Analysis of System Effects of Driver Assistance Systems by Traffic Simulation

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Abstract

The interest in in-vehicle Advanced Driver Assistance Systems (ADAS) is increasing. New systems such as Adaptive Cruise Controls and Collision Avoidance Systems are currently introduced at a rapid pace. To exploit the full potential of these systems it is necessary to estimate the systems future impact already at early development stages. This paper introduces a traffic simulation framework for analysis of the effects of ADAS on the traffic system. The framework considers both the system functionalities of the ADAS as well as behavioural changes of drivers in equipped vehicles. Such behavioural changes have usually not been considered in previous traffic simulation studies of ADAS. Application of the simulation framework is exemplified by two studies of ADAS that assist drivers on two-lane highways.

Keywords: ITS, ADAS, system effects, traffic simulation

1 Introduction

Systems, services and products are at an increasing rate developed to improve quality of service, safety and the environmental impact of the road traffic system. One category of such systems is Advanced Driver Assistance Systems (ADAS) that support individual drivers or vehicles. Examples of ADAS include Adaptive Cruise Control, Intelligent Speed Adaptation and Collision Avoidance Systems.

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ADAS can be viewed as an intermediate step towards a fully automated road traffic system. Even though fully automated highway systems are possible to achieve using today's technology, as have been demonstrated by among others Thorpe et al. (1997), it is still considered to be a Utopia. The driver will, for the foreseeable future, remain "in the loop" 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 can be observed in acceptance studies of ADAS which show higher acceptance of purely information systems than of systems that take over control of parts of the driving task. Consequently, driver behaviour is and will remain crucial for successful ADAS introductions in the road traffic system.

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 prioritization and as a consequence ADAS need to be evaluated already at early development stages.

It is for obvious reasons not possible to base such evaluations on field data, one need to rely on laboratory studies and traffic modelling. It is appropriate to start ADAS evaluations with studies of the system's impact on driver behaviour. Such behavioural impacts can be studied by for example allowing test persons to drive an instrumented vehicle equipped with the considered ADAS. Another approach is to implement the ADAS functionality in a driving simulator and record test persons' behaviour in the simulator.

In the next step, traffic modelling play an important role to assess or "extrapolate" effects of the ADAS functionality together with the observed changes in driver behaviour on to the overall traffic system level. In particular, microscopic traffic simulation models that consider individual vehicles in the traffic stream allow ADAS functionality and induced driver behaviour to be included in driver/vehicle sub-models. This makes it possible to estimate the effects on the traffic system by means of traffic simulation.

Simulations of traffic including ADAS-equipped vehicles have been performed by several authors including Minderhoud and Bovy (2001), Liu and Tate (2004) and Hoogendoorn (2005). In these works, the system functionality of certain ADAS, e.g. distance controllers or speed limiters, has been modelled in detail. Changes in driver behaviour due to the ADAS are, on the contrary, usually not considered.

This paper presents a traffic micro-simulation framework for analysing the aggregation of individual driver/vehicle effects to the overall traffic system level. The presented framework considers both system functionalities of ADAS, e.g. distance controllers and speed limiters, as well as behavioural changes of drivers in equipped vehicles. Observed behavioural changes include changes in reaction times, speeds and following distances. The purpose of the paper is to describe how traffic simulation can be utilized to make predictions of effects of ADAS on the traffic system. This is exemplified by studies of rumple strips and overtaking assistance on two-lane highways. Both of these studies used a driving simulator to study individual driver behaviour. The presented simulation framework will then be used to assess the collective effect of the systems.

The remainder of this paper is organized as follows. The next section discusses different types of ADAS and requirements placed on a traffic simulation model for ADAS evaluation. The simulation framework for ADAS evaluation is then described in the subsequent section. This is followed by a presentation of two applications of the developed simulation framework. Then, in the last section conclusions and directions for further research sum up the paper.

2 Simulation of ADAS-equipped Vehicles

Simulation of ADAS-equipped vehicles and simulation based evaluation of ADAS place specific requirements on the traffic simulation model. These requirements depend on characteristics of the ADAS to be simulated. This section provides an overview of ADAS in general including ADAS functionalities and observed changes in driver behaviour. Requirements on driver/vehicle behaviour models for traffic simulation imposed by the different ADAS categories are also discussed.

2.1 ADAS categories

ADAS can be divided into sub-categories that depend on which part of the driving task the ADAS is supporting. One categorization that can be made is the following (Flodas et al., 2005):

- *Lateral control.* Lateral control ADAS include lane-keeping aids and lane change collision avoidance systems. These systems improve road safety by prevention of unintentional lane departures or lane changes. Changes in driver behaviour that needs to be investigated include changes in lane changing or overtaking behaviour. One likely consequence of lateral control ADAS is for example modified gap-acceptance behaviour with respect to surrounding and oncoming vehicles.

- *Longitudinal control.* Longitudinal control ADAS include Intelligent Speed Adaptation (ISA), Adaptive Cruise Control (ACC) and Collision Avoidance Systems (CAS). ISA systems are designed to control vehicle speeds. Vehicles are commonly guided towards keeping the speed limit. ACC systems support the distance-keeping parts of the driving task. CAS are aimed at preventing collisions with surrounding objects in different situations. Observed changes in driver behaviour due to longitudinal control ADAS include changes in desired speeds, following distances and reaction times (Saad et al., 2004).

- *Parking/reversing aids.* Parking and reversing aids are systems that detect obstacles in low speed situations. These ADAS are primarily comfort systems and will not have any impact on the traffic system and are therefore not of interest within the context of this paper.

- *Vision enhancement.* Vision enhancement systems support drivers in situations with reduced visibility. Possible changes in driver behaviour for these systems are the same as those observed for longitudinal control ADAS.

- *Driver monitoring.* Driver monitoring systems are focused on the driver's physiological status. These systems are not aimed at assisting the driver in any part of the driving task but rather to give information in situations when the driving task cannot be adequately performed by the driver.

- *Pre-crash systems.* Pre-crash systems are systems that pre-activate a vehicle's safety systems, e.g. seat-belts and air-bags, when an accident is unavoidable. The driver has no possibility of interfering with the system and behavioural changes are unlikely since the system kicks in when an accident is unavoidable.

- *Road surface/low-friction warning.* Road surface or low-friction warning systems give warnings to the driver in case of poor road conditions. The warning system may also be connected to an ISA system and guide the driver towards an appropriate speed given the current road condition. Possible changes in driver behaviour relevant for these systems are the same as the behavioural changes described for longitudinal control ADAS.

Today, the commercially available ADAS include mainly longitudinal control ADAS and parking aids. Lateral control ADAS are considered to be close to the market, blind spot and lane-keeping assistants have for example recently been introduced by some car-manufacturers. Other types of ADAS are still under early research and development (Flodas et al., 2005).

Traffic simulation will be of use for evaluation of ADAS that have an impact on the behaviour of individual vehicles and therefore also on the overall traffic system. All of the ADAS listed above except parking aids and pre-crash systems are likely to have such an impact on vehicle behaviour. Changes that need to be considered include changes in lane-changing and overtaking behaviour, desired speeds, following distances and reaction times. These changes can be referred to both modified vehicle properties due to installed systems and changes in the behaviour of drivers in the equipped vehicles.

2.2 Requirements on driver/vehicle models for traffic simulation including ADAS-equipped vehicles

Vehicle movements in a traffic simulation model are controlled by sub-models that govern lateral and longitudinal movements respectively. Commonly considered lateral movements include lane-changings and overtakings, a vehicle's position within its current lane is however usually not taken into account. Modelled longitudinal movements are car-following with respect to vehicles in front and speed adaptation with respect to road and traffic control characteristics. A traffic simulation model to be used for ADAS evaluation should take in to account both the system functionality of the ADAS and the behaviour of drivers in ADAS-equipped vehicles. This requires modification and extension of the sub-models for lateral and longitudinal vehicle movements.

Lane-changing and overtaking models to be used for simulation of vehicles equipped with lateral control ADAS should include the gap-acceptance behaviour of the equipped vehicles. This requirement leads to implications for the gap-acceptance modelling with respect to surrounding vehicles in the vehicles' own direction in lane-changing models for motorways or urban streets. A blind spot detection system may for example result in more careful lane-changes with longer accepted gaps to surrounding vehicles. On two-lane highways it is also necessary to consider the gap-acceptance behaviour with respect to oncoming vehicles in overtaking situations. An overtaking assistant that supports the driver in judging whether or not an overtaking opportunity is safe may result in fewer risky overtakings for equipped vehicles. On the other hand, some drivers may also accept a shorter gap if the system tells them that it is safe to overtake.

Car-following and speed adaptation models to be used for simulation of ADAS-equipped vehicles should allow modelling of ADAS system functionalities such as distance controllers and speed limiters. The system may for example accelerate or decelerate equipped vehicles using system specific acceleration rates. There may also be a certain delay in the reactions of the system. In addition, some systems only support the driver in certain traffic situations, e.g. standard Adaptive Cruise Control systems only work at speeds above a certain threshold corresponding to free flow traffic conditions. All of these aspects should be taken into account in a car-following model for ADAS evaluation. It has been observed that drivers in vehicles equipped with ADAS change reaction time, following distances and speeds. The car-following model should therefore also include parameters that control these driver properties.

Other issues that deserve modelling attention are driver reactions at the boundaries of the functional area of the ADAS. For example, driver reactions when the ADAS takes over parts of the driving task and reaction delays when parts of the driving task are given back to the driver. To include the behaviour found among real drivers with and without the support of ADAS, the simulation model must also reflect differences between drivers as well as the inconsistency of one driver's actions in different situations.

The effect of many ADAS is likely to increase with increasing traffic volumes, as increasing traffic volumes also imply increasing interactions between vehicles. The sub-models used for simulation of traffic including ADAS-equipped vehicles should therefore preferably be able to describe vehicle interactions also in congested traffic states. Important properties with respect to modelling of congested traffic includes a continuous acceleration function, consideration of several vehicles ahead and inclusion of forced merging and lane-changing behaviour. A continuous acceleration function is necessary to prevent artificial instabilities due to regime switching in the car-following and speed adaptation models. Consideration of several vehicles ahead becomes important to allow modelling of observed vehicle behaviours such as maintaining a distance to the vehicle in front that is shorter than the driver's reaction time. The need to model forced merging and lane-changing follows from the increased impact of such situations on the traffic performance in congested traffic states.

In summary, simulation of ADAS-equipped vehicles place additional requirements on the driver/vehicle models used in the traffic simulation. The models must allow inclusion of both ADAS functionalities as well as the behaviour of drivers in equipped vehicles. This motivates use of more complex driver/vehicle models than what is necessary for typical traffic simulation studies of urban network design. Examples of promising driver/vehicle modelling approaches to be used for simulation of traffic including ADAS-equipped vehicles are the works by Treiber et al. (2006) and Hoogendoorn and Ossen (2006).

3 A Traffic Simulation Framework for Analysis of ADAS

This section presents the framework for analysis of traffic system effects of ADAS. The central component of the evaluation framework is the ADAS under consideration. This ADAS's effects on driver behaviour are studied in the first step of the analysis. The tools used for this task have in common that they consider test drivers' behaviour in a laboratory situation. Since the ADAS under consideration is 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 instrumented 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 are on the other hand concerning the realism of the simulator. There are also other alternatives for studying driver behaviour, e.g. stated preference methods.

In the next analysis step a traffic simulation model is extended with vehicles including the ADAS functionality and the observed driver behaviour. The traffic simulation model that is utilized in this analysis step has to be capable of describing traffic in the road environments that the ADAS gives support in. Implementation of ADAS system functionality and driver behaviour for ADAS-equipped vehicles in a traffic simulation model involves modification of the driver/vehicle sub-models. It is consequently important that these sub-models are appropriate for simulation of ADAS-equipped vehicles as described in section 2.

The basic result from a microscopic traffic simulation model run is a set of vehicle trajectories. To use these vehicle trajectories to estimate traffic performance, the trajectories need to be aggregated into performance indicators that are related to the traffic properties that are of interest in the current study. For example, quality of service is commonly measured by indicators such as "average journey speed", "queue length" and "time spent following".

Similarly, if the goal is to assess the resulting road safety effect then safety related indicators are needed. Work on safety related indicators for traffic simulation have been performed by e.g. Minderhoud and Bovy (2001), Barceló et al. (2003) and Archer (2005).

The basis for environmental impact analysis of road traffic is the analysis of vehicle emissions. Vehicle emission models use vehicle trajectories as the fundamental input. The environmental impact of the ADAS can therefore be estimated via vehicle emissions modelling using the resulting vehicle trajectories from the simulation as input.

The traffic simulation framework for analysis of the system effects of ADAS is shown in Figure 1. In the centre of the figure is the ADAS under

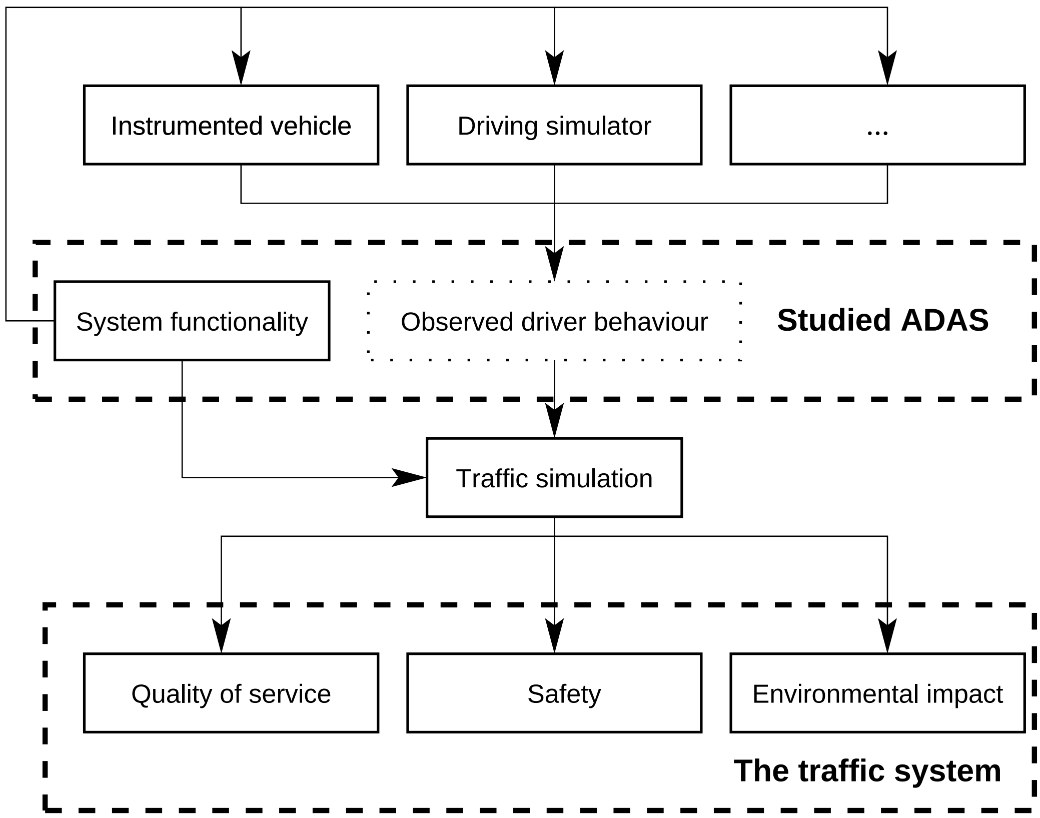

Figure 1: ADAS evaluation framework

consideration. Changes in driver behaviour due to the ADAS functionality are studied using instrumented vehicles, driving simulators or other methods as depicted in the top part of Figure 1. The observed driver behaviour and the ADAS functionality is then implemented in a traffic simulation model including ADAS-equipped vehicles. Finally, as shown in bottom part of Figure 1, the simulation results are aggregated in to suitable indicators to assess the traffic system effects of the ADAS.

The use of traffic simulation to "extrapolate" the individual driver/vehicle behaviour to the traffic system level makes it possible to study the ADAS impact for alternative ADAS introduction scenarios. For example, effects of different ADAS penetration levels can straightforwardly by studied by varying the proportion of ADAS-equipped vehicles in the simulated traffic. Moreover, if different behaviour has been observed for different driver categories then this can be taken into account in the simulation by using different categories of ADAS-equipped vehicles. Another important effect of ADAS introductions in the traffic system is that the ADAS may have an effect also on surrounding non-equipped vehicles. As an example consider systems that reduce driver reaction times, this will be beneficial also for non-equipped vehicles since more time will be available for corrective actions. Such effects can also be studied using traffic simulation as indicated by Lundgren and Tapani (2006).

4 Application of the Simulation Framework

The simulation framework is applicable to studies of ADAS-impacts in all road environments. Many ADAS are however primarily developed to improve safety. As the majority of fatal traffic accidents occur on single carriageway highways with high speeds this is one of the most important road environments to consider when studying effects of ADAS introductions. As described in section 2, the simulation model to be used in the framework for analysis of ADAS should be able to describe traffic operations in the road environment that is to be studied. Consequently, a simulation model for two-lane highway traffic is needed if traffic on single carriageway roads is to be studied.

This section presents two applications of the traffic simulation framework for analysis of the effects of ADAS on single carriageway highways. The traffic simulation model that is utilized for both applications is the Rural Traffic Simulator (RuTSim) (Tapani, 2005). RuTSim is a dedicated traffic micro-simulation model for rural road traffic. The model takes into account interactions between oncoming vehicles in overtaking situations as well as speed adaptation with respect to the road alignment.

4.1 System effects of rumble strips and driver fatigue

This study considers the effects of centre line rumble strips on rural highways. The objective is to compare the effects of physical milled rumble strips to the effects of virtual rumble strips presented to the driver as an in-vehicle ADAS. The possibility of different effects for alert and fatigue drivers is also considered.

The effects of the rumble strips on individual driver behaviour has been studied in a driving simulator study that was conducted as part of the European project IN-SAFETY. A repeated measures design was adopted for the study. Each test person drove the simulator in both alert and fatigue condition. During each drive the test persons drove on the same road without rumble strips, with visible milled rumble strips and with rumble strips presented as an in-vehicle ADAS (with only sound and vibration). For each rumble strip condition, the test persons were given multiple opportunities to overtake a slower vehicle in front. The given overtaking opportunities differed with respect to the distance to the closest oncoming vehicle.

Findings of this driving simulator study with respect to both overtaking, longitudinal acceleration and speed adaptation behaviour will be included in the RuTSim model. Simulation runs with varying proportion of fatigue drivers and varying degree of rumble strip assistance will then allow the traffic effects of driver fatigue and the different rumble strip scenarios to be investigated. The result of these simulation experiments will be reported in a forthcoming paper.

4.2 Traffic impacts of a prototype overtaking assistant

Overtaking on two-lane highways is a complex task. The driver must for example assess the distance available for the overtaking in the same time as he or she estimates the required overtaking length. There is a potential to improve the safety and comfort of overtaking on two-lane highways by introducing an overtaking assistant that support the driver in judging whether or not an overtaking opportunity is safe.

Hegeman et al. (2005, 2007) have investigated the feasibility of designing such an overtaking assistant. Their work included observational studies, overtaking task analysis and the design of a prototype overtaking assistant. The impact on driver behaviour of the prototype system was also studied in a driving simulator study. It was for example observed that the test persons made overtakings with shorter gaps to the oncoming vehicle when supported by the overtaking assistant.

In this application of the simulation framework the overtaking behaviour of drivers in vehicles equipped with the overtaking assistant will be included in the RuTSim model. The simulation results will be aggregated into indicators of quality of service and traffic safety and the impact of the overtaking assistant on the traffic system will then be assessed. This traffic system impact will be the topic of a future paper.

5 Conclusions

A traffic simulation framework for analysis of system effects of ADAS has been presented. The simulation framework takes into account both ADAS system functionalities as well as changes in driver behaviour in ADAS-equipped vehicles. System functionalities of ADAS are for example distance controllers and speed limiters. Possible changes in driver behaviour include changes in reaction times, following distances and desired speeds. It is important that the driver/vehicle sub-models of the traffic simulation model that is used in the framework are suitable for extensions to allow simulation of ADAS-equipped vehicles. The models should allow modelling of observed driver behaviour in ADAS-equipped vehicles. In addition, as the impact of many ADAS is likely to increase with increasing traffic volumes it is important that the simulation model is able to handle modelling of large traffic volume scenarios.

Two future applications of the framework have also been presented. These applications consider ADAS that support drivers on rural highways. Driving simulator studies have been performed to study the driver behaviour in ADAS-equipped vehicles. Future research on the path outlined in this paper includes, in addition to the two presented applications of the framework, driver/vehicle modelling for traffic simulation including vehicles equipped with certain ADAS.

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