Simulation of vehicles in a driving simulator using microscopic traffic simulation

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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 experiment in driving simulators therefore has to include surrounding traffic.

This paper 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 sub-models for driving behavior while vehicles in the outer regions are updated according to a less time-consuming model. The presented work includes a new framework for generation and simulation of vehicles within a moving area. It also includes the development of an enhanced model for overtakings and a simple mesoscopic traffic model.

The developed model has been 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 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.


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. This is especially true nowadays since the number of driving related interactions is increasing. Today drivers also interact with advanced driver assistance systems, in-vehicle information systems, different NOMAD-devices, such as mobile phones, personal digital assistants, etc. These technical systems influence drivers’ behavior and their ability to drive a vehicle.

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 impossible to conduct due to ethical reasons. Test tracks offer a safer environment and the possibility of giving test drivers more equal conditions but lack a lot in realism. 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. 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. 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 surrounding vehicles must behave in a realistic and trustworthy way. Microscopic simulation of traffic is one possibility for simulating these surrounding vehicles. Micro models use different sub-models for car-following, lane-changing, speed adaptation, etc. to simulate driver behavior at a microscopic level. This papers concerns simulation of surrounding vehicles in driving simulators using traditional techniques for microscopic simulation of traffic.

The common approach for simulation of vehicles in driving simulators is to use deterministic models, i.e. all vehicles behave according to predetermined patterns. There are for experimental design issues desirable to keep the variation in test conditions between different drivers as low as possible. Deterministic models make it easier to create driving simulator scenarios in which all participants get the same test conditions. By using stochastic 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. The main reason for using stochastic simulated traffic is that it increases the realism of the surrounding traffic and thereby decreases the risk for getting experimental results that is not valid for real driving. Simulated traffic also makes it possible to conduct driving simulator experiments with dense traffic conditions.

Some trials to use commercial software packages as AIMSUN (Barceló and Casas, 2002) and VISSIM (PTV, 2003) to simulate surrounding vehicles in driving simulators has been conducted, see for example Bang et al. (2004) and Jenkins (2004). However, since commercial programs simulate a specified geographic area, very large areas have to be simulated when running long driving simulator experiments (1-2 hours driving). A more efficient approach is therefore to only simulate the closest neighborhood of the driving simulator vehicle. This area of course moves with the same speed as the simulator vehicle, which on the other hand implies new techniques for generation of vehicles. Unlike most applications of traffic simulation the important output for this application is at the micro level, i.e. the actual behavior of the simulated vehicles/drivers. 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. This application therefore requires a more detailed modeling of vehicle movements than used in most softwares. Another reason for not using available commercial softwares is that they are not able to simulate rural roads with oncoming traffic, or that the modeling of such roads is not detailed enough for this kind of application. In the light of these facts a couple of models specialized for the application of simulation of surrounding vehicles in driving simulators has been developed. Three of the most well-known models are the ARCHISIM model (El hadouaj and Espli, 2002, Espli, 1995), the NADS model (Ahmad and Papelis, 2001), and the DRIVERSIM model (Wright, 2000). Research within this area has to a large extent been focused on decision making modeling concepts. 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.

The objective of this project 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. corresponds to real data. 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.

The developed simulation model including the general simulation framework, methods for generation of vehicles, and sub-models for driving behavior is presented in section 2. In section 3 follows a presentation of the two performed validation studies. Section 4 ends with some concluding remarks and suggestions for future research.

The main contribution of this paper is the general simulation framework, the technique for generation of new vehicles, the enhanced overtaking model, and the mesoscopic simulation model.

2 THE SIMULATION MODEL

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 traffic composition. The model uses the simulator vehicle’s speed, position, etc. as input and generates the corresponding information about the surrounding vehicles as output.

As in most traffic simulation models vehicles and drivers are treated as one unit, i.e. the interaction between the driver and the vehicle is not modeled. These vehicle-driver units are described by a set of driver or vehicle characteristics, including desired speed, desired following time gap, power/mass-ratio, etc. 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.

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 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.
2.1 The moving window

Instead of simulating a specific geographical area, we use an approach where only the closest neighborhood of the simulator vehicle is simulated. Similar approaches have been used in the ARCHISIM model (Espié, 1995) and in the NADS model (Bonakdarian et al., 1998). This neighborhood or 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. 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. 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.

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. 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 sub-models for car-following, overtaking and speed adaptation, etc. The inner area is called the simulated area. The behavior of vehicles traveling further away from the simulator vehicle is less important. These vehicles, traveling in the outer regions, are simulated according to a simple mesoscopic model. 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. At the end of the candidate areas vehicles that travels out of the system is removed from the model and new vehicles are generated.

2.2 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. 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, but for vehicles in the driving simulator vehicle direction a new generation technique has been developed. The generation method do only generates faster vehicles behind and slower vehicles in front of the simulator vehicle. The basic principle is to generate new temporarily vehicles until a faster/slower one is generated and then discard the temporarily ones. The time headways and desired speeds of the discarded vehicles are then used to calculate a correct arrival time for the faster/slower vehicle according to

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

where \(\Delta t_i\) and \(v_i\) is the time headway and speed of the \(i\) th discarded vehicle, respectively, \(v_{DS}\) is the speed of the accepted vehicle and \(v_{DS}\) is the current speed of the driving simulator vehicle. On rural roads is the time headways \(\Delta t_i\) drawn from an exponential distribution. On freeways are the time headway instead assumed to follow the time headway distribution developed in the HUTSIM/TPMA model (Blad, 2002), which has been specially developed for time headways on Swedish freeways.

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, and analogous for the edge in front of the simulator vehicles. 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 within this range, thus \( v_{DS} < v_n \leq 1.05 \cdot v_{DS} \) 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 oncoming vehicles on freeways the HUTSIM/TPMA model is used (Blad, 2002).

### 2.3 Sub-models for driving behavior and vehicle movements

#### Car-following

The utilized car-following model is based on the HUTSIM/TPMA (Kosonen, 1999) model with some modifications, see Janson Olstam (2005) for details. The car-following model uses three regimes: Free, Stable, and Forbidden. The regimes are defined by headways. The forbidden headway \( d_f(v_n, v_{n+1}) \) is a function of the speed of the follower and the leader. The forbidden headway also depends on a driver dependent 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 width of the stable regime, \( W_{stable} \), depend on \( d_f(v_n, v_{n-1}) \).

When a vehicle is in the free regime, \( x_{n-1} - x_n > d_f + W_{stable} \), the driver accelerates or decelerates in order to reach its desired speed. In the stable regime, \( d_f < x_{n-1} - x_n \leq d_f + W_{stable} \), the driver does not take any action. 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 acceleration for vehicle \( n \) is calculated as

\[
a_n = \frac{P_n}{v_n} - \left( C_A \right)_n \cdot v_n^2 - \left( C_{R_1} \right)_n - \left( C_{R_2} \right)_n \cdot v_n - g \cdot i(x_n),
\]

where \( P_n \) is the power/mass 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 \( n \).

#### Lane changing

The 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 desire to change lane. The pressure is defined as

\[
P = \frac{(v_{des} - v_{obs})^2}{2 \cdot s},
\]

where \( v_{des} \) is the desired speed of the rearmost vehicle, \( v_{obs} \) is the speed of the obstacle vehicle, and \( s \) is the distance between the two vehicles. Decision for changes to the left is based on the pressure to the closest vehicle in front in the own lane and to the first vehicle in the left lane according to the rules presented in Figure 1. For lane changes to the right, the pressure from the back vehicle in the left lane is used. The parameters \( c_l \) and \( c_r \) are calibration parameters, which controls the willingness to change lane to the left and right, respectively.
Figure 1 The lane-changing logic, based on the model presented in Kosonen (1999).

Speed adaptation

The sub-model 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). The model starts from an average basic desired speed, \( v_0 \). This basic desired speed is then reduced with respect to speed limit, road width, and curvature to an average desired speed, \( v_3 \), for a specific road section. The desired speed for a vehicle \( n \) at a road section is finally calculated as

\[
v_{3n} = (v_{0n} - (1 - \alpha) \cdot (v_0^Q - v_0^Q))^{\frac{1}{Q}},
\]

where \( v_{0n} \) 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. \( Q = 1 \) implies a parallel shift of the basic desired speed distribution curve. Values of \( Q < 1 \) also implies an anticlockwise rotation of the distribution curve around the median, which leads to that the desired speed of drivers with high basic desired speed are more affected than drivers with low basic desired speeds.

Overtaking

The model used for overtaking on rural roads with oncoming traffic is based on the VTISim model (Brodin and Carlsson, 1986). This model is based on probability functions that describe the probability of starting an overtaking as a function of the available overtaking gap. The probability function is defined as

\[
P(d_{gap}) = e^{-A \cdot e^{-k \cdot d_{gap}}},
\]

where \( d_{gap} \) is the available gap, that is

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

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).

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 power/mass ratio.
When overtaking, the overtaking vehicle must continuously revaluate 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 overtaking model has therefore been enhanced with a more detailed modeling of overtakings including decision rules for abortion of overtakings. The developed 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 left of the overtaking. That is if \(TTC + t_{\text{safety}} < t_{\text{left}}\), where \(t_{\text{safety}}\) is a safety margin and \(t_{\text{left}}\) is the time left of the overtaking estimated as

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

where \(\Delta d = x_{n-1} - x_n + l_n + d_{\text{min}}\). \(d_{\text{min}}\) is the critical lag gap for lane changes to the right and \(t_{\text{change}}\) is the time it takes to perform the lane change back to the normal lane. The variables \(v_n, x_n, v_{n-1}, \) and \(x_{n-1}\) refer to the speed and position of the overtaking vehicle and the vehicle being overtaken, respectively. The acceleration \(a_n\) is calculated according to equation (2). In situations where \(TTC + t_{\text{safety}} < t_{\text{left}}\) and the driver has not yet passed the lead vehicle, 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. If the vehicle’s power/mass ratio 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 power/mass ratio needed to drive at the new desired speed exceeds the maximum power/mass 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.

**Lateral movements**

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 movements has been tested. In the first one the vehicles lane-changing movements is assumed to follow a sine-curve. 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. It seems 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 Salvucci et al. (2001) or a control theory based model.

**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. 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 m/s\(^2\). Drivers are assumed to use the turn signals 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.

2.4 The candidate areas

In the candidate areas the vehicles are simulated by a new mesoscopic traffic simulation model. The traffic stream is still represented by individual vehicles but interactions are modeled at an aggregated level using speed-flow functions from SRA (2001). The speed of vehicle \( n \) is calculated as

\[
    v_n = \left( f(q)^Q + \left( (v^\text{des}_n)^Q - f(0)^Q \right) \right)^{1/Q},
\]

where \( v^\text{des}_n \) 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 parameter \( Q \) controls the rotation of the speed distribution curve. Values of \( Q < 1 \) implies that the speed of vehicles traveling fast will decrease more than the speed of vehicles that drive slow. Two different values on \( Q \) have been tested, 1 and \(-0.2\). \( Q = 1 \) implies no rotation, thus vehicles will be able to drive as much faster or slower than the average speed as it does at free flow conditions. \( Q = -0.2 \) is the value used for speed adaptation to speed limits in the similar speed adaptation model presented in Brodin and Carlsson (1986). The model seems to perform well at both values of \( Q \), but a value of \( Q < 1 \) seems to be more realistic. Further calibration and evaluation is needed before a recommendation can be made.

Apart from the reduction of speed according to equation (7), 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.

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. For a vehicle 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 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 adopt 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 avoid hard decelerations when entering the simulated area. In the freeway environment cars are also given the possibility of entering the simulated area in the left lane. Whether this is possible or not is checked using both the lane-changing and the car-following model. 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 or not.

3 VALIDATION

The primary outputs of the developed model are the behavior of the simulated vehicles, thus the primary output is at a microscopic level and not at a macroscopic level which is the case for most applications of traffic simulation. The simulation model has therefore been validated at a microscopic level. The overall objective for our application is that the simulator drivers consider the surrounding vehicles’ “behavior” as realistic. If this is not the case the simulator drivers may behave differently compared to when driving a real car. The problem is that it is hard to define “realistic”. It is also hard to state how realistic the behavior has to be in order for the model to be valid. The ultimate goal is, of course, a model where the simulator driver cannot conclude whether a surrounding vehicle is driven by another human or by a computer.
Two separate validation studies have been performed within this project. The first is a study on overtaking rates of the driving simulator vehicle and the second one is a study on how realistic human drivers think that the simulated drivers behave.

### 3.1 Overtaking rates

An important part that is connected to the observed realism is the number of vehicles that catch 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 catch up with you (passive catch-ups) and that you catch up with (active catch-ups) is not realistic. We have in this project compared active and passive catch-ups generated by the model with an analytical expression for estimating number of catch-ups of a floating car, originally presented in Carlsson (1995). Passive catch-ups is according to this expression estimated as

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

where $q$ is the traffic flow (vehicles/h), $L$ 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 distribution. The number of active catch-ups is calculated in a similar way. One of the underlying assumptions for these functions 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.

The values from the model were generated by not only simulating the surrounding vehicles but also simulating the driving simulator vehicle. Simulations were performed with varying desired speed of the simulator vehicle and at varying traffic flows. For rural roads the simulated values correspond quite well to the analytical calculation, see example with 400 vehicles/h in each direction in Figure 2a and b. However, the simulated number of active catch-ups on freeways seems to be too low, see example with 1000 vehicles/h in Figure 2c and d. The reason for this seems to be a too high frequency of lane changes. Noticeable is however that the analytical expression is an upper limit and that the simulated values is generally smaller than the corresponding analytical value.

**Figure 2** Simulated and calculated number of passive (a & c) and active (b & d) catch-ups per km of the driving simulator vehicle (DS) on a straight and plain rural highway with oncoming traffic (a & b) and a freeway (c & d).
3.2 User evaluation

We have in this work also tried to validate the simulation model by using simulator drivers as measurement devices. 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 are. In order to get these statements a small driving simulator experiment with 10 participants, 3 females and 7 males, has been conducted. The experiment 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. For the rural scenario the part of the National Road Rv 34 between Målilla and Hultsfred was used. The road is 9 meter wide with a carriageway of 7 meters. The posted speed limit is 90 km/h. For the freeway scenario a part of the European Road E4 between Linköping and Norrköping was used. The road has 2 lanes in each direction and a posted speed limit of 110 km/h. All intersections and ramps were removed from the scenario roads. The Rv 34 and E4 were chosen as they are good representatives of Swedish highways and freeways. The participants were not exposed to any critical situations. The participants were instructed to drive as they normally do in the two road environments.

After the ride, the participants were asked to give comments about the simulated vehicles’ behavior by filling in an evaluation form and answering some interview questions. The participants were first asked questions about the realism of other parts of the driving simulator (steering, accelerator pedal, screen depth, etc) in order to avoid that opinions about those things influenced the answers on the forthcoming questions. The participants were then, among others, asked to estimate to which extent they thought that the other road users behave like real drivers. The results were quite good, with a mean of 5.4 on a seven-grade scale for both the rural road and the freeway. The most common comments were that the simulated drivers drove aggressively on the rural road and that the simulated drivers drove slower than in reality. Some participants also thought that some of the simulated drivers drove long time in the left lane on freeways before changing back to the right lane.

The reason for the aggressive behavior was probably due to a too small safety margin at overtakings. Later conducted tests with a larger safety margin indicate that this seem to solve this problem. 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 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 correspond to the sight distances experienced by the simulator driver.

The reason for 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. 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 it betters corresponds to a real vehicle.

4 CONCLUDING REMARKS AND FUTURE RESEARCH

The simulation model presented in this paper is able to generate and simulate surrounding traffic for a driving simulator, both 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 model includes, among others, 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 model has been integrated and tested within the VTI Driving simulator III. The performed validation showed that the simulated vehicle-driver units to a large extent behave as real drivers. The result from the validation studies also indicates that further enhancements and calibration of for example the sub-models for overtaking and lane-changing is needed.
The development of a model for generation and simulation of surrounding traffic for driving simulators do not only increase the realism in driving simulators. It also creates possibilities to develop new or enhance existing traffic simulation models. Data concerning all movements, including the driving simulator vehicle’s movements, can be gathered. This data can then be used to study, for example, car-following, lane-changing-, and overtaking behavior in order to create more realistic sub-models for driving behavior. The combination of a driving simulator and a traffic simulation model also creates new additional ways for validation of traffic simulation models. The validity of a model can now also be checked by driving around in the simulated traffic, such subjective or qualitative analysis can be a good complement to the traditional comparisons of speeds, flows, queue lengths, etc.

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 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 developed model can only be used in driving simulator scenarios in which participants would not be exposed to 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 should, in an unnoticeable way for the driver, turn from stochastic to be totally controlled according to the defined scenario.

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6 REFERENCES


