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# A Framework for Simulation of Surrounding Vehicles in Driving Simulators

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## Abstract

This article describes a framework for generation and simulation of surrounding vehicles in a driving simulator. The proposed framework generates a traffic stream, corresponding to a given target flow and simulates realistic interactions between vehicles. The framework is based on an approach in which only a limited area around the driving simulator vehicle is simulated. This closest neighborhood is divided into one inner area and two outer areas. Vehicles in the inner area are simulated according to a microscopic simulation model including advanced submodels for driving behavior while vehicles in the outer areas are updated according to a less time-consuming mesoscopic simulation model. The presented work includes a new framework for generating and simulating vehicles within a moving area. It also includes the development of an enhanced model for overtakings and a simple mesoscopic traffic model. The framework has been validated on the number of vehicles that catch 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. The reason for this seems to be deficiencies in the utilized lane-changing model. It has been verified that the framework is able to achieve the target flow and that

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there is a gain in computational time of using the outer areas. The framework has also been tested within the VTI Driving simulator III.

## 1 Introduction

Many traffic accidents are caused by failures in the interaction between the driver, the vehicle, and the traffic system. Thus, knowledge about these interactions is essential and this is especially true nowadays since the number of driving related interactions is increasing. Today drivers 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 get knowledge on how these kinds of systems influence drivers, 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 impossible to conduct due to ethical reasons. Test tracks offer a safer environment and the possibility of giving test drivers more equivalent conditions, but they lack realism. Driving simulators on the other hand offer a quite realistic environment in which test conditions can be controlled and varied in a safe way.

Driving simulators are used to conduct experiments in many different areas. Examples include alcohol, medicines and drugs, driving with disabilities, human-machine interaction, fatigue, road design, and vehicle design. A driving simulator is designed to imitate driving a real vehicle. The driver interface can be realized with a real vehicle cabin or only a seat with a steering wheel and pedals, and anything in between. The surroundings are presented for the driver on a screen. It is important that the performance of the simulator vehicle, the visual representation, and the behavior of surrounding objects be as realistic as possible. For example, it is important that the ambient vehicles behave in a realistic and trustworthy way. In this article we present a

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traffic simulation framework that is able to generate and simulate these surrounding vehicles.

Microscopic simulation of traffic is one possibility for simulating these ambient vehicles. Micro-simulation has become a very popular and useful tool in studies of traffic systems. Micro-simulation models are time discrete models which simulate individual vehicle/driver units. The behavior of vehicles/drivers and the interaction between those are simulated using different submodels for car-following, lane-changing, speed adaptation, and so on. The submodels use the current road and traffic situation as inputs and generate individual driver decisions regarding, for example, acceleration and preferred lane.

An important difference between simulation of surrounding vehicles for a driving simulator and traditional applications of traffic simulation is that one of the vehicles is driven by a human being. This puts additional demands on the modeling of vehicle movements since it is the actual behavior of the simulated vehicles that is the primary output. Most traffic simulation models are designed for generating correct outputs at a macroscopic level, for example, average speeds or queue lengths. The 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 does not affect macro measurements appreciably.

One approach for the simulation of the surrounding vehicles is to use available commercial micro traffic simulation tools. Some trials to use software packages such as AIMSUN (Barceló and Casas, 2002) and VISSIM (PTV, 2003) to simulate surrounding vehicles in driving simulators have been conducted; see for example Ciuffo et al. (2007) and Jenkins (2004). One problem with using commercial programs is that they simulate a specified geographic area, for example, a part of a city or a road. Because of this, very large areas and thereby many vehicles, have to be simulated when running long driving simulator experiments (1-2 hours driving). For example, one-hour experiment at a traffic flow of 1000 vehicles/h will require that on average, 1000 vehicles per time step have to be updated. Another problem is that many of the programs do not fulfill the additional demands on the modeling of vehicle movements we mentioned. A third drawback is that most commercial programs are not able to simulate rural roads with oncoming traffic, or

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that the modeling of such roads is not detailed enough for this kind of application.

Another approach is to develop models specialized for the application of simulation of surrounding vehicles in driving simulators. Three of the most wellknown models following this approach are the ARCHISIM model (El hadouaj and Espié, 2002; Espié, 1995), the NADS model (Ahmad and Papelis, 2001), and the DRIVERSIM model (Wright, 2000). Research in this area has to a large extent been focused on decision making modeling concepts, for example the development of Hierarchical Concurrent State Machines (HCSM) (Cremer et al., 1995), which are used in the NADS model, the eco-resolution principle, which is used in the ARCHISIM model (Espié, 1999) and fuzzy logic modeling, which is used in the DRIVERSIM model (Wright, 2000). Focus has also to a large extent been limited to simulation of freeways. There has been little focus on modeling of rural roads and on algorithms for generation of realistic traffic streams.

In this article we present a framework for simulation and generation of surrounding vehicles in a driving simulator. We present a traffic generation model that is able to generate realistic traffic streams: traffic streams with statistically correct time headway distributions. We also present both microscopic and mesoscopic<sup>1</sup> traffic simulation models which, can be used to simulate the surrounding vehicles close and far away from the simulator vehicle, respectively. The aim has been to base, as extensively as possible, the submodels for driving behavior on already developed models.

We only consider freeways with two lanes in each direction and without ramps, and rural roads with oncoming traffic but without intersections.

The article is organized as follows: In Section 2 the developed simulation framework is presented. Section 3 then continues with a more detailed description of the different components in the framework. First the microscopic traffic simulation model and its submodels for driving behavior are described. Then follows a description of the mesoscopic simulation model that is used to simulate vehicles further away from the driving simulator vehicle. After that follows a description of the model for the transition between the mesoscopic and the microscopic models.

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<sup>1</sup>A mesoscopic traffic model simulates individual vehicles or packets of vehicles. The difference compared to micro-simulation is that the vehicles' behavior is described at an aggregate level, for example by using travel time functions.

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The section ends with a description of the model for generation of new vehicles. The performed validation is presented in Section 4. Section 5 ends the article with some concluding remarks and suggestions for future research.

## 2 The simulation framework

When simulating traffic for a driving simulator, the area of interest is the closest neighborhood of the driving simulator vehicle. It is only within this neighborhood that vehicles have to be simulated. Similar approaches has been proposed both in Espié (1995) and in Bonakdarian et al. (1998). The area of interest moves with the same speed as the simulator vehicle and can be interpreted as a moving window, which is centered on the simulator vehicle. We have developed a simulation framework for generation and simulation of vehicles within such a moving window (see Figure 1). The framework consists of four components: a microscopic traffic simulation model, a mesoscopic traffic simulation model, rules for the transition between the mesoscopic and the microscopic models, and a model for generation of new vehicles. This section describes how these four components are related to each other, and their basic functions. A more detailed description of each of these components is given in Section 3.

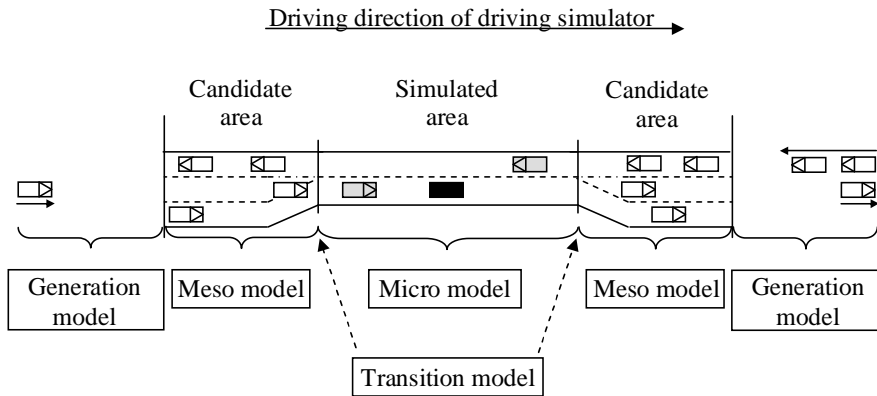


Figure 1: Illustration of the simulation framework. The black vehicle is the driving simulator, the grey vehicles are simulated vehicles and the white vehicles are candidate vehicles.

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The basic idea of the moving window is to avoid simulating vehicles several miles ahead of or behind the simulator vehicle, which is not efficient from a computational point of view. However, the window cannot be too small. First, the size of the window is constrained by the sight distance. The window must at least be as long as the sight distance, so that vehicles do not pop up in front of the simulator vehicle. Second, the window must be large enough to make the traffic realistic and to allow for speed changes of the simulator vehicle.

In order to get a wide enough window but at the same time limit the computational effort, the moving window is divided into one inner and two outer areas. The inner area is called the simulated area and the outer areas are called candidate areas. Vehicles traveling in the simulated area are simulated according to a microscopic simulation model that uses advanced submodels for car-following, overtaking and speed adaptation, and so on. It is important that the vehicles in the simulated area behave like real drivers, but the behavior of vehicles traveling further away from the simulator vehicle is less important. These vehicles, traveling in the candidate areas, are simulated according to a less time consuming mesoscopic model. When getting closer to the simulated area, these vehicles become candidates to move into the simulated area. In the approach proposed in Espié (1995) vehicles further away are simulated according to a macroscopic traffic model. The advantage with using a mesoscopic model is that it still simulates individual vehicles, but not a traffic stream as in a macroscopic model. This makes the transition of vehicles to and from the microscopic model more straightforward. At the end of the candidate areas, vehicles that travel out of the system are removed from the model and new vehicles are generated.

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 vehicle are assumed not to affect the driving simulator driver since they are not visible for the simulator driver. Oncoming vehicles far behind the simulator vehicle may only affect the simulator driver in rare circumstances, for example by incidents that create congestion in the oncoming lane on rural roads.

### **3 Simulation and generation models**

In order to be useful, the presented framework needs to be filled with suitable models for generation and simulation of vehicles. This section

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presents the developed models for simulation and generation of vehicles starting with a description of how vehicles and drivers are represented.

### **3.1 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 among different vehicle types. The vehicle types used are cars, buses, trucks, trucks with trailer with 3-4 axes, and trucks with trailer with 5 or more axes.

#### **3.1.1 Vehicle parameters**

The characteristics used to describe a vehicle are length, width, and the power to mass ratio, also called p–value. The p–value is the ratio between a vehicle’s power, available at the wheels, and its mass. For all vehicle types except cars, the p–value describes the vehicle’s maximum acceleration. For cars, the p–value describes the acceleration behavior at normal conditions. The average power/weight ratio for passenger cars is typically about 19 W/kg. 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. All vehicle parameters are assumed to be normally distributed within vehicles of a certain vehicle type.

#### **3.1.2 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 speed is assumed to be normally distributed for drivers driving a certain vehicle type. 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 at the desired speed. If that is not the case the vehicle–driver unit is assigned a new p–value.

The desired time gap is the time gap that a driver wants to keep from a preceding vehicle in car-following situations. The desired time gap is assumed to be lognormally distributed for drivers driving a certain vehicle type.



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## 3.2 The microscopic model

The microscopic 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 traffic composition. The model uses the simulator vehicle's speed, position, and so on, as input, and generates the corresponding information about the surrounding vehicles as output. The simulation model follows a traditional time-discrete update approach. The update procedure has been divided into two parts. In the first part the speed and position are updated for all vehicles, and in the second part the behavior of the simulated vehicles is updated: acceleration, lane-changing and overtaking decisions, and so on. In this way the update order of vehicles does not affect the result.

The submodels for vehicle movements and driving behavior used in this work are to a large extent based on submodels from the TPMA-model (Davidsson et al., 2002; Kosonen, 1999) and the VTISim model (Brodin and Carlsson, 1986). These two simulation models are documented in great detail and they have been well calibrated and validated for Swedish roads. However, some adjustments and further development have been necessary. In the following we give a brief description of the submodels for speed adaptation to the infrastructure, car-following, lane-changing, overtaking, oncoming avoidance, lateral movements, turn signals, and braking lights. The new model for behavior while overtaking will be given some extra focus. A more detailed description of the different submodels can be found in Janson Olstam (2005).

### 3.2.1 Infrastructure speed adaptation

The submodel for determining a vehicle's desired speed at a section is based on the speed adaptation model used in VTISim (Brodin and Carlsson, 1986). This model describes speed adaptation on rural roads and has therefore been recalibrated for freeways; see Janson Olstam (2005) for details. The model starts from a median basic desired speed,  $v^{max}$ . This median basic desired speed is then reduced with respect to speed limit, road width, and curvature to a median desired speed,  $v^{des}$ , for a specific section of a road. The desired speed for a vehicle  $n$  at a

road section is finally calculated as

$$v_n^{des} = \left( (v_n^{max})^Q - (1 - \alpha) \cdot \left( (\bar{v}^{max})^Q - (\bar{v}^{des})^Q \right) \right)^{\frac{1}{Q}}, \quad (1)$$

where  $v_n^{max}$  is the basic desired speed of vehicle  $n$  and  $0 \leq \alpha \leq 1$  is a vehicle type dependent parameter, equal to 0 for cars. The parameter  $Q$  is a transformation measure that depends on the reason for reduction: speed limit, road width, or curvature.  $Q = 1$  implies a parallel shift of the basic desired speed distribution curve. Values of  $Q < 1$  imply a counter clockwise rotation of the distribution curve around the median. This indicates that the desired speed of a driver with a high basic desired speed is more affected than a driver with a low basic desired speed. This rotation makes it possible to capture for example, that a vehicle with a high basic desired speed has to reduce its speed more in order to be able to drive through a sharp curve. An example of this rotation is given in Figure 2. This work used the calibrated values from Brodin and Carlsson (1986).

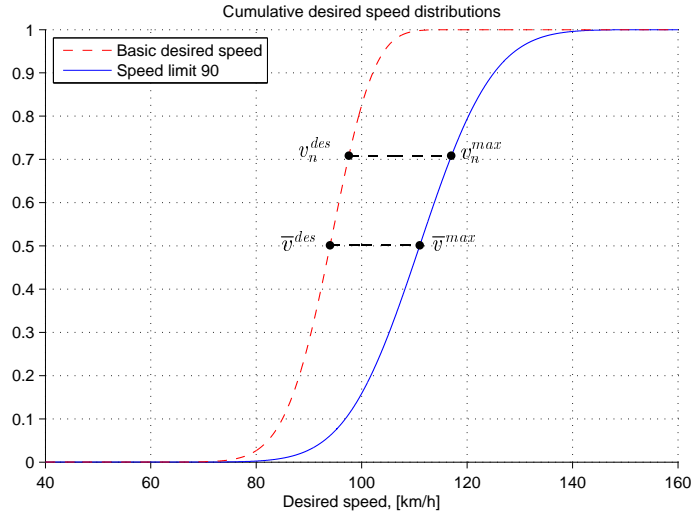


Figure 2: Example of shift and rotation of a desired speed distribution.

### 3.2.2 Car-following

Research on car-following models started in the 1950s and several models have been presented since then. The most well known car-following

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model is probably the GHR-model (Chandler et al., 1958), the Gipps model (Gipps, 1981), and the Wiedemann model (Wiedemann, 1974; Wiedemann and Reiter, 1992). For an overview on car-following models, see for example Brackstone and McDonald (1998) or Toledo (2007). The utilized car-following model is based on the HUTSIM/TPMA (Kosonen, 1999) model with some modifications. The car-following model uses three regimes: *Free*, *Stable*, and *Forbidden*. The regimes are defined by headways. The forbidden headway  $d_f$  is a function of the speed of the follower,  $v_n$ , and the speed of the leader,  $v_{n-1}$ ; see Janson Olstam (2005) for details. The forbidden headway also depends on a driver-specific minimum desired time gap, an average normal deceleration rate, and a minimum distance between stationary vehicles. The stable regime is defined as the regime enclosed by the forbidden regime and the free regime. The length of the stable regime,  $d_s$ , also depends on  $v_n$ ,  $v_{n-1}$ , the minimum desired time gap, the average normal deceleration rate, and the minimum distance between stationary vehicles.

When a vehicle is in the free regime,  $x_{n-1} - x_n > d_f + d_s$  (where  $x_n$  is the position of vehicle  $n$ ), the driver accelerates or decelerates in order to reach its desired speed. In the stable regime,  $d_f < x_{n-1} - x_n \leq d_f + d_s$ , the driver does not take any action—no acceleration or deceleration. If a vehicle enters the forbidden regime,  $x_{n-1} - x_n \leq d_f$ , the driver decelerates in order to reenter the stable regime.

For free accelerations, the acceleration model presented in Brodin and Carlsson (1986) is used, in which the free acceleration for vehicle  $n$  is calculated as

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

where  $p_n$  is the p-value 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  $n$ . For eventual decelerations in the free regime, vehicles are assumed to use an engine deceleration rate equal to the effect of rolling- and air-resistance and the gravitational acceleration, approximately  $0.5 \text{ m/s}^2$  when driving at  $90 \text{ km/h}$ . For decelerations in the forbidden regime, the deceleration rate depends on the ratio between the actual headway and the forbidden headway. For ratios close to 0, the driver brakes as hard as possible and for ratios close to 1 the driver uses the engine deceleration rate. In between these two

extremes the deceleration rate follows a piece-wise linear relationship; see Janson Olstam (2005) for details.

### 3.2.3 Lane-changing

There has recently been a focus on lane-changing models. The state-of-the-art in lane-changing models includes Gipps (1986), Hidas (2002, 2005) and Toledo et al. (2005, 2003). For an overview of lane changing models see Toledo (2007) or Janson Olstam (2005). The utilized lane-changing model is also based on the HUTSIM/TPMA (Kosonen, 1999) model, with some minor modifications; see Janson Olstam (2005) for details. In this model a pressure function is used for deciding whether or not a driver desires to change lane. The pressure is an estimation of the deceleration a vehicle needs to apply in order to avoid a collision with a vehicle in front. The decision to change to the left is based on the pressure to the closest vehicle in front in their own lane,  $P_f$ , and to the first vehicle in the left lane,  $P_{fl}$ , according to the rules presented in Figure 3. For lane changes to the right, the pressure from the vehicle behind in the left lane,  $P_b$ , and the pressure to the vehicle in front in the right lane,  $P_{fr}$ , is used. The parameters  $c_l$  and  $c_r$  are calibration parameters, that control the willingness to change lane to the left and right, respectively. We have used the values suggested in Gutowski (2002).

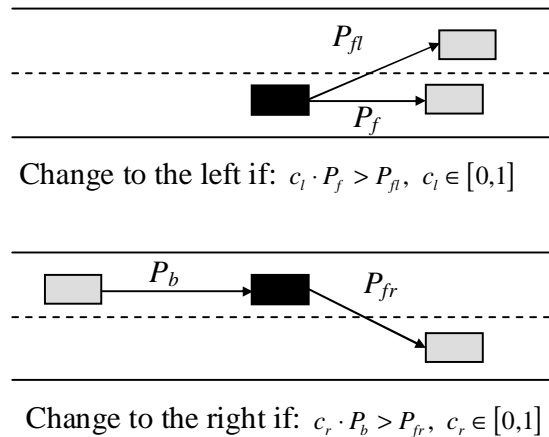


Figure 3: Lane-changing logic based on the model presented in Kosonen (1999)

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The pressure  $P$  between two vehicles is defined as

$$P = \frac{(v_{back}^{des} - v_{front})^2}{2 \cdot s}, \quad (3)$$

where  $v_{back}^{des}$  is the desired speed of the rearmost vehicle,  $v_{front}$  is the speed of the vehicle in front, and  $s$  is the distance between the two vehicles. In calculations of  $P$ ,  $v_{back}^{des}$  has to be replaced with an estimate of the desired speed since the rearmost vehicle may be the driving simulator vehicle. In these situations the desired speed,  $v_{back}^{des}$ , has been estimated as the maximum of the current speed and the highest speed at which the vehicle was traveling at the last time it could have been considered free: not accelerating or decelerating.

If a driver desires to change lane, the possibility of a lane change is checked using a traditional gap-acceptance model; see Kosonen (1999) and Janson Olstam (2005) for details. If a lane change is both desirable and possible, the driver will initiate the lane change.

Observations of the simulation animation indicate that the simulated drivers change lane more frequently than one would expect and that the lane changing model lacks in anticipation of future traffic conditions in the different lanes. This causes the average travel speed to decrease more with increasing flow than the decrease seen in the speed-flow diagrams for two-lane freeways. Thus, the lane-changing model is not working as it should be and needs to be enhanced or replaced.

### 3.2.4 Overtaking

The state-of-the-art in overtaking and rural road models includes the TWOPAS model (Leiman et al., 1998), the TRARR model (Hoban et al., 1991), and the VTISim model (Brodin and Carlsson, 1986). The VTISim model is currently being further developed in the RuTSim model (Tapani, 2005a,b). For an overview of overtaking and rural road models see for example McLean (1989) or Tapani (2005a). The model used for overtaking on rural roads with oncoming traffic is based on the VTISim model (Brodin and Carlsson, 1986). This model states that a driver 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 meters ahead. Re-

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strictions 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,  $d_{gap}$ , as defined in the following.
3. *Ability to execute an overtaking.* The estimated overtaking distance must be shorter than 1000 meters. This constraint is used to avoid extremely 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 that is defined as

$$W(d_{gap}) = e^{-A \cdot e^{-k \cdot d_{gap}}}, \quad (4)$$

where  $d_{gap}$  is the available gap, defined as:

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

and  $A$  and  $k$  are constants that depend on type of overtaking {flying, accelerated}, type of sight limitation {oncoming vehicle, natural}, type and speed of vehicle being overtaken, and the current road width. Calibrated values of  $A$  and  $k$  for Swedish road conditions is available in Carlsson (1993) and Janson Olstam (2005).

All drivers are assumed to have a higher desired speed during overtakings, currently set to an temporarily increase of 10 km/h. Car drivers are also assumed to use higher acceleration rates during overtakings, which is modeled as an increase in their p-value.

When overtaking, the overtaking vehicle must continuously reevaluate the distance to the vehicle in the oncoming lane and the distance remaining for the overtaking. This was not included in the model presented in Brodin and Carlsson (1986). The overtaking model has therefore been enhanced with a more detailed modeling of overtakings including decision rules for abortion of overtakings. The developed

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model for overtaking abortions is based on the assumption that a driver takes action if the time to collision,  $TTC$ , with the oncoming vehicle is less than the estimated time remaining for the overtaking. Thus, if  $TTC + t_{safety} < t_{left}$ , where  $t_{safety}$  is a safety margin and  $t_{left}$  is the estimated time remaining for the overtaking. The time remaining is estimated as

$$t_{left} = -\frac{v_n - v_{n-1}}{a_n} + \sqrt{\left(\frac{v_n - v_{n-1}}{a_n}\right)^2 + 2\frac{\Delta d}{a_n} + 0.5 \cdot t_{change}}, \quad (5)$$

where  $\Delta d = x_{n-1} - x_n + l_n + d_{min}$ . The parameter  $l_n$  is the length of vehicle  $n$ ,  $d_{min}$  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 reason for only adding half the time of a lane change is that this time is enough for clearing the oncoming lane and thereby avoiding a collision with an oncoming vehicle. The acceleration,  $a_n$ , is calculated according to Equation 2. In situations where  $TTC + t_{safety} < t_{left}$ , and the driver has not yet passed the lead vehicle, the driver is assumed to have aborted 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. If the vehicle's p-value is too low in order to be able to accelerate to the new desired speed, checked via Equation 2, the vehicle is temporarily assigned a new power/mass value. However, if the p-value needed to drive at the new desired speed exceeds the maximum p-value for the current vehicle type, the driver aborts the overtaking and falls back in order to merge into the normal lane behind the vehicle that was to be overtaken.

### 3.2.5 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 onto the shoulder

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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 signals with the high beam. However, if the  $TTC < 1.5 \cdot t_{change}$ , the driver brakes and moves as far out on the shoulder as he or she can in order to avoid a collision, and lets the oncoming overtaking vehicle safely end or abort the overtaking.

### 3.2.6 Lateral movements

The vehicle's lateral position, defined as the perpendicular distance to the center line of the road, is assumed only to change as a result of a change of lane. During a change of lane two different approaches for modeling the lateral movements have been tested. In the first, the vehicle's lane-changing movement is assumed to follow a sine curve. In the second alternative, the movement follows a function that uses a second order polynomial in the beginning and at the end of the movement, and a linear relationship in between. Both approaches look quite realistic on freeways, where the lane-changing movements are made over quite a long period of 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 during evasive maneuvers or when aborting an overtaking. It seems that neither of the two functions correctly represents lateral movements for quick lane changes. Another drawback is that these functions assume that all lane changes that are started, 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 Salvucci et al. (2001), or a control theory based model.

### 3.2.7 Turn signals and brake lights

In ordinary traffic simulations 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. Brake lights have in this work been assumed to be on when using deceleration rates higher than an engine deceleration rate, assumed to be  $0.5 \text{ m/s}^2$ .



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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.

### 3.3 The mesoscopic model

The mesoscopic model that is used to simulate vehicles within the candidate areas must simulate individual vehicles and not packages of vehicles, which is an approach used in for example the mesoscopic model CONTRAM (Taylor, 2003). The model must also assign each vehicle an individual speed, not an average speed, as in several mesoscopic models; see for example the DYNASMART model (Jayakrishnan et al., 1994) or the MEZZO model (Burghout, 2004).

In an earlier version of the simulation framework the candidate vehicles were assumed to drive at their desired speed, (Janson Olstam, 2003; Janson Olstam and Simonsson, 2003). This worked properly for low traffic flows on freeways. However, on rural roads 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 vehicle and congestion in the candidate area behind the simulator vehicle.

The developed mesoscopic model is based on the representative speed–flow relationships for Swedish roads presented in SRA (2001). These speed–flow relationships vary with road type, vehicle type, speed limit, number of lanes, road width, and sight class<sup>2</sup> 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. The speed of vehicle  $n$  is calculated as

$$v_n = \left( f(q)^Q + \left( (v_n^{des})^Q - f(0)^Q \right) \right)^{1/Q}, \quad (6)$$

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. The

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<sup>2</sup>The sight class is used in SRA (2001) for classification of the sight distance conditions along a road, more or less a classification of the overtaking possibilities along a road.

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parameter  $Q$  controls the rotation of the speed distribution curve. Values of  $Q < 1$  imply that a vehicle with a high basic desired speed reduces its speed more than vehicles with a lower basic desired speed. Two different approaches have been tested, namely with or without rotation. In the case without rotation,  $Q = 1$ , vehicles will be able to drive as much faster or slower than the average speed than they do at free flow conditions.  $Q = -0.2$  has been chosen for the case with rotation. This is the value used for speed adaptation to speed limits in the speed adaptation model presented in Brodin and Carlsson (1986). The model seems to perform well at both values of  $Q$ , but a value of  $Q < 1$  appears to be more realistic, since deviations in speed generally are higher under free flow conditions than under congested conditions. Further calibration and evaluation is needed before a recommendation can be made.

Apart from the reduction of speed according to Equation 6, 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. This can be interpreted as if every vehicle is driving in a separate lane, which is illustrated by the multiple lanes in the simulator vehicle direction in Figure 1.

### 3.4 Transition between the meso and the micro models

A candidate vehicle that reaches boundary of the simulated area, is allowed to travel into the simulated area only if there is a sufficient distance to the first vehicle in the simulated area. The rules for checking this differ between the two boundaries.

For vehicles in the driving simulator vehicle's direction that want to enter the simulated area from the candidate area behind the simulator vehicle, the car-following model is used to deduce whether it can do so or not. The same applies for oncoming vehicles that want to enter the simulated area from the candidate area in front of the simulator vehicle. The vehicle is allowed to enter the simulated area if it can do so without decelerating, 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 but the position is locked at the edge between the candidate area and the simulated area. This means that the vehicle's position will be calculated using the speed of the window instead of using the vehicle's own speed, and that the vehicle consequently will

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move a shorter distance than its speed implies. The vehicle gets a new opportunity to pass into the simulated area in the next time step. While waiting for a sufficient gap, the candidate vehicle adjusts its speed in order to avoid rapid deceleration when entering the simulated area. There is also a minimum gap criterion, that the gap to the front vehicle must at least be larger than a minimum-distance-between-stationary-vehicles-parameter. Vehicles that are waiting at the boundary are treated as any other candidate vehicle but with the exception that their position increment may be restricted if they would pass into the simulated area without fulfilling the entering constraints. The vehicles at the boundary, as well as the other candidate vehicles, can overtake each other without any time delay. If there are several vehicles waiting at the boundary, the vehicle that first fulfills the entering constraints will be allowed to pass into the simulated area. This sometimes implies that this vehicle will overtake other candidate vehicles that are waiting at the boundary. When a vehicle is allowed to enter the simulated area, the calculation of its position will return to being based on its real speed instead of the speed of the boundary. In the freeway environment cars are also given the possibility of entering the simulated area in the left lane. In this case, a car is allowed to enter the simulated area if the lane changing model suggests a lane change to the left lane and if the car-following model returns a non-negative acceleration.

A similar approach is used for the transition of vehicles from the candidate area in front of the simulator vehicle to the simulated area. 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. Consequently, the candidate vehicle at the boundary is allowed to enter the simulated area if its entering does not imply a deceleration for the first vehicle in the simulated area.

There are no rules for the transition from the simulated area to either of the candidate areas. If a vehicle in the simulated area reaches the boundary of the simulated area, it will directly enter the candidate area and become a candidate vehicle. If the boundary behind the driving simulator vehicle catches-up with a slower simulated vehicle, the simulated

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vehicle will immediately become a candidate vehicle and any candidate vehicles waiting at the boundary will thereby overtake this vehicle without any time delay. It sometimes happens that a simulated vehicle who wants to drive at only a slightly lower speed than the driving simulator vehicle, hinders the entering of candidate vehicles from the candidate area behind the simulator vehicle for quite a long time. In order to avoid this, vehicles that are closer than 100 meters from this boundary and that have a desired speed lower than the simulator vehicle's speed are directly moved to the candidate area behind the simulator vehicle.

### 3.5 Generation of new vehicles

Vehicles traveling much slower or faster than the simulator vehicle 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 1. As the edges always 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 does not only depend on its own speed and headway but also on the speed of the simulator vehicle.

In the 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, vehicle arrival time is drawn from a time headway distribution. The av-

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erage 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 form a subgroup of the total population of vehicles moving faster than the driving simulator vehicle, the actual average distance between vehicles in this subgroup is 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. For generation of a new vehicle behind the simulator vehicle, the algorithm works as follows:

1. Set  $i = 1$ .
2. Generate a new vehicle with a desired speed,  $v_i^{des}$ , and time headway,  $\Delta t_i$ , to the vehicle in front of it.
3. Calculate the vehicle's speed,  $v_i$ , given its desired speed and the traffic flow, according to the mesoscopic model; see Equation 6.
4. If the speed is lower than the simulator vehicle's present speed: increase  $i$  and go to step 2, otherwise let  $n = i$ .
5. Calculate the time to arrival as

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

where  $v_{DS}$  is the present speed of the simulator vehicle.

6. Discard all vehicles except the last generated.
7. When the simulation time has reached the time of arrival, add the generated vehicle to the relevant candidate area and rerun the algorithm to generate a new vehicle.

On rural roads the time headways  $\Delta t_i$  are drawn from an exponential distribution. On freeways the time headways are instead assumed to

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follow the time headway distribution developed in the HUTSIM/TPMA model (Blad, 2002), which has been specially developed for time headways on Swedish freeways. At the edge in front of the simulator vehicle, new vehicles are generated according to a corresponding algorithm. The stop criterion is then a vehicle with a speed lower than the simulator vehicle's present speed.

There is a risk that the algorithm gets stuck when for example trying to generate faster vehicles when the simulator vehicle is driving very fast. In order to avoid that and to limit the computational effort, new vehicles are only generated behind the simulator vehicle when it is traveling slower than the highest speed in the current desired speed distribution, and analogously for the edge in front of the simulator vehicle. For the same reason the number of tries at each time step has been restricted, currently to 10 presumptive new vehicles per time step:  $n \leq 10$ .

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 within this range,  $v_{DS} < v_n \leq 1.05 \cdot v_{DS}$  for the edge behind the simulator vehicle and  $0.95 \cdot v_{DS} < v_n \leq v_{DS}$  for the edge in front, a speed equal to  $1.05 \cdot v_{DS}$ , respectively  $0.95 \cdot v_{DS}$  is instead used in the calculations of the arrival time.

Vehicles in the oncoming direction on rural roads are generated according to the vehicle platoon generation model presented in Brodin and Carlsson (1986). For an oncoming vehicle on freeways the HUTSIM/TPMA model is used (Blad, 2002).

## 4 Validation

The aim of the developed simulation framework is to create realistic traffic situations around the simulator driver by coordinating different models for generation and simulation of vehicles. We have in this article validated the framework by looking at the number of overtakings or catch-ups that the simulator vehicle experiences. The number of catch-ups is affected by all components in the framework. The generation model has to generate the correct number of vehicles and with the correct characteristics; the rules for speed choices, lane changing, overtaking, and so on, in the micro and meso models have to be correct; and the transition model has to let the correct number of vehicles into the simulated area from the candidate areas. In addition to this, we have compared the output flow from the simulation model with the

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input target flow. We have also estimated the computational savings of using the candidate areas.

The primary output of the developed simulation framework is the behavior of the simulated vehicles in the simulated area; thus the primary output is at a microscopic level and not at a macroscopic level, as is the case for most applications of traffic simulation. The overall objective for our application is that the simulator drivers experience the surrounding vehicles' behaviors as realistic. If this is not the case the simulator drivers might behave differently than they would if they were driving a real car. However, the focus in this article is the simulation framework and not the submodels for driver behavior. We have therefore, at this point, not done any validation of the actual driving behavior that the micro-simulation model generates. We have instead performed a small driving simulator study with the aim of getting a hint of how well the submodels for driving behavior describe real driving.

The section starts with a presentation of the study of overtaking rates of the driving simulator vehicle. It then continues with a comparison of target and obtained flows followed by a comparison of computational time when running the framework with or without the candidate areas. The section ends with a description and results from the driving simulator experiment.

## 4.1 Overtaking rates

An important aspect relative to the observed realism, is the number of vehicles that catch up with the driving simulator vehicle 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 the number when driving on a real road, but you certainly react if the proportion between vehicles that catch up with you (passive catch-ups) and the ones you catch up with (active catch-ups) is not realistic. We have compared active and passive catch-ups generated by the model with an analytical expression for estimating the number of catch-ups of a floating car, originally presented in Carlsson (1995). The number of passive catch-ups is estimated as

$$U_p = qL \int_{v_0}^{\infty} \left( \frac{1}{v_0} - \frac{1}{v} \right) f_t(v) dv, \quad (7)$$

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where  $q$  is the traffic flow,  $L$  is the length of the observed road section,  $v_0$  is the speed of the studied vehicle, and  $f_t(v)$  is the time mean speed<sup>3</sup> distribution. The number of active catch-ups is calculated in a similar way. One of the underlying assumptions for these functions is that all vehicles 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.

The values from the model were generated by simulating the driving simulator vehicle in addition to simulating the surrounding vehicles. In the rural environment, active catch-ups were estimated as the sum of the number of active overtakings and the queue length in front of the simulator vehicle at the end of the simulation. The passive catch-ups were estimated in a similar way. In the freeway environment, active and passive catch-ups were measured as the number of vehicles that the driving simulator vehicle passed and the number of vehicles that passed the driving simulator vehicle, respectively. Simulations were conducted with varying desired speeds of the simulator vehicle and at varying traffic flows. For rural roads the simulated values correspond quite well to the analytical calculation; see the example with 400 vehicles/h in each direction in Figures 4a and 4b. However, the simulated number of active catch-ups on freeways seems to be too low; see the example with 1000 vehicles/h in Figure 4d. The simulated values of the number of catch-ups are generally smaller than the corresponding analytical values as is predicted, because the analytical expression is an upper limit. However, there are some values in Figure 4b that lie over the analytical expression. The reason for this is that the driving simulator vehicle in these cases was driving in quite long platoons—15–25 vehicles—at the end of the simulation.

We suspect that the reason for the deviation of active catch-ups on freeways is due to the deficiencies in the lane-changing model, stated in Section 3.2. The deficiencies in the lane-changing model cause the speed–flow relationship generated by the microscopic model to differ from the correct one used in the mesoscopic model and in the generation model. In order to make a fair comparison without the effects of the deficiencies in the lane-changing model, a second simulation series was conducted. In these simulations, the speed–flow relationship used

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<sup>3</sup>Time mean speed is the arithmetic mean of individual speed observations. The alternative is the space mean speed, also known as the mean travel speed, which is the harmonic mean of individual speed observations.



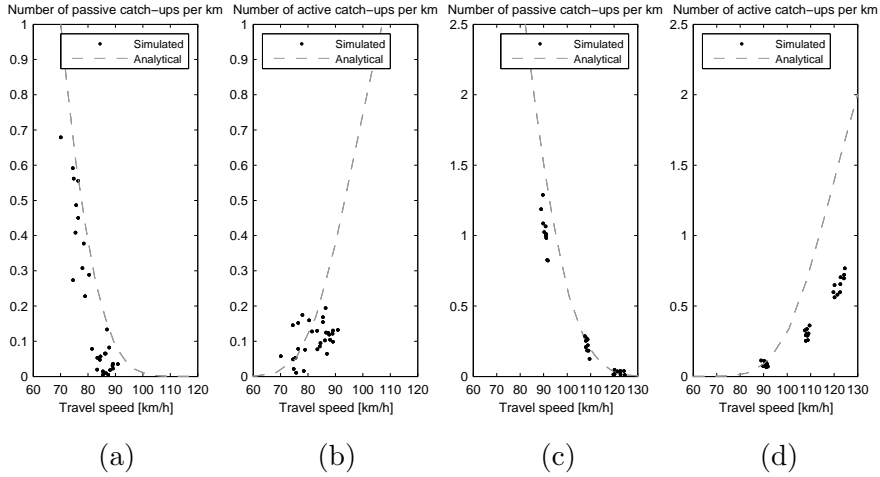


Figure 4: Simulated and calculated number of passive (a and c) and active (b and d) catch-ups per km of the driving simulator vehicle (DS) on a straight and plain rural highway with oncoming traffic (a and b) and a freeway (c and d).

in the mesoscopic model was changed to correspond to the incorrect speed–flow relationship that the microscopic model results in. This is a temporary solution for making a fair comparison and in the end, the lane-changing model has to be enhanced so that the microscopic model generates valid speed–flow relationships. The resulting number of active and passive catch-ups is presented in Figure 5. As expected, the correspondence between the simulated values and the predicted analytical values increases significantly. This allows us to conclude that it is important that the simulation models used in the different areas generate corresponding results, and that the utilized microscopic model has to be enhanced since it does not generate valid speed–flow relationships.

## 4.2 Comparison of flows and computation times

Another way to validate the framework is to compare the resulting traffic flow from the simulation model with the input target flow. The traffic flow is the number of vehicles passing a point per time unit, thus it is not possible to measure the flow in an area around the driving simulator vehicle. However, the traffic flow can be estimated as the product of the density and the space mean speed. We have used this method to

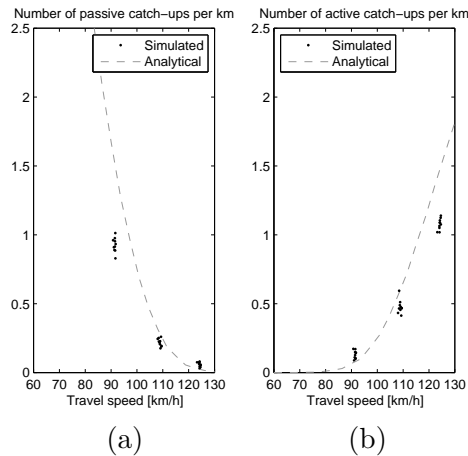


Figure 5: Simulated and calculated number of passive (a) and active (b) catch-ups per km of the driving simulator vehicle (DS) on a straight and plain freeway when using an adjusted speed-flow relationship.

estimate the flow within the moving area starting 2 km behind and ending 2 km in front of the driving simulator vehicle. Table 1 presents estimations of the traffic flow on a straight rural highway with a target flow of 400 vehicles/h and a straight freeway with a target flow of 1000 vehicles/h. Since the 95 % confidence intervals include the target flow, the null hypothesis (average of simulated flow equal to the target flow) cannot be rejected. However, the deviation in flow is large and further analysis with different flow levels and more replications is needed in order to obtain more reliable results.

Table 1: Average Obtained Flows and 95 % Confidence Intervals for 2.5 Hour Simulations, 10 Replications per Condition.

Road type	Target flow [vehicles/h]	Obtained flow [vehicles/h]
Straight rural highway	400	424 ± 163.7
Straight freeway	1000	1029 ± 77.7

One of the main motives for dividing the window into one inner and two outer areas was to limit the computational effort. In order to check if this is the case, freeway simulations with and without the candidate

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areas have been conducted. The total window length was set to 12 km in both cases. In the case with candidate areas, the length of each of the candidate areas was set to 2 km, resulting in an 8 km long simulated area. The average increase in computation time when only using a simulated area is about 9% and 15% at a flow level of 1000 vehicles/h and 2000 vehicles/h, respectively.

### 4.3 Driving simulator experiment

A small driving simulator experiment has been conducted in order to get a hint on how well the submodels for driving behavior work. The experiment included 10 participants and was performed in the VTI Driving Simulator III (VTI, 2006). After 10 minutes of warm-up driving, the participants drove 15 minutes along a rural road and 15 minutes on a freeway.

After the drive, the participants were asked to give comments about the simulated vehicles' behavior. The overall conclusion was that the simulated vehicles behave quite realistically but that there is room for enhancements. The most typical comments were that the simulated drivers drove aggressively on the rural road and that the simulated drivers drove more slowly than in reality. Some participants also thought that some of the simulated drivers drove a long time in the left lane on freeways before changing back to the right lane. This indicates that the gap-acceptance parameter for lag gaps at lane changes to the right may need to be adjusted. The reason for the aggressive behavior was probably due to a too small safety margin at overtakings. Later tests conducted with a larger safety margin indicate that this seemed to solve this problem. A probable reason that some of the participants thought that the simulated drivers sometimes started overtakings at risky places, for example, places with limited sight, is that it can be quite difficult for the participants 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 corresponds to the sight distances experienced by the simulator driver. The reason that the simulated drivers seemed to drive slowly was probably due to that the speedometer in the driving simulator shows the actual speed and not a speed 5–8 km/h higher than the actual speed, which is the case in most real cars; see for example Wallén Warner (2006). The result is that the participants drive faster in the simulator than they

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think that they normally do, which leads to the surrounding vehicles seeming to drive more slowly than in real life.

## 5 Concluding remarks and future research

The simulation framework presented in this article is able to generate and simulate surrounding traffic for a driving simulator on rural roads and on freeways. The model generates realistic streams of vehicles both in the same and the oncoming direction as the simulator vehicle. The contribution includes a new technique for generating traffic on a moving area around a specific vehicle, an enhanced version of the VTISim (Brodin and Carlsson, 1986) overtaking model, and a mesoscopic simulation model for road links. The framework has been tested within the VTI Driving III simulator. The validation study showed that the framework is able to create realistic traffic situations on rural roads and on freeways in terms of a realistic number of active and passive catch-ups. The only question mark is active catch-ups on freeways, which seem to be too few due to a too high lane-changing frequency. Thus, the lane-changing model has to be enhanced. Observations made during the test in the VTI driving simulator indicate the need for smaller adjustments regarding the overtaking model and the displayed speed. The comparison of traffic flows and computational times verified that the framework is able to achieve the target flow and that there is a gain in computational time when using the candidate areas compared to only using one large simulated area.

The microscopic simulation model is only able to simulate road links; roads without intersections and ramps. In order to be really usable, the model must also include modeling of on ramps 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 application since driving simulator drivers may not follow this behavior. 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 most common approach for simulation of vehicles in driving simulators is to use models in which all vehicles behave according to predetermined patterns. For experimental design reasons it is desir-

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able to keep the variation in test conditions among different drivers as low as possible. The use of models based on predetermined patterns makes it possible to give all participants in principle exactly the same test conditions even at a micro level. By using microscopic simulation of surrounding traffic, drivers will experience different situations at the micro level depending on how they drive. The simulator drivers' conditions will still be comparable at a higher, more aggregated level, if this is sufficient or not varies depending on the type of experiment. It may be possible to both increase the realism and keep the reproducibility by combining microscopic simulation and predetermined situations. The basic idea is to use the microscopic 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 should, in an unnoticeable way for the driver, turn from being simulated according to the microscopic model to be totally controlled according to the defined scenario.

The development of a framework for generation and simulation of surrounding traffic for driving simulators does not only increase the realism in driving simulators; it also creates possibilities to develop new, or to enhance existing, traffic simulation models. Data concerning all movements, including the driving simulator vehicle's movements, can be gathered. This data can then be used to study, for example, car-following, lane-changing, and overtaking behavior in order to create more realistic submodels for driving behavior. The combination of a driving simulator and a traffic simulation model also creates additional methods for validation of traffic simulation models. The validity of a model can now also be checked by driving in the simulated traffic; such subjective or qualitative analysis can be a good complement to the traditional comparisons of speeds, flows, queue lengths, and so on.

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