# Traffic Simulation Modelling of Rural Roads and Driver Assistance Systems

Andreas Tapani

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# Abstract

Microscopic traffic simulation has proven to be a useful tool for analysis of various traffic systems. This thesis consider microscopic traffic simulation of rural roads and the use of traffic simulation for evaluation of driver assistance systems.

A traffic simulation modelling framework for rural roads, the Rural Traffic Simulator (RuTSim), is developed. RuTSim is designed for simulation of traffic on single carriageway two-lane rural roads and on rural roads with separated oncoming traffic lanes. The simulated traffic may be interrupted by vehicles entering and leaving the modelled road at intersections or roundabouts.

The RuTSim model is applied for analysis of rural road design alternatives. Quality-of-service effects of three alternatives for oncoming lane separation of an existing Swedish two-lane road are analysed. In another model application, RuTSim is used to simulate traffic on a Dutch two-lane rural road. This application illustrates that the high level of model detail of traffic micro-simulation may call for use of different modelling assumptions regarding driver behaviour for different applications, e. g. for simulation of traffic in different cultural regions.

The use of traffic simulation for studies of driver assistance systems facilitate impact analyses already at early stages of the system development. New and additional requirements are however then placed on the traffic simulation model. It is necessary to model both the system functionality of the considered driver assistance system and the driver behaviour in system equipped vehicles. Such requirements can be analysed using RuTSim.

In this thesis, requirements on a traffic simulation model to be used for analysis of road safety effects of driver assistance systems are formulated and investigated using RuTSim. RuTSim is also applied for analyses of centre line rumble strips on two-lane roads, of an overtaking assistant and of adaptive cruise control. These studies establish that the assumptions made regarding driver behaviour are crucial for traffic simulation based analyses of driver assistance systems.

# Populärvetenskaplig sammanfattning

Trafiksimulering är ett användbart verktyg för att utvärdera olika förslag till förändringar i vägtrafiksystemet. Till exempel kan vägutformningsalternativ, nya vägsträckningar eller trafikregleringar vägas mot varandra med hjälp av trafiksimulering. En trafiksimuleringsmodell beskriver trafikens rörelse i ett trafiksystem bestående av ett vägnät med tillhörande trafik. De modeller som utvecklats och studerats inom ramen för detta avhandlingsarbete är mikroskopiska trafiksimuleringsmodeller vilka beskriver samspelet mellan enskilda fordon i trafiken och mellan fordon och infrastrukturen. En mikroskopisk trafiksimuleringsmodell består av delmodeller som beskriver olika delar av förar- och fordonsbeteendet. Till exempel styrs interaktionen mellan fordon i samma körfält av en fordonsföljandemodell och körfältsbyten kontrolleras av en körfältsbytesmodell.

En trafiksimuleringsmodell för landsvägstrafik, RuTSim, har utvecklats inom avhandlingsarbetet. Modellen beskriver trafik på tvåfältsvägar samt mötesfria landsvägar, d.v.s. vägar med vajerräcke mellan mötande körfält. RuTSim har redan kommit till praktisk nytta, bland annat för att ta fram beslutsunderlag inför byggnationer av mötesfria landsvägar.

Dagens fordon blir allt mera avancerade, utrustning såsom adaptiva farthållare och kollisionsvarningssystem har till exempel blivit allt vanligare. För att säkerställa att dessa förarstöd leder till avsedda effekter, t.ex. förbättrad framkomlighet, trafiksäkerhet eller miljö, måste systemen utvärderas. Trafiksimulering möjliggör utvärdering av effekter av förarstöd redan i tidiga skeden av systemutvecklingen. Denna tillämpning ställer dock nya krav på trafiksimuleringen.

Trafiksimulering för utvärdering av förarstöd behandlas också i avhandlingen. De krav som ställs på trafiksimuleringsmodeller som ska användas för utvärdering av trafiksäkerhetseffekter av förarstöd undersöks med hjälp av RuTSim. RuTSim används också för analyser av räfflor i vägmitt på tvåfältsvägar, ett omkörningsstöd och adaptiva farthållare. Dessa studier visar att modelleringen av förarbeteende är avgörande för resultaten av trafiksimuleringsbaserade analyser av förarstöd.

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Andreas Tapani

# Contents

# 1 Introduction

Road traffic is continuously changing in nature. New vehicle and infrastructure technology creates new traffic conditions. At the moment, Intelligent Transportation Systems (ITS) are becoming an increasingly important element in the traffic system. ITS can be described as telecommunications, computer and automatic control systems that interact with the vehicles in the traffic system and provide support for a more efficient utilisation of the available resources. Examples of ITS include applications for traffic management, traveller information, public transport, logistics and driver assistance.

The main motivation for changes and standard improvements in the traffic system has traditionally been to increase capacity and the quality-of-service, i. e. to allow increased speed and to reduce the time spent queueing. Today more attention is turning towards other issues such as road safety and the environmental impact of traffic. To remedy congestion, safety and pollution problems, it is important that the measures taken provide real benefits. In addition, scarce resources require prioritisation among alternatives. Impact assessments of proposed changes in the traffic system are therefore necessary. Traffic simulation models that describe operations in a traffic system has proven to be of use for such analyses.

ITS increase the complexity of the interactions between individual vehicles and the surrounding traffic and between vehicles and the infrastructure. Simulation is a powerful method for studies of complex systems. Traffic simulation is therefore likely to become more essential in studies of all road traffic systems.

Many traffic simulation studies of the design of urban street networks and motorway operations have been performed. The road mileage is however in most countries dominated by rural roads (European Union Road Federation, 2007). So far, the use of traffic simulation for rural roads has not increased as much as the use of simulation for other road types. Today's growing awareness of issues such as road safety and the environment has however brought an increasing interest in the performance of rural roads. Since traffic simulation has proven to be a useful tool for other road environments there is also a potential to use traffic simulation for rural roads to a greater extent than today. In addition, to account for the ever changing traffic system there is a need for flexible simulation models capable of describing effects of the ITS-applications of today and of the future.

This thesis consider microscopic traffic simulation modelling of rural roads and the use of traffic simulation as a tool for evaluation of driver assistance systems. Various aspects of this wide area are covered by the papers that are included in this thesis. A traffic simulation modelling framework for rural roads is developed and applied for rural road design analysis. Issues in relation to the application of detailed traffic micro-simulation models are explored and requirements imposed on traffic simulation models to be used for analysis of driver assistance systems are analysed.

The remainder of this thesis is organised as follows. An introduction to traffic simulation is given in Chapter 2. This chapter is completed by a presentation of the state-of-the-art in rural road traffic simulation. Chapter 3 gives an overview of driver assistance systems. Evaluation of the effects of driver assistance systems is also discussed. Chapters 2 and 3 enlighten the research needs that motivated the work described in the papers included in this thesis. The objectives, contributions and delimitations of this work are discussed in Chapter 4. Paper summaries and suggestions for further research are also included in this chapter. Finally, seven papers are included in the back of the thesis.

# 2 Rural road traffic simulation

Simulation is a powerful and versatile technique. This chapter provides an introduction to traffic simulation in general and microscopic rural road traffic simulation in particular.

## 2.1 Introduction to traffic simulation

A simulation model is a mathematical representation of a dynamic system that can be used to draw conclusions about the properties of the real system. Time is the basic independent variable of a simulation model.

In computer implementations of simulation models, the model state is updated at discrete times. A simulation model can either apply a time-based scanning approach, in which the model is updated at regular intervals, or an event-based approach, in which the model is updated at the points in time where the state of the system is changing. Event-based updating is less computer resource demanding as the simulation model is updated more sparsely than in a time-based model with equal accuracy. Event-based simulation does however imply calculation of the next change in the state of the model after each update. This procedure becomes very complicated for complex systems including many entities that change state frequently. Event-based simulation is consequently more appropriate for systems of limited size and for systems in which the entities change state infrequently. Time-based scanning is considered to be appropriate for systems including large numbers of entities with frequently changing states.

Simulation models may be either deterministic or stochastic. Deterministic simulation models do not include any randomness and are therefore appropriate for systems with little or no random variation. Stochastic simulation models make use of statistical distributions for some of the model parameters to reproduce the variability of the real system. The result of a model run of a stochastic model will consequently differ depending on the realisation of the random numbers that are used to determine parameter values in the model.

Simulation was first applied to road traffic in the early 1950's (May, 1990). Traffic simulation models are designed to mimic the time evolving traffic operations in a road network. Today's traffic simulation models commonly apply a time-based scanning simulation approach. Some early traffic simulation models applied an event-based approach due to the limited computer power available before the 1980's. Since there is a vast number of events of different types in a traffic system, the event based simulation models included very simple traffic descriptions. This restricted the applicability of the models and the event-based approach was largely abandoned as faster computers became available. There has however been recent interest in event-based traffic simulation due to the computation time requirements imposed on simulation models applied for dynamic traffic assignment (Florian et al., 2006).

Both deterministic and stochastic traffic simulation models have been developed. Since traffic includes a non-negligible amount of randomness, the deterministic simulation models can be viewed as representations of the average traffic state. One run of a stochastic traffic simulation model is in contrast a representation of the traffic states during a time period corresponding to the length of the simulation run. The average traffic conditions can be estimated using a stochastic traffic simulation model by conducting multiple simulation runs with different random number realisations.

A traffic simulation model consists of the representation of the road network together with the traffic in the network representing the supply and demand sides of the traffic system, respectively. The road network includes both the actual infrastructure and the traffic control systems. The traffic demand is commonly specified by an origin-destination matrix which specifies the number of trips per time unit between all origins and destinations in the traffic network during the time period that is to be simulated.

Traffic simulation models are often classified with respect to the level of modelling detail. Macroscopic, microscopic and mesoscopic models are commonly used classifications. Macroscopic simulation models use entities such as average speed, flow and density to describe traffic or, in other words, traffic conditions is in a macroscopic model governed by the fundamental relationship between flow, speed and density. Macroscopic simulation models are capable of modeling large traffic networks due to this aggregated treatment of traffic. The common application of macroscopic simulation models is for this reason analysis of traffic operations covering large urban areas and freeway networks. Examples of macroscopic traffic simulation models are the Cell Transmission Model (Daganzo, 1994, 1995) and METANET (Messmer and Papageorgiou, 1990). The macroscopic modelling approach makes it difficult to describe the consequences of elements in the traffic system that have an impact on individual vehicles, or properties that depend on individual vehicle behaviour. For example, studies of motorway weaving sections, highway passing lanes and some ITS-applications are difficult to conduct with a macroscopic model.

Microscopic simulation models consider individual driver and vehicle units in the traffic stream. During a simulation run, vehicles are moved through the network on the paths between the vehicles' origin and destination. Interactions between individual vehicles and between vehicles and the infrastructure are modelled during this process through equations designed to mimic real driver behaviour. These equations are commonly organised into sub-models that handle specific parts of the driving task. Car-following and lane-changing models are examples of sub-models. A car-following model controls a simulated vehicle's interactions with vehicles in front in the same lane and lane-changing decisions are governed by a lane-changing model. The most common application of traffic micro-simulation is quality-of-service studies of specific locations in urban street or motorway networks. A majority of the micro-simulation models are also developed for these road environments (ITS Leeds, 2000). The use of traffic micro-simulation for safety assessments and pollutant emission estimation is also explored concurrently with the growing awareness of road safety and the environment. The potential of traffic simulation based road safety analysis were for example investigated by Minderhoud and Bovy (2001), Barceló et al. (2003) and Archer (2005). The works of Liu and Tate (2004) and Panis et al. (2006) are examples of micro-simulation based environmental impact analysis. ITS developed to support individual vehicles in the traffic stream can also be studied using micro-simulation. Examples of micro-simulation models are MITSIM (Yang, 1997), VISSIM (PTV, 2008), AIMSUN (TSS, 2008) and Paramics (Quadstone Paramics, 2008) for urban and motorway environments and TRARR (Hoban et al., 1991), TWOPAS (McLean, 1989) and VTISim (Brodin and Carlsson, 1986) for rural road environments. The detailed traffic description in a micro-simulation model leads to resource demanding calibration and long simulation model run times for large networks. Microscopic models are consequently considered to be appropriate for networks of limited size.

The third class of traffic simulation models are the mesoscopic models. The level-of-detail used in these models is in between the low detail of the macroscopic models and the high detail of the microscopic models. One utilised modelling approach is for example to model individual vehicle movements, as in a microscopic model, using speed-flow relationships, as in a macroscopic model. Mesoscopic modelling approaches allow simulation of larger networks than with microscopic models with more accuracy than what is possible to obtain by using a macroscopic model. An application where this property is of particular importance is dynamic traffic assignment. Examples of mesoscopic traffic simulation models are CONTRAM (Taylor, 2003), DYNAMEQ (Florian et al., 2006) and MEZZO (Burghout, 2004).

The models developed and studied in the work presented in this thesis are stochastic microscopic traffic simulation models. Traffic simulation will therefore henceforth be used as an abbreviation of traffic micro-simulation.

## 2.2 Traffic simulation models for rural roads

A microscopic traffic simulation model uses equations designed to mimic real driving behaviour to move individual vehicles through the simulated road network. Since traffic is modelled with this level-of-detail, different road environments will place different requirements on the simulation models. The requirements on a model used to simulate the traffic flow on a rural road are, for example, substantially different from the requirements on a model used for traffic in an urban or freeway network. This difference is due to fundamental differences in the interactions between vehicles and the infrastructure. The travel time delay in an urban or freeway network is dominated by vehicle-vehicle interactions, whereas the travel time delay on a rural road is also significantly influenced by interactions between vehicles and the infrastructure. For example, speed adaptation with respect to the road geometry has a more prominent role on rural roads than it has on urban streets. A model describing traffic flows on rural roads must therefore consider the interaction between vehicles and the infrastructure in greater detail than models for urban or freeway traffic. Interactions between vehicles are nevertheless important on rural roads, particularly in overtaking and passing situations.

This section reviews the state-of-the-art in rural road traffic simulation. The interest in rural road traffic simulation began in the 1960's. Among the first to attempt to simulate two-lane road traffic were Shumate and Dirksen in 1964 and Warnshuis in 1967 (McLean, 1989). These early attempts were however limited by the computing power available in the 1960's. The 1970's brought an increasing interest in rural road traffic simulation. Programming languages more suitable for simulation and more powerful computers made it possible to construct models with the detail needed to simulate the traffic on two-lane rural roads. Since the 1970's most modeling efforts have been focused on urban or motorway traffic. As a consequence, the current position of rural road traffic simulation is not far from the position of the early 1980's. The recent works of Kim and Elefteriadou (2007) and Brilon and Weiser (2006) does however indicate the remaining relevance of two-lane road traffic simulation. The main applications of rural road traffic simulation models have been studies of traffic conditions due to changes in road alignment, cross-section design and traffic composition and volume.

Examples of models for rural road traffic simulation includes the Traffic on Rural Roads (TRARR) model developed by the Australian Road Research Board (Hoban et al., 1991), the Two-Lane Passing (TWOPAS) model originally developed by the Midwest Research Institute (McLean, 1989) and the model developed by the Swedish National Road and Transport Research Institute (VTISim) (Brodin and Carlsson, 1986). A recently developed model is the TWO-Lane two-way highway SIMulator (TWOSIM) presented by Kim and Elefteriadou (2007). TWOSIM was developed specifically for capacity estimation of two-lane roads.

The development of the TRARR, TWOPAS and VTISim models started before fast and powerful personal computers became available. All three of the models bear traces of the prioritising that had to be made to run a traffic micro-simulation model using the computers of the 1970's. VTISim applies an event-based simulation approach that is very efficient from a computer resource perspective but modeling of complex traffic interactions is difficult. TRARR and TWOPAS are time-based simulation models with a fixed time step of 1 s. This may be sufficient for quality-of-service studies of two-lane roads. Kim and Elefteriadou (2007) stated that the early models are not applicable for capacity estimation. Moreover, new applications such as evaluation of ITS and simulation based road safety and environmental impact assessments require a rural road simulation model with a more detailed simulation approach.

The focus of the modelling efforts has been on speed adaptation with respect to the road geometry and on the modelling of overtaking decisions. The state-of-the-art in these modelling areas is consequently relatively well developed. However, TRARR, TWOPAS and VTISim apply different speed adaptation and overtaking logic. Calibration and validation of the speed adaptation and overtaking models for different rural road environments followed by a model comparison is needed to distinguish differences in the models abilities to reproduce different traffic conditions.

None of the early rural road simulation models consider the effects of intersections or roundabouts on the traffic on the main road. This limitation was also identified by Kim and Elefteriadou (2007) and TWOSIM was therefore developed to handle intersections along the simulated road. Nor do the early models handle new rural road types such as roads with separated oncoming traffic lanes. There is empirical evidence that the traffic flow is different on two-lane road sections without oncoming traffic than on two-lane roads with auxiliary overtaking/passing lanes (Carlsson and Brüde, 2005). Models for auxiliary overtaking/passing lanes are therefore not applicable to roads with separated oncoming lanes.

In summary, there is a need for a rural road simulation model that handles all types of rural roads including roads with separated oncoming traffic lanes. The effects of rural intersections should also be taken into account. Moreover, new traffic simulation applications such as ITS evaluations, road safety assessments and studies of the environmental impact of traffic, require a versatile and detailed simulation model. Since new ITS are constantly developed and the characteristics of the traffic system is continuously changing, a traffic simulation model should be designed to allow adaptation to the current traffic conditions.

# 3 Driver assistance systems

Driver assistance systems are in-vehicle technologies that give support to various aspects of the driving task. The systems considered in this thesis are commonly described as Advanced Driver Assistance Systems (ADAS). ADAS is one category of ITS that is expected to have substantial impact on future road traffic (Berghout et al., 2003). This chapter gives an overview of ADAS. The ADAS related papers included in this thesis consider the use of traffic simulation for analysis of the traffic system impacts of ADAS. An introduction to evaluation of ADAS is therefore included in the presentation.

## 3.1 Examples of driver assistance systems

ADAS is used to describe a diverse group of in-vehicle support systems that can be viewed as intermediate steps towards a fully automated road traffic system. Even though fully automated roads are possible to achieve using today's technology, cf. Thorpe et al. (1997), it is still considered to be a Utopia. The driver will, for the foreseeable future, remain as an essential part of the driving process. Examples of ADAS include systems from adaptive cruise control, intelligent speed adaptation and lane departure warning to driver vigilance monitoring, pre-crash vehicle preparation and parking aid. Thorough listings of available ADAS and systems under research and development are given by Oei et al. (2002), Floudas et al. (2005) and Technical Research Centre of Finland (2005). Currently available ADAS are autonomous systems. Co-operative systems based on vehicle-to-vehicle communication are expected to be introduced in the future (Ehmanns and Spannheimer, 2004).

The conclusion to be drawn from the literature is that ADAS include very different types of functions. It is consequently useful to categorise ADAS into different groups suitable for the current context. A technology based classification according to the enabling technologies of the ADAS can be useful for system specification and development. Examples of ADAS enabling technologies are laser, radar and video based sensors and wireless communication techniques suitable for vehicle-to-vehicle and vehicle–infrastructure communication. Examples of systems based on radar and/or laser sensors include adaptive cruise control that extends the functionality of fixed speed cruise control with car-following distance keeping, rear-end collision warning that warns in case of potential collisions and parking aid that keeps track of adjacent vehicles and assists during parking manoeuvres. Examples of systems based on vehicle-to-vehicle communication are intersection collision avoidance systems that detect potential collisions in intersections and overtaking assistance that gives advise on overtaking opportunities on two-lane roads. Systems that rely on communication and road network positioning are for example intelligent speed adaptation that guides drivers towards keeping the posted speed limit and post-crash alerting that notifies the rescue service in case of an accident.

In a road safety context, Oei et al. (2002) classified ADAS according to which phase of the accident process that the systems give support in. Systems were determined as either pre-crash, crash or post-crash support systems. Systems that give support during normal driving were classified as pre-crash systems. Examples of pre-crash systems include all of the examples given for the technology based classification except post-crash alerting which for obvious reasons is categorised as a post-crash support system. Crash support systems are systems that pre-activate the vehicles safety systems before an un-avoidable accident, e. g. systems that pre-inflate airbags for maximum protection.

A functional classification of ADAS is commonly applied for studies of driver behaviour in relation to the systems. This categorisation is based on grouping criteria that take into account which type of driver and which part of the driving task that the systems give support to. Michon's hierarchical control model, see e. g. the review by Ranney (1994), that divides driving into strategic, tactical and operational tasks were for example used by Oei et al. (2002) to categorise ADAS. Strategic driving tasks involves tasks related to navigation and route choice. Examples of systems that support strategic driving tasks are systems that give information of conditions along the driver's desired route. Tactical driving tasks are overtaking, lane-changing, intersection negotiation and car-following. Many ADAS support tactical driving tasks. Examples include adaptive crusie control, intelligent speed adaptation and lane-change collision avoidance that detect vehicles in the blind spot.

Operational driving tasks are the basic vehicle handling. ADAS that support operational driving tasks are for example vision enhancement systems that support driving in poor visibility conditions and road surface monitoring systems that give information of e. g. low road friction. Categorisation of ADAS into longitudinal and lateral control systems is another example of a functional ADAS classification. Longitudinal control systems include for example intelligent speed adaptation and adaptive cruise control. Lateral control ADAS are e. g. lane-change collision avoidance and lane/road departure warning systems.

Golias et al. (2002) introduced an ADAS categorisation according to the potential system impacts. Criteria for road safety and traffic efficiency impacts were used to categorise a set of ADAS. Systems that scored high on both road safety and traffic efficiency were road surface monitoring, adaptive cruise control and lane-change collision avoidance. An impact oriented ADAS categorisation is useful to prioritise among ADAS and to allocate resources to the most promising alternatives.

Most research and development efforts related to ADAS have been focused on enabling technologies and human machine interfaces. This is natural since the driving force behind introductions of ADAS come from vehicle manufacturers and the demand of their customers. However, from society's perspective, to increase traffic safety and to remedy congestion and pollution problems, it is important that ADAS lead to real benefits. Scarce resources require prioritisation and as a consequence ADAS need to be evaluated already at early development stages. Evaluation of ADAS is discussed in the following section.

## 3.2 Evaluation of driver assistance systems

To assess impacts of already well-tried measures to improve the traffic system, one can conduct before and after studies or cross-sectional studies based on field data. Road safety analysis of traditional safety measures can for example be conducted based on the actual accident turn out. New technologies such as ADAS can however not be reliably evaluated based only on field data. Even though some ADAS already have been introduced in the traffic system, the proportion of equipped to unequipped vehicles is still too small for conclusions to be drawn. Instead, evaluations of ADAS have to be based on laboratory studies and modelling.

As presented in the previous section, the driver will for the foreseeable future remain as an essential part of the driving process. There are several reasons for this, one non-negligible factor is that people are not willing to hand over the responsibility of driving to the vehicle. This conclusion can be drawn from the results of acceptance studies of ADAS which often show higher acceptance of purely information systems than of systems that take over control of parts of the driving task (Brookhuis et al., 2001). Consequently, driver behaviour is, and will remain, crucial for successful introductions of ADAS in the road traffic system. It is therefore appropriate to start evaluations of ADAS with the system's impact on driver behaviour.

The tools used for studying the system's impact on individual driver behaviour have in common that they consider test drivers' behaviour in a laboratory situation. Since the ADAS under consideration can be assumed not to be widely available in the traffic system it is not possible to measure data directly in the field. However, if test persons are allowed to drive an ADAS-equipped vehicle in real traffic then it is still possible to observe the test persons behaviour under real traffic conditions. A drawback of this approach is that it is not possible to control the traffic situations that the test person is exposed to. An alternative approach is to implement the ADAS system functionality in a driving simulator. This approach has the advantage that it is possible to control the traffic situation completely. Possible drawbacks of the driving simulator approach concern the realism and validity of the simulator. There are also other alternatives for studying driver behaviour, e. g. stated preference methods.

Knowledge of the impact of ADAS on driver behaviour can be sufficient to enable system design for improved driver comfort. However, in order to evaluate the systems' potential to remedy road safety, traffic flow quality-of-service and environmental issues, it is necessary to aggregate the effects on individual driver behaviour to the traffic system level. This aggregation relies on modelling and estimation of the effects of the ADAS under different traffic conditions, on different road types and in traffic including different proportions of ADAS-equipped vehicles. Traffic simulation models which describe conditions in a traffic network given the properties of the road network and the traffic demand are useful for such analyses. Microscopic traffic simulation models consider individual vehicles in the traffic stream. It is therefore possible to include ADAS functionality and ADAS induced driver behaviour in the driver/vehicle sub-models of the simulation. This makes it possible to estimate the effects of ADAS on the traffic system through traffic simulation experiments.

The traffic simulation approach is appropriate for ADAS functions which have an impact on the driver/vehicle unit's interactions with surrounding vehicles and with the infrastructure during normal driving. Examples of such ADAS functions include speed and distance keeping support and overtaking assistance. Traffic simulation is however not a useful tool for other ADAS functions developed primarily to remedy driver errors in critical situations. Examples of such functions are driver monitoring and pre-crash preparation systems.

Traffic simulation based evaluations of ADAS have been performed by several authors. Hogema (1999) developed a driver model for microscopic traffic simulation including vehicles equipped with Adaptive Cruise Control (ACC). The driver model included not only driving with the ACC active but also the tasks of engaging and disengaging the ACC. Driving with ACC and normal driving was modelled using distance controllers with different desired headway functions.

Minderhoud and Bovy (1999) studied the impact of ACC on motorway capacity using traffic simulation. ACC was in this study modelled by assuming a shorter reaction delay for ACC-equipped vehicles than for standard vehicles. The results showed that the ACC headway setting has a large influence on the achievable motorway capacity. The impact of ACC on time-to-collision based safety indicators were studied by the same authors in 2001. Results of this study indicated that some ACC designs were more safety critical than the studied reference case without these systems.

ACC was also considered by Davis (2004, 2007). Davis modelled ACC as a distance controller without delay. A car-following model including a reaction delay was used to model standard vehicles in the simulated traffic. The first study considered jam formation in motorway traffic with varying proportions of ACC-equipped vehicles. The results showed that jams could be suppressed by introduction of 20 % ACC-vehicles in the simulated traffic. The second study considered ACC extended with co-operative merging functionality. During merging situations, the ACC controller took into account both the vehicle in front in the equipped vehicle's own lane and in the adjacent lane. It was shown that the throughput of traffic with 100 % vehicles equipped with ACC and co-operative merging is limited only by the speed limit and the selected ACC headway.

The jam suppressing potential of ACC was also investigated by Kesting et al. (2007a, 2007b). In these studies, the same model was used for both ACC-equipped and standard vehicles. Jam-avoiding ACC-vehicles were modelled by modification of the model parameters. The simulation results showed that already a low proportion of jam-avoiding ACC-vehicles could improve traffic performance and reduce congestion.

Effects of a co-operative following (CF) system closely related to ACC was studied by van Arem et al. (2006). This system can be described as an ACC system based on vehicle-to-vehicle communication. The use of inter-vehicle communication make it possible for equipped vehicles to travel closer together than non-equipped vehicles or vehicles equipped with a standard autonomous ACC system. The CF system was modelled as a distance controller without reaction delay and CF-vehicles were assigned a short desired following headway. The simulation results showed that introduction of a CF system can reduce the number of shock waves in traffic with a large proportion of CF-vehicles.

A similar CF system was studied by Liu et al. (2006). This study considered the impact on safety caused by information delay in the CF system. Car-following models with different reaction delays were used to model information delay in the CF system and time-to-collision based safety indicators were used to measure the safety effects. The results showed that information delay had an impact on the safety indicators.

Alkim et al. (2000) studied the effects of CF and a speed control system. The speed control system can be viewed as an Intelligent Speed Adaptation (ISA) system which guides drivers towards keeping an appropriate speed. The simulation results for the speed control system indicated that both speeds and the number of shock waves can be reduced when a speed control system is introduced.

Hoogendoorn and Minderhoud (2001, 2002) studied impacts of ACC and ISA on motorway traffic. ACC was in this work modelled using a distance controller with a short system response time. ISA was modelled by preventing ISA equipped vehicles to exceed the speed limit. The simulation results indicated that ACC have a potential to improve motorway bottleneck capacity. Increased variability of the bottleneck capacity was however also observed. No effects of ISA could be established.

A traffic simulation based evaluation of ISA was also performed by Liu and Tate (2004). ISA was in this study modelled by reducing the speed suggested by the car-following model if this speed was higher than the speed limit. The simulation results showed that ISA is more efficient in less congested traffic. High speeds and the speed variation was reduced by the ISA system in such conditions.

Another simulation study of ISA was presented by Hoogendoorn and Louwerse (2005). This study focused on the potential safety effects of ISA. ISA-equipped vehicles were assumed not to exceed the speed limit and a constant deceleration rate was used to slow down ISA vehicles at locations where the speed limit was lowered. The simulation results showed that ISA reduced average speeds in the simulated road network. It was therefore concluded that ISA can provide safety benefits.

The impact of fixed speed limiters on motorway traffic was evaluated by Toledo et al. (2007). The speed limiters were modelled by modification of the desired speed distribution for vehicles in the simulation. The simulation results show that speed limiters have a potential to reduce average speeds by 10 %. The speed variability could also be reduced.

A majority of the simulation studies are concerned with traffic flow quality-of-service and safety effects of longitudinal control ADAS, i. e. different types of adaptive crusie control and intelligent speed adaptation systems. Longitudinal control ADAS can be modelled straightforwardly by modifications of the car-following model of the simulation. Changes in driver behaviour due to the ADAS are however rarely considered in the previous studies. Driver behaviour in ADAS equipped vehicles is crucial for the impacts of ADAS since the driver will remain responsible for driving his or her vehicle. There is consequently a potential to improve traffic simulation based evaluations of ADAS by including the driver behaviour associated with the ADAS in the applied traffic simulation model. This potential was also recognised by Klunder et al. (2006).

Traffic simulation including driver behaviour in vehicles equipped with ADAS will place new and additional requirements on the traffic simulation model. ADAS functions are very diverse. A model to be used for simulation of traffic including ADAS-equipped vehicles should therefore allow substitution of its sub-models. The utilised sub-models should also be flexible enough to allow modelling of the ADAS function and the observed changes in driver behaviour. Sufficiently detailed modelling of non-equipped vehicles in the traffic stream is a requirement placed on the simulation model if traffic including a combination of equipped and non-equipped vehicles is to be studied. Some ADAS can be assumed to have an impact not only on the equipped vehicles but also on neighbouring non-equipped vehicles. Quantification of such effects relies on the accuracy of the modelling of the surrounding non-equipped vehicles. The simulation model should also enable derivation of suitable performance indicators to allow use of the results for the application at hand. The basic result from a traffic micro-simulation model run is a set of vehicle trajectories for all vehicles that have traversed the modelled road network during the simulated time. Many indicators used for simulation based safety and environmental impact analysis are based on details of these resulting vehicle trajectories. A requirement imposed on the simulation model to be used for such analysis is for this reason access to the resulting vehicle trajectories.

# 4 The present thesis

The themes of this thesis are microscopic traffic simulation modelling of rural roads and modelling issues in relation to the use of traffic micro-simulation as a method for evaluation of driver assistance systems. Various aspects of these two themes are explored in the included papers. The objectives, contributions and delimitations of the thesis are discussed in this chapter. Paper summaries and suggestions for further research are also given.

## 4.1 Objectives

One main objective of this work is to develop a traffic simulation modelling framework for rural roads. The aim of this development is that the developed model should be able to describe traffic conditions on both single carriageway two-lane roads and on rural roads with separated oncoming traffic lanes. Traffic interrupted by vehicles entering and leaving at intersections or roundabouts should also be considered.

There is an increasing interest in the performance of rural roads. As described in Chapter 2, traffic micro-simulation of rural roads is less studied than traffic simulation of other road types. There is a need for traffic micro-simulation models that handle common types of rural roads including the impacts of rural intersections. A traffic micro-simulation model for rural roads should be designed to allow modelling of ITS and traffic simulation based road safety and environmental impact analysis.

Another main objective of this work is to investigate issues in relation to the application of traffic simulation for evaluation of ADAS. This investigation is focused on the modelling of driver behaviour in traffic simulations including ADAS-equipped vehicles.

The last decade has, as presented in Chapter 3, brought an interest in the use of traffic micro-simulation to evaluate traffic system impacts of driver assistance systems. Simulation of traffic including ADAS-equipped vehicles will place new and additional requirements on the traffic simulation model. These requirements have not yet been thoroughly explored. Driver behavioural adaptations in relation to ADAS can for example be expected to have important implications for the impacts of ADAS on the traffic system. A link between studies of driver behaviour and traffic simulation based evaluations of ADAS is however not established.

## 4.2 Contributions

This thesis contain the following contributions to the existing research:

- A new traffic micro-simulation model for rural roads, The Rural Traffic Simulator (RuTSim), is developed. RuTSim handles single carriageway two-lane rural roads and rural roads with separated oncoming traffic lanes. The traffic on the simulated road may be interrupted by vehicles entering and leaving at intersections or roundabouts.

- Driver behaviour sub-models for time-based rural road traffic micro-simulation are developed. The developed sub-models control vehicle accelerations and overtaking manoeuvres.

- Quality-of-service effects of different alternatives for oncoming lane separation of an existing two-lane rural road are analysed using RuTSim. It was concluded that RuTSim is able to describe traffic on the existing road and that oncoming lane separation of the road can be done with only a slight reduction of the quality-of-service.

- Insights are gained into model complexity issues that arise when using detailed micro-simulation approaches. These issues are related to overfitting of statistical models. There is also a risk that modelling assumptions become in-valid for later applications of the model.

- It is shown that the high level of detail of traffic micro-simulation models may bring a need to use models based on different assumptions regarding driver behaviour when modelling traffic in different cultural regions.

- A traffic simulation framework for analysis of the impacts of driver assistance systems on the traffic system is developed. Driver assistance system functionalities and changes in driver behaviour due to driver assistance systems are considered in the framework.

- Requirements imposed on traffic simulation models to be applied for studies of road safety effects of driver assistance systems are formulated and tested using RuTSim.
- It is established that the assumptions made regarding driver behaviour are crucial for traffic simulation based evaluations of driver assistance systems.
- Issues in relation to the application of driver behaviour data collected in driving simulator studies for traffic simulation modelling are identified. New driving simulator study designs are needed. It becomes necessary to observe the subjects' continuous actions and reactions while driving.
- Traffic system impacts of different types of rumble strips on rural roads are analysed using RuTSim. Indications of changes in speeds and safety related indicators were found amongst the simulation results.
- Driver comfort, quality-of-service and safety implications of an overtaking assistant are analysed using RuTSim. It was found that the overtaking assistant can provide safety benefits without having negative consequences for traffic efficiency and driver comfort.
- A traffic simulation study of potential vehicle trajectory impacts of adaptive cruise control has been performed using RuTSim. It is shown that adaptive cruise control can result in improved conditions in terms of reduced acceleration and deceleration rates even though the macroscopic traffic situation may remain unchanged. This result supports the hypothesised positive road safety and environmental effects of adaptive cruise control.

## 4.3 Delimitations

The traffic simulation modelling framework developed in this thesis is designed for rural roads. Other road types are not considered. The model handles one main rural road stretch per simulation, i. e. route choice in rural road networks is not modelled. The number of paths between a specific origin–destination pair in a rural road network is typically very small. Route choice is therefore often of little consequence for the traffic volume on a rural road. The intersection modelling is limited to un-signalised intersections. Traffic signals are not considered since they are rarely used in rural environments. The present work does not include a complete validation of the developed simulation model for all rural road types and traffic conditions. Validation of a simulation model involve modelling of a large number of real world systems. Only partial model validation is consequently within the scope of this thesis.

Issues in relation to the use of traffic simulation for evaluation of ADAS are studied through the modelling of rural road traffic using the developed traffic simulation modelling framework. The findings can however be generalised to traffic on other road types. The main purpose of the performed simulation studies of example ADAS is to study issues in relation to the modelling of the ADAS and not to evaluate impacts of the specific ADAS.

## 4.4 Summary of papers

There are seven papers included in this thesis. Microscopic traffic simulation modelling of rural roads is considered in Paper I–III and the use of traffic simulation as a tool for evaluation of ADAS is investigated in Paper IV–VII. Brief summaries of the seven papers are given in this section. The contributions of the author of this thesis to the papers that are written together with co-authors are also stated.

### Paper I: Versatile Model for Simulation of Rural Road Traffic

The purpose of the work presented in Paper I is to develop a traffic microsimulation model for rural roads. The paper presents the simulation approach and the traffic modelling used in the developed model, the Rural Traffic Simulator (RuTSim).

The development of RuTSim is based on the rural road traffic simulation model developed by the Swedish National Road and Transport Research Institute (VTISim, cf. Chapter 2). VTISim was chosen as a basis for the development of RuTSim because it has been well validated for the road conditions in Sweden.

RuTSim is a time-based stochastic simulation model capable of modelling single carriageway two-lane rural roads and rural roads with separated oncoming traffic lanes. The model consist of sub-models that handle specific tasks. The use of sub-models simplifies future modification of the model. RuTSim handles one road stretch in each simulation run, i. e. rural road networks are not considered. The main road may incorporate intersections and roundabouts and the traffic on the main road may be interrupted by vehicles entering the main road at intersections located along the simulated stretch.

A verification of the RuTSim model is also included in the paper. RuTSim was found to produce speed–flow relationships for uninterrupted traffic on two-lane roads close to those of VTISim. The conclusion was therefore that RuTSim is capable of describing traffic on Swedish two-lane rural roads. RuTSim was also found to be able to reproduce traffic flow properties on roads with separated oncoming traffic lanes. The verification tests presented in the paper are not intended to be a validation of the RuTSim model. Such a validation requires comparisons with empirical data. Partial validation of the RuTSim model is performed through the work described in Paper II and III.

Paper I is published in:

- *Transportation Research Record 1934*, 2005, pp. 169–178.

The content of Paper I has been presented at:

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

An earlier version of Paper I was presented at:

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

### Paper II: Rural Highway Design Analysis Through Traffic Micro-Simulation

An application of RuTSim for rural road design analysis is presented in Paper II. The objectives of the paper are to describe quality-of-service effects of oncoming lane separation of rural roads and to illustrate how RuTSim can be applied for quality-of-service analysis of single carriageway two-lane rural roads and rural road design alternatives with oncoming lane separation.

The presented simulation study is concerned with quality-of-service effects of different alternatives for oncoming lane separation of an existing two-lane rural road. The studied road was a 13 meter wide two-lane road with several intersections. RuTSim was calibrated and validated for this road based on measured spot speeds. The results indicate that RuTSim is able to reproduce the measured speeds on the existing road.

The alternatives analysis revealed that none of the alternatives for oncoming lane separation give as good quality-of-service as the existing two-lane road. Oncoming lane separation is however installed primarily for safety reasons and the simulation results showed that two of the studied design alternatives would give acceptable quality-of-service. The Swedish Road Administration has chosen to reconstruct the road to a design close to one of these studied alternatives.

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

Paper II is published in:

- Nakamura, H. and T. Oguchi (Eds.) *Proceedings of the 5th International Symposium on Highway Capacity and Quality of Service*, JSTE, Tokyo, 2006, pp. 249–258.

The content of Paper II has been presented at:

- The *5th International Symposium on Highway Capacity and Quality of Service*, Yokohama, July 25–28, 2006.

In addition to Paper II, there are related technical reports that present results from projects in which the RuTSim model has been applied for rural road design analysis (Carlsson and Tapani, 2005; Tapani, 2006, 2007).

### Paper III: On the Application of Traffic Micro-Simulation to Road Environments in Different Regions

Paper III discusses challenges and issues in relation to the application of traffic micro-simulation models in different cultural regions, i. e. regions or countries with different social, economical or technological conditions. The purpose of the paper is to bring focus to modelling considerations that are important for today's increasingly detailed traffic micro-simulation applications.

The concerns raised in the paper can be summarised as follows. There is a general trend in the traffic micro-simulation area towards more sophisticated and detailed models. This development is facilitated by the increased availability and use of vehicle trajectory data. The increased modelling detail may create a need to apply different modelling assumptions regarding driver behaviour for different applications or when simulating traffic in different cultural regions. It may not be sufficient to adjust model parameters in the calibration process to reproduce details of the local traffic condition.

A case study in which RuTSim is applied for simulation of traffic on a two-lane rural road in the Netherlands is presented. This case study supports the argument that different modelling assumptions may be needed to simulate traffic in different cultural regions. It was necessary to modify the overtaking model in order to allow RuTSim to reproduce the observed overtaking frequencies, whereas parameter adjustments were sufficient for calibration of flows and speeds. The changes made to the overtaking model reflect regional differences in overtaking behaviour between Sweden and the Netherlands. This is an example were more detailed output, in this case overtaking frequencies, required modified modelling assumptions.

This paper is co-authored with Geertje Hegeman and Serge Hoogendoorn. The author of this thesis has contributed to the paper as main author of the paper and by major involvement in the research planning, in the modelling and simulation work and in the analysis of the results.

Paper III is published in:

- *Proceedings of the 87th Annual Meeting of the Transportation Research Board*, Transportation Research Board, Washington, D.C., 2008.

The content of paper III has been presented at:

- The *87th Annual Meeting of the Transportation Research Board*, Washington. D.C., January 13–17, 2008.

### Paper IV: Evaluation of Safety Effects of Driver Assistance Systems Through Traffic Simulation

The purpose of Paper IV is to formulate necessary features of a traffic simulation model to be used for ADAS safety evaluation. The analysis is delimited to longitudinal control ADAS, i. e. systems that support speed and distance keeping with respect to the vehicle in front. The longitudinal control part of the driving task is in a traffic simulation model controlled by a car-following model. The focus of the paper is therefore on the requirements imposed on the car-following modelling.

A car-following model that meets the identified requirements is proposed and implemented in RuTSim. Simulation runs with the proposed car-following model indicated that behavioural changes caused by the considered ADAS are important factors for the ADAS' safety impacts. The simulation results indicated also that longitudinal control ADAS may have consequences not only for the equipped vehicles but also for surrounding un-equipped vehicles in the traffic.

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

Paper IV is published in:

- *Transportation Research Record 1953*, 2006, pp. 81–88.

The content of Paper IV has been presented at:

- The *Workshop on Traffic Modeling: Simulation Models: From the labs to the trenches*, Sedona, September 18–21, 2005.
- *Transportforum*, Linköping, January 11–12, 2006.
- The *85th Annual Meeting of the Transportation Research Board*, Washington, D.C., January 22–26, 2006.

Requirements on traffic simulation models to be used for road safety assessments of ITS and ADAS are also discussed in the related paper:

- Tapani, A. (2005). Traffic Simulation for Road Safety Assessment of Intelligent Transportation Systems, In Fritzon, P. (Ed.), *SimSafe 2005, Proceedings of the Conference on Modeling and Simulation for Public Safety*, Linköping University, Linköping, pp. 1–9.

### Paper V: Analysis of Rumble Strips and Driver Fatigue Using Traffic Simulation

Paper V presents a traffic simulation framework for analysis of traffic system impacts of ADAS. Both ADAS functionalities and driver behaviour in ADAS equipped vehicles are taken into account in the evaluation framework. The purpose of the paper is to illustrate the use of traffic simulation to aggregate observed individual driver/vehicle behaviour to effects on the traffic system.

Application of the simulation framework is exemplified by a study of centre line rumble strips on two-lane rural roads. The effects of physical milled rumble strips are compared to the effects of "virtual" in-vehicle rumble strips for both alert and sleep deprived drivers. Individual driver behaviour data from a driving simulator study was used for the traffic simulation. In the driving simulator study, test persons drove the simulator in both alert and sleep deprived condition on a road without centre line rumble strips, with physical milled rumble strips and with "virtual" in-vehicle rumble strips. The test persons free driving speeds, overtaking gap-acceptance behaviour and reaction times were extracted from the driving simulator data and used for traffic simulation modelling of rumble strips in RuTSim.

The simulation results displayed differences in average journey speeds and safety indicators on simulated roads with different types of centre line rumble strips. An interesting issue within the context of the present thesis is the use of driving simulator data as input to traffic simulation modelling. Estimation of car-following and overtaking situations from the driving simulator data were found to be difficult. Application of driving simulator studies to collect data to be used for traffic simulation place new requirements on the driving simulator scenario design.

Paper V is published in:

- *Advances in Transportation Studies 14*, 2008, pp. 69–80.

The content of paper V has been presented at:

- *Road Safety and Simulation, RSS2007*, Rome, November 7–9, 2007.

The use of traffic simulation for evaluation of the traffic system impacts of ADAS is also discussed in the related paper:

- Tapani, A. (2007). Analysis of System Effects of Driver Assistance Systems by Traffic Simulation, In *Proceedings of the Young Researchers' Seminar 2007*, CDV, Brno.

## Paper VI: Overtaking Assistant Assessment Using Traffic Simulation

Paper VI presents a traffic simulation based evaluation of an overtaking assistant. The overtaking assistant is modelled in RuTSim and the assistant's impacts on driver comfort, road safety and traffic efficiency are studied for various assistant settings and proportions of equipped vehicles in the simulated traffic. The aim of the paper is to describe potential effects of an overtaking assistant. From the perspective of the present thesis, the contribution of the paper is the traffic simulation modelling of the overtaking assistant. Previous traffic simulation based studies of driver assistance systems have mainly considered systems that support longitudinal parts of the driving task, i. e. speed limiters and cruise controls.

The overtaking assistant considered in the paper assists the driver in the judgement of whether or not an overtaking opportunity can be accepted based on the time gap to the next oncoming vehicle. This functionality was implemented in RuTSim by modification of the overtaking decision process in the model. The modelled road was the same Dutch two-lane road as in the case study presented in Paper III.

The results of the simulations indicate that an overtaking assistant can provide safety benefits in terms of increased time-to-collision to the next oncoming vehicle during overtaking manoeuvres. This safety benefit can be achieved without negative consequences for traffic efficiency and driver comfort.

This paper is co-authored with Geertje Hegeman. The author of this thesis has contributed to the paper by major involvement in the research planning, in the modelling and simulation work, in the analysis of the results and in the writing process.

Paper VI is under revision for publication in *Transportation Research Part C*.

## Paper VII: Vehicle Trajectory Impacts of Adaptive Cruise Control

In Paper VII, vehicle trajectories from traffic simulations are used to study impacts of Adaptive Cruise Control (ACC). The aim of the paper is to quantify potential impacts of ACC on vehicle acceleration and deceleration rates in mixed traffic including both ACC-equipped and standard vehicles. The dependence of the results on driver behaviour in terms of desired speeds, desired following time gaps and reaction times is also investigated. Changes in these driver behaviour parameters have been observed in studies of driving with ACC. The purpose of this work is not to evaluate a specific ACC system but to provide knowledge of potential vehicle trajectory impacts of ACC functionality and driver behavioural adaptations related to ACC.

The analysis presented in the paper is based on RuTSim simulations with car-following models including ACC functionality and driver behaviour in ACC-equipped as well as standard non-equipped vehicles. Impacts of ACC on vehicle trajectories from the simulation are quantified using the indicator acceleration noise.

The results show that ACC can result in improved conditions in terms of reduced acceleration and deceleration rates even though the macroscopic traffic situation may remain unchanged. It is also established that appropriate modelling of driver behaviour is crucial for the reliability of traffic simulation based analyses of ACC.

The content of Paper VII has been presented at:

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

## 4.5 Future research

The work presented in the papers included in this thesis give inspiration for further research. A simulation model should be validated through the modelling of a large number of real world systems. The RuTSim applications presented and referred to in this thesis does only amount to partial validation of the model. There is consequently a need for continued validation of RuTSim. A general research need is cross-validation of traffic micro-simulation models using data sets collected in different regions.

A need to improve RuTSim's ability to handle large traffic volumes has also been identified. Such model improvements will involve further development of some of the sub-models of the simulation. Improved gap-acceptance and overtaking modelling are for example needed. A possible improvement of the intersection gap-acceptance logic is to take drivers' impatience in to account, e. g. by allowing the critical time gap to be a function of the waiting time. Improvement of the overtaking modelling should rely on traffic and vehicle trajectory data collected in high traffic volume conditions, cf. Paper III.

Selection of the appropriate level-of-detail of the traffic simulation model for the application at hand is another interesting topic for further research. This is not commonly discussed in the traffic simulation literature. There are however works related to this issue in other fields of research, cf. Paper III. Application of this knowledge for traffic simulation modelling can improve the reliability of traffic simulation based analyses.

The work presented in this thesis has established that it is important to consider driver behaviour in traffic simulation based analyses of driver assistance systems. The current practice of driver behaviour studies is however not suitable to allow use of the findings for traffic microsimulation modelling. Driving simulator experiments are for example often designed to reveal the test persons' reactions in relation to isolated critical situations. Driver behaviour studies performed for subsequent use of the results for traffic simulation modelling involve observation of the driver's continuous actions and reactions. There is, for this reason, a need for research on the design of experiments for collection of driver behaviour data for traffic simulation modelling.

Simulation based road safety and environmental impact analyses can be conducted using performance indicators derived from the resulting vehicle trajectories of the simulation. Relationships between simulation based indicators and effects in real traffic have, however, in many cases not been established. This is consequently an important topic for further research.

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