Swedish National Road and Transport Research Institute (VTI), Linköping, Sweden.
- Burghout, W. (2004). *Hybrid microscopic-mesoscopic traffic simulation*. Doctorial thesis at Department of Infrastructure, Royal Institute of Technology, Stockholm, Sweden. ISBN: 91-7323-099-5.
- Carlsson, A. (1993), *Beskrivning av VTIs trafiksimuleringsmodell (Description of VTIs traffic simulation model, In Swedish)*. VTI Notat T 138. Swedish National Road and Transport Research Institute (VTI), Linköping.
- Carlsson, A. (1995). *Omkörning av floating car (Number of overtakings of a floating car, in Swedish)*. Linköping, Sweden, VTI (unpublished working paper).
- Carlsson, A. and H.-Å. Cedersund (2000), *Makromodeller för på- och avfarter (Macro models for on- and off ramps, In Swedish)*. Centre for Traffic Research, Stockholm, Sweden.
- Champion, A., S. Espié and J.-M. Auberlet (2001). "Behavioral Road Traffic Simulation with ARCHISIM". In Proceedings of: *Summer Computer Simulation Conference*, Orlando, USA.
- Champion, A., R. Mandiau, C. Kolski, A. Heidet and A. Kemeny (1999). "Traffic generation with the SCANerII simulator: towards a multi-agent architecture". In Proceedings of: *Driving Simulator Conference, DSC'99*, Paris, France.
- Champion, A., M.-Y. Zhang, J.-M. Auberlet and S. Espié (2002). "Behavior Simulation: Towards High-Density Network Traffic Studies". In: *Traffic and Transportation Studies (Proceedings of ICTTS 2002)*. K. Wang, C.P., X. G., L. Nie and H. Yang. Reston, Virginia, USA, ASCE: pp. 988-995.
- Chandler, R. E., R. Herman and E. W. Montroll (1958). "Traffic Dynamics: Studies in Car following." *Operations Research* Vol. 6: 165-184.
- Cremer, J., J. Kearney and Y. Papelis (1995). "HCSM: A Framework for Behavior and Scenario in Virtual Environments." *ACM Transactions on Modelling and Computer Simulation* Vol. 5(2): 242-267.
- Cremer, J., J. Kearney and P. Willemsen (1997). "Directable behavior models for virtual driving scenarios." *Transactions of The Society of Computer Simulation* Vol. 14(2): 87-96.
- Daganzo, C. F. (1981). "Estimation of gap-acceptance parameters within and across the population from direct roadside observation." *Transportation Research B* Vol. 15: 1-15.
- Daganzo, C. F. (1994). "The cell transmission model: a dynamic representation of highway traffic consistent with hydrodynamic theory." *Transportation Research B* Vol. 28(4): 269-287.
- Daganzo, C. F. (1995). "The cell transmission model, part II: Network traffic." *Transportation Research B* Vol. 29B(2): 79-93.
- Davidsson, F., I. Kosonen and A. Gutowski (2002), *TPMA Model-1 final report*. Centre for Traffic Research, Royal Institute of Technology, Stockholm, Sweden. [http://www.infra.kth.se/ctr/projekt/tpma/tpma\\_en.htm](http://www.infra.kth.se/ctr/projekt/tpma/tpma_en.htm).

- El hadouaj, S., A. Drogoul and S. Espié (2000). "How to combine Reactivity and Anticipation the Case of Conflicts Resolution in a Simulation Road Traffic". In Proceedings of: *MABS'2000 workshop*, Boston, USA.
- El hadouaj, S. and S. Espié (2002). "A generic road traffic simulation model". In Proceedings of: *ICTTS (Traffic and transportation studies)*, Guilin, China.
- Espié, S. (1995). "ARCHISIM: Multiactor parallel architecture for traffic simulation". In Proceedings of: *The second world congress on Intelligent Transport Systems'95*, Yokohama.
- Espié, S., F. Saad, B. Schneztler and F. Bourlier (1995). "Microscopic traffic simulation and driver behaviour modelling: The ARCHISIM project". In Proceedings of: *VTI Konferens 2A part 3*, Linköping.
- FHWA (1996), *CORSIM User Manual VI.01*. Federal Highway Administration, McLean, USA.  
[http://www.itsdocs.fhwa.dot.gov/JPODOCS/REPTS\\_TE/4Y001!.PDF](http://www.itsdocs.fhwa.dot.gov/JPODOCS/REPTS_TE/4Y001!.PDF).
- Fritzsche, H.-T. (1994). "A model for traffic simulation." *Transportation Engineering Contribution* Vol. 5: 317 - 321.
- Gettman, D. and L. Head (2003), *Surrogate Safety Measures From Traffic Simulation Models*. FHWA-RD-03-050. Federal Highway Administration, McLean, USA. <http://www.tfhrc.gov/safety/pubs/03050/index.htm>.
- Gipps, P. G. (1981). "A behavioural car-following model for computer simulation." *Transportation Research B* Vol. 15(2): 105-111.
- Gipps, P. G. (1986). "A model for the structure of lane-changing decisions." *Transportation Research B* Vol. 20(5): 403-414.
- Gregersen, N. P., T. Falkmer, J. Dols and J. Pardo (2001), *Driving simulator scenarios and requirements*. TRAINER-project: System for driver Training and Assessment using Interactive Evaluation tools and Reliable methodologies - Deliverable 4.1,  
[http://www.trainer.iao.fraunhofer.de/deliverables/TRAINER%20D4.1\\_Final.zip](http://www.trainer.iao.fraunhofer.de/deliverables/TRAINER%20D4.1_Final.zip), Accessed February 8, 2005.
- Gutowski, A. (2002). "Part D6: Calibration of a freeway Link Model using Box's Complex method". In: *TPMA - Model-1 final report*. F. Davidsson, I. Kosonen and A. Gutowski. Stockholm, Sweden, Centre for Traffic Research (CTR): pp.
- Hidas, P. (2002). "Modelling lane changing and merging in microscopic traffic simulation." *Transportation Research C* Vol. 10(5-6): 351-371.
- Hidas, P. (2005). "Modelling vehicle interactions in microscopic simulation of merging and weaving." *Transportation Research C* Vol. 13(1): 37-62.
- Hillo, K. and I. Kosonen (2002). "Part D4: Calibration of ramp operations". In: *TPMA - Model-1 final report*. F. Davidsson, I. Kosonen and A. Gutowski. Stockholm, Sweden, Centre for Traffic Research (CTR): pp.
- Hoban, C. J., R. J. Shephard, G. J. Fawcett and G. K. Robinson (1991), *A model for simulating traffic on two-lane rural roads - User guide and manual for TRARR version 3.2*. Technical Manual ATM No. 10B. Australian Road Research Board, Victoria, Australia.
- Hoogendoorn, S., P. and P. H. L. Bovy (2001). "State-of-the-art of Vehicular Traffic Flow Modelling." *Journal of Systems and Control Engineering* Vol. 215(4): 289-303.
- Janson Olstam, J. (2003). "Traffic Generation for the VTI Driving Simulator". In Proceedings of: *Driving Simulator Conference - North America, DSC-NA 2003*, Dearborn, Michigan, USA.

- Janson Olstam, J. (2005). "Simulation of rural road traffic for driving simulators". In Proceedings of: *84th Annual meeting of the Transportation Research Board*, Washington D.C., USA.
- Janson Olstam, J. and J. Simonsson (2003), *Simulerad trafik till VTI:s körsimulator - en förstudie (Simulated traffic for the VTI driving simulator - a feasibility study, In Swedish)*. VTI Notat 32-2003. Swedish National Road and Transport Research Institute (VTI), Linköping, Sweden.
- Janson Olstam, J. and A. Tapani (2004), *Comparison of Car-following models*. VTI meddelande 960 A and LiTH-ITN-R-2004-5. Swedish National Road and Transport Research Institute (VTI) and Linköping University, Department of Science and Technology, Linköping, Sweden.
- Jayakrishnan, R., H. S. Mahmassani and T.-Y. Hu (1994). "An evaluation tool for an advanced traffic information and management systems in urban networks." *Transportation Research C* Vol. 2(3): 129-147.
- Jenkins, J. M. (2004). *Modeling the interaction between passenger cars and trucks*. Doctorial thesis at Texas A&M University, Texas.
- Kosonen, I. (1999). *HUTSIM - Urban Traffic Simulation and Control Model: Principles and Applications*. Doctorial thesis at Department of Civil and Environmental Engineering, Helsinki University of Technology, Helsinki, Finland.
- Kuwahara, M. and M. Sarvi (2004). "Freeway ramp merging phenomena in congested traffic using simulation combined with a driving simulator." *Computer-Aided Civil and Infrastructure Engineering* Vol. 19: 351 - 363.
- Leiman, L., A. R. Archilla and A. D. May (1998), *TWOPAS model improvements*. University of California, Berkeley, USA.
- Leutzbach, W. (1988). *Introduction to the theory of traffic flow*. Berlin, Springer Verlag. 3-540-17113-4.
- Liu, A. and D. D. Salvucci (2002). "The time course of a lane change: Driver control and eye-movement behavior." *Transportation Research F* Vol. 5(2): 123-132.
- Liu, R. and J. Tate (2000). "Microsimulation modelling of intelligent speed adaptation". In Proceedings of: *European Transport Conference*, Cambridge.
- Lundgren, J. and A. Tapani (2005). "Evaluation of Safety Effects of Driver Assistance Systems through Traffic Simulation". In Proceedings of: *Submitted for the 85th Annual meeting of the Transportation Research Board*, Washington, USA.
- May, A. D. (1990). *Traffic Flow Fundamentals*. Upper Saddle River, Prentice Hall.
- McLean, J. R. (1989). *Two-lane Highway Traffic Operations - Theory and Practice*. New York, Gordon and Breach Science Publishers. 2-88124-725-3.
- Michon, J. A. (1985). "A critical view of driver behavior models: what do we know, what should we do?" In: *Human behavior & traffic safety*. L. Evans and R. C. Schwing. New York, Plenum Press: pp. 485 - 520. ISBN: 0-306-42225-5.
- Miller, A. J. (1967). "Queuing in Rural Traffic". In: *Vehicular Traffic Science*. New York, USA, Elsevier: pp. 122 - 137.
- Nilsson, L., J. Törnros, N. Brook-Carter, A. M. Parkes, M. Dangelmair, K. Brookhuis, A.-J. Roskam, D. De Waard, A. Bauer, C. Gelau, F. Tango, S.

- Damiani, I. Jaspers, A. Ernst and M. Wiethoff (2002), *ADVISOR Deliverable D 4/5.2 - An integrated methodology pilot evaluation results*. Project GRD1/2000/25361 S12.319626.  
[http://www.advisors.iao.fraunhofer.de/ADVISORS\\_Del%204b\\_5b.pdf](http://www.advisors.iao.fraunhofer.de/ADVISORS_Del%204b_5b.pdf).
- Papageorgiou, M., J.-M. Blossville and H. Hadj-Salem (1989). "Macroscopic modelling of traffic flow on the Boulevard Périphérique in Paris." *Transportation Research B* Vol. 23(1): 29-47.
- PTV (2003), *VISSIM User Manual - Version 3.70*. PTV Planung Transport Verkehr AG, Karlsruhe, Germany.
- Quadstone (2004a), *Quadstone Paramics V5.0 - Technical Notes*. Quadstone Limited, Edinburgh, Scotland. [http://www.paramics-online.com/public\\_docs/Technical%20Notes%20V5.0.pdf](http://www.paramics-online.com/public_docs/Technical%20Notes%20V5.0.pdf).
- Quadstone (2004b), *Quadstone Paramics V5.0 - Viewer User Guide*. Quadstone Limited, Edinburgh, Scotland. [http://www.paramics-online.com/public\\_docs/ParamicsV5-ViewerUserGuide.pdf](http://www.paramics-online.com/public_docs/ParamicsV5-ViewerUserGuide.pdf).
- Salem, H. H., J. Chrisoulakis, M. Papageorgiou, N. Elloumi and P. Papadakos (1994). "The use of metacor tool for integrated urban and interurban traffic control evaluation in corridor Périphérique, Paris". In Proceedings of: *IEEE Vehicle navigation & information Systems Conference*, Yokohama, Japan.
- SRA (2001). "Appendix 1 - VQ-diagrams". In: *Effects of different road measurements - Construction and improvement*. Borlänge, Sweden, Swedish Road Administration: pp.
- Swedish National Road and Transport Research Institute (VTI), 2004, *Driving Simulators - Pictures and film*.  
[http://www.vti.se/templates/Page\\_3260.aspx](http://www.vti.se/templates/Page_3260.aspx), accessed January 24, 2004
- Tapani, A. (2005). "A Versatile Model for Rural Road Traffic Simulation". In Proceedings of: *84th Annual meeting of the Transportation Research Board*, Washington D.C., USA.
- Taylor, N. B. (2003). "The CONTRAM Dynamic Traffic Assignment Model." *Networks and Spatial Economics* Vol. 3: 297-322.
- Toledo, T., C. F. Choudhury and M. E. Ben-Akiva (2005). "A lane-changing model with explicit target lane choice". In Proceedings of: *84th Annual meeting of the Transportation Research Board*, Washington D.C., USA.
- Toledo, T., H. N. Koutsopoulos, A. Davol, M. E. Ben-Akiva, W. Burghout, I. Andréasson, T. Johansson and C. Lundin (2003). "Calibration and Validation of Microscopic Traffic Simulation Tools - Stockholm Case Study." *Transportation Research Record* Vol. 1831: 65-75.
- van Wolfelaar, P. C. (1999), *Functional Aspects of the Driving Simulator at the University of Groningen*. University of Groningen, Groningen, Netherlands.
- Wiedemann, R. and U. Reiter (1992). "Microscopic traffic simulation: the simulation system MISSION, background and actual state". In: *Project ICARUS (V1052) Final Report*. Brussels, CEC. 2: pp. Appendix A.
- Wright, S. (2000). *Supporting intelligent traffic in the Leeds driving simulator*. Doctorial thesis at School of Computing, University of Leeds, Leeds.
- Wright, S., N. J. Ward and A. G. Cohn (2002). "Enhanced Presence in Driving Simulators Using Autonomous Traffic with Virtual Personalities." *Presence: Teleoperators and Virtual Environments* Vol. 11(6): 578 - 590.

- Wu, J., M. Brackstone and M. McDonald (2000). "Fuzzy Sets and Systems for a Motorway Microscopic Simulation Model." *Fuzzy Sets and Systems* Vol. 116(1): 65-76.
- Yang, Q. (1997). *A Simulation Laboratory for Evaluation of Dynamic Traffic Management Systems*. Doctorial thesis at Department of Civil and Environmental Engineering, Massachusetts Institute of Technology, Cambridge.
- Yang, Q. and H. N. Koutsopoulos (1996). "A microscopic traffic simulator for evaluation of dynamic traffic management systems." *Transportation Research C* Vol. 4(3): 113 - 129.
- Östlund, J., L. Nilsson, O. Carsten, N. Merat, A. H. Jamson, S. Jamson, S. Mouta, J. Carvalhais, J. Santos, V. Anttila, H. Sandberg, J. Louma, D. de Waard, K. Brookhuis, E. Johansson, J. Engström, T. Victor, J. Harbluk, W. Janssen and R. Brouwer (2004), *HASTE Deliverable 2 - HMI and safety-related driver performance*. Project GRD1/2000/25361 S12.319626.  
<http://www.its.leeds.ac.uk/projects/haste/Haste%20D2%20v1-3%20small.pdf>.



## Appendix A – Driver/Vehicle parameter values

*Table A.1 Vehicle-driver parameters for personal cars*

<b>Cars</b>	<b>Average</b>	<b>Std. dev.</b>	<b>Min</b>	<b>Max</b>	
<b>Basic desired speed:</b>	111	11.5	80	140	km/h
<b>Power/weight ratio</b>	19	7	8	41	W/kg
<b>Desired time gap:</b>	2	1	-	6	s

*Table A.2 Vehicle-driver parameters for trucks*

<b>Trucks</b>	<b>Average</b>	<b>Std. dev.</b>	<b>Min</b>	<b>Max</b>	
<b>Basic desired speed:</b>	95.5	10.5	69	122	km/h
<b>Power/weight ratio</b>	11.5	4	3	25	W/kg
<b>Desired time gap:</b>	2.5	1.1	-	6	s

*Table A.3 Vehicle-driver parameters for buses*

<b>Buses</b>	<b>Average</b>	<b>Std. dev.</b>	<b>Min</b>	<b>Max</b>	
<b>Basic desired speed:</b>	95.5	10.5	69	122	km/h
<b>Power/weight ratio</b>	11.5	4	3	25	W/kg
<b>Desired time gap:</b>	2.5	1.1	-	6	s

*Table A.4 Vehicle-driver parameters for trucks with trailer with 3 – 4 axes*

<b>Trucks with trailer (3-4 axes)</b>	<b>Average</b>	<b>Std. dev.</b>	<b>Min</b>	<b>Max</b>	
<b>Basic desired speed:</b>	87.5	5.4	71	104	km/h
<b>Power/weight ratio</b>	8	1.5	3	14	W/kg
<b>Desired time gap:</b>	2.5	1.2	-	6	s

*Table A.5 Vehicle-driver parameters for trucks with trailer with 5 or more axes*

<b>Trucks with trailer (5 or more axes)</b>	<b>Average</b>	<b>Std. dev.</b>	<b>Min</b>	<b>Max</b>	
<b>Basic desired speed:</b>	87.5	5.4	71	104	km/h
<b>Power/weight ratio</b>	6	1.5	3	12	W/kg
<b>Desired time gap:</b>	2.5	1.2	-	6	S



## Appendix B – Overtaking parameters

*Table B.1. Parameter values used in the overtaking probability function*

<i>A</i>	<i>k</i>	Overtaken vehicle		Road width	Sight limitation	Type of overtaking
3.30	0.00350	Type 1	< 70 km/h	< 11 m	Natural	Accelerating
11.8	0.01220	Type 1	< 70 km/h	< 11 m	Natural	Flying
11.0	0.00460	Type 1	< 70 km/h	< 11 m	Oncoming	Accelerating
11.5	0.00988	Type 1	< 70 km/h	< 11 m	Oncoming	Flying
6.30	0.00910	Type 1	< 70 km/h	≥ 11 m	Natural	Accelerating
2.30	0.01430	Type 1	< 70 km/h	≥ 11 m	Natural	Flying
7.50	0.00700	Type 1	< 70 km/h	≥ 11 m	Oncoming	Accelerating
2.30	0.01403	Type 1	< 70 km/h	≥ 11 m	Oncoming	Flying
3.78	0.00334	Type 1	< 90 km/h	< 11 m	Natural	Accelerating
11.8	0.01220	Type 1	< 90 km/h	< 11 m	Natural	Flying
11.0	0.00430	Type 1	< 90 km/h	< 11 m	Oncoming	Accelerating
11.5	0.00988	Type 1	< 90 km/h	< 11 m	Oncoming	Flying
6.90	0.00867	Type 1	< 90 km/h	≥ 11 m	Natural	Accelerating
3.00	0.01207	Type 1	< 90 km/h	≥ 11 m	Natural	Flying
7.50	0.00664	Type 1	< 90 km/h	≥ 11 m	Oncoming	Accelerating
3.00	0.01207	Type 1	< 90 km/h	≥ 11 m	Oncoming	Flying
4.30	0.00317	Type 1	≥ 90 km/h	< 11 m	Natural	Accelerating
11.8	0.01220	Type 1	≥ 90 km/h	< 11 m	Natural	Flying
11.0	0.00399	Type 1	≥ 90 km/h	< 11 m	Oncoming	Accelerating
11.5	0.00988	Type 1	≥ 90 km/h	< 11 m	Oncoming	Flying
7.50	0.00822	Type 1	≥ 90 km/h	≥ 11 m	Natural	Accelerating
6.00	0.00988	Type 1	≥ 90 km/h	≥ 11 m	Natural	Flying
7.50	0.00664	Type 1	≥ 90 km/h	≥ 11 m	Oncoming	Accelerating
6.00	0.00988	Type 1	≥ 90 km/h	≥ 11 m	Oncoming	Flying
6.10	0.00440	Type 2	< 70 km/h	< 11 m	Natural	Accelerating
37.0	0.01480	Type 2	< 70 km/h	< 11 m	Natural	Flying
11.65	0.00430	Type 2	< 70 km/h	< 11 m	Oncoming	Accelerating
13.74	0.00920	Type 2	< 70 km/h	< 11 m	Oncoming	Flying
3.30	0.00510	Type 2	< 70 km/h	≥ 11 m	Natural	Accelerating
1.40	0.01270	Type 2	< 70 km/h	≥ 11 m	Natural	Flying
4.20	0.00370	Type 2	< 70 km/h	≥ 11 m	Oncoming	Accelerating
1.40	0.01270	Type 2	< 70 km/h	≥ 11 m	Oncoming	Flying
6.90	0.00420	Type 2	< 90 km/h	< 11 m	Natural	Accelerating
37.0	0.01480	Type 2	< 90 km/h	< 11 m	Natural	Flying
11.65	0.00403	Type 2	< 90 km/h	< 11 m	Oncoming	Accelerating
13.74	0.00920	Type 2	< 90 km/h	< 11 m	Oncoming	Flying
3.60	0.00484	Type 2	< 90 km/h	≥ 11 m	Natural	Accelerating
1.61	0.01074	Type 2	< 90 km/h	≥ 11 m	Natural	Flying
4.20	0.00347	Type 2	< 90 km/h	≥ 11 m	Oncoming	Accelerating
1.61	0.01074	Type 2	< 90 km/h	≥ 11 m	Oncoming	Flying
6.90	0.00420	Type 2	≥ 90 km/h	< 11 m	Natural	Accelerating
37.0	0.01480	Type 2	≥ 90 km/h	< 11 m	Natural	Flying
11.65	0.00403	Type 2	≥ 90 km/h	< 11 m	Oncoming	Accelerating
13.74	0.00920	Type 2	≥ 90 km/h	< 11 m	Oncoming	Flying
3.60	0.00484	Type 2	≥ 90 km/h	≥ 11 m	Natural	Accelerating
1.61	0.01074	Type 2	≥ 90 km/h	≥ 11 m	Natural	Flying

Appendix B

Page 2(2)

4.20	0.00347	Type 2	≥ 90 km/h	≥ 11 m	Oncoming	Accelerating
1.61	0.01074	Type 2	≥ 90 km/h	≥ 11 m	Oncoming	Flying
6.90	0.00331	Type 3 & 4	-	< 11 m	Natural	Accelerating
37.0	0.01480	Type 3 & 4	-	< 11 m	Natural	Flying
14.0	0.00353	Type 3 & 4	-	< 11 m	Oncoming	Accelerating
13.74	0.00920	Type 3 & 4	-	< 11 m	Oncoming	Flying
4.20	0.00484	Type 3 & 4	-	≥ 11 m	Natural	Accelerating
2.08	0.00532	Type 3 & 4	-	≥ 11 m	Natural	Flying
4.20	0.00347	Type 3 & 4	-	≥ 11 m	Oncoming	Accelerating
2.08	0.00532	Type 3 & 4	-	≥ 11 m	Oncoming	Flying

(Source: Carlsson (1993))







8. Approximately how many miles drove you last year? \_\_\_\_\_ miles
9. How many years have you had your driving license? \_\_\_\_\_ years
10. Which year are you born? \_\_\_\_\_
11. Gender?  
 Women  
 Man
12. Which type of car do you normally drive? \_\_\_\_\_



## Appendix D – Interview questions

This is a translation of the interview question, originally in Swedish, used in the experiment described in Section 6.3.

1. **Did you experience any traffic situation that felt strange or unrealistic during your ride? In other words did any other driver behave strange or unrealistic at any time?**

- Yes (go to question 2b)  
 No (go to question 2a)

2. a) **If you answered no in question 1. In your opinion could all situations during your driving happen in real life?**  Yes  
 No

- b) **If you answered yes in question 1. Try to describe the situation/situations**

**Situation 1:**

Road type (mark with a circle):          Rural          Freeway

Describe the situation: \_\_\_\_\_

\_\_\_\_\_

\_\_\_\_\_

\_\_\_\_\_

- Do you think that this situation could appear in real life?  Yes  
 No

**Situation 2:**

Road type (mark with a circle):          Rural          Freeway

Describe the situation: \_\_\_\_\_

\_\_\_\_\_

\_\_\_\_\_

\_\_\_\_\_

- Do you think that this situation could appear in real life?  Yes  
 No

**Situation 3:**

Road type (mark with a circle):          Rural          Freeway

Describe the situation: \_\_\_\_\_

\_\_\_\_\_

\_\_\_\_\_

\_\_\_\_\_

Do you think that this situation could appear in real life?           Yes

No

**Situation 4:**

Road type (mark with a circle):          Rural          Freeway

Describe the situation: \_\_\_\_\_

\_\_\_\_\_

\_\_\_\_\_

\_\_\_\_\_

Do you think that this situation could appear in real life?           Yes

No

**3. Which opinions do you have regarding other drivers' behavior in connection with:**

- You changing lane (freeway)? \_\_\_\_\_

---

---

---

- Other drivers changing lane (freeway)? \_\_\_\_\_

---

---

---

- You overtaking (rural road)? \_\_\_\_\_

---

---

---

- Other drivers overtaking (rural road)? \_\_\_\_\_

---

---

---

- Other situations \_\_\_\_\_

---

---

---

4. **We have the possibility to let a human drive one of the other vehicles. Do you think that a human being drove any of the other vehicles in this experiment?**

Yes

No

*If Yes*

- can you specify which vehicle? \_\_\_\_\_

\_\_\_\_\_

\_\_\_\_\_

*If No*

- why not? \_\_\_\_\_

\_\_\_\_\_

\_\_\_\_\_

## Appendix E – Answers from the interview questions

*Table E.1 Background information about the participants*

Participant nr.	Age	Gender	Yearly mileage [km]	Years with license
1	54	Female	20 000	23
2	44	Male	15 000	26
3	48	Male	18 000	30
4	45	Male	15 000	27
5	35	Male	10 000	17
6	76	Male	12 000	57
7	52	Female	20 000	33
8	27	Male	4 000	9
9	75	Male	17 000	54
10	53	Female	2 000	35

*Table E.2 Answers from question 1 in the questionnaire*

Participant nr.	Steer	Brake	Acc	Speed	Lat. pos.	Pictures	Depth
1	6	5	4	5	6	6	5
2	7	4	7	7	7	6	6
3	6	3	2	5	6	5	3
4	5	4	4	6	5	4	5
5	5	4	5	6	6	6	5
6	7	2	4	5	7	5	5
7	6	2	6	7	7	5	6
8	6	3	4	7	5	5	3
9	4	3	2	5	6	6	5
10	5	1	5	4	4	5	3

*Table E.3 Answers from question 2 – 4 in the questionnaire, which dealt with the rural road environment.*

Participant nr	Question 2 (Realism behavior)	Question 3 (speed choices)	Question 4 (headways)
1	5	5	4
2	7	2	4
3	7	4	5
4	5	3	4
5	3	4	3
6	7	4	3
7	6	4	4
8	6	2	4
9	3	5	4
10	5	3	4

**Table E.4** Answers from question 5 – 7 in the questionnaire, which dealt with the freeway environment.

Participant nr	Question 5 (Realism behavior)	Question 6 (speed choices)	Question 7 (headways)
1	5	5	3
2	7	6	4
3	5	3	5
4	5	4	4
5	7	4	4
6	7	3	3
7	4	4	4
8	6	2	4
9	5	3	3
10	3	4	2