ADAS Impact Assessment by Micro-Simulation

S.P. Hoogendoorn and M.M. Minderhoud
Transportation and Traffic Engineering Section
Faculty of Civil Engineering and Geosciences
Delft University of Technology
Delft
The Netherlands

EJTIR, **1**, no. 3 (2001), pp. 255 - 275

Received: July 2001
Accepted: November 2001

This article presents the results of a ex-ante impact assessment study of Advanced Driver Assistance Systems. It focuses on two systems supporting longitudinal driving tasks, namely Autonomous Intelligent Cruise Control and Intelligent Speed Adaptation (ISA). The article addresses and compares the impacts of these systems on efficiency, reliability, driving comfort and safety by micro-simulation, for different penetration levels and bottleneck lay-outs.
The analysis reveals that deployment of cruise control improves bottleneck capacity, while on the contrary, the bottleneck reliability generally reduces. The impact on traffic safety is undetermined, and the cruise control has a negative impact on driver comfort. ISA has no considerable effect on capacity. Also, no substantial contribution to the bottleneck reliability could be established. The expected safety benefits of ISA could generally not be established using the assessment methodology applied in this research.

1. Introduction

Advanced Vehicle Control Systems (AVCS) represent a subclass of Intelligent Transport Systems (ITS) dealing with vehicle control automation and driver support functions. AVCS applications can support or replace driving tasks. Automated Vehicle Guidance (AVG) incorporate all systems that can fully or partially replace subtask of the driver on dedicated or existing infrastructure. Advanced Driver Assistance Systems (ADAS) are a subclass of AGV systems, describing electronic systems that partially replace some of the tasks of the driver, or assist the driver in performing these tasks. The system functionality can be either informing, warning or actively supporting.
It is generally expected that within a few years, car manufacturers will introduce ADAS on the public market. Recent technological developments in the field of driving task automation,

such as the development Autonomous Intelligent Cruise Control (AICC) and Intelligent Speed Adaptation (ISA), as well as small-scale pilot studies of ISA for urban and rural roadways, are the main reasons for aiming to gain more insights into the impacts of these systems on traffic flow operations.
It has been claimed (e.g. Broqua *et al*, 1991) that ADAS may increase roadway capacity and will provide considerable safety benefits, while at the same time improving comfort and convenience of driving. These claims are however not self-evident. Even the reverse may be possible. Nevertheless, even if large safety benefits are not expected, reductions caused by these semi-automated systems are not acceptable.
It is well known that efficiency is determined by the weakest facilities in the network, i.e. its bottlenecks (on-ramps, merges, weaving areas). This is true not only from the viewpoint of network efficiency, but also from a traffic safety perspective. It is therefor proficient to first consider the impacts of ADAS on bottleneck traffic flow operations.

1.1 Scope of the research

Based on the results of an impact pre-assessment study (section 3), it was concluded that ADAS supporting the longitudinal driving tasks have promising characteristics with respect to impacts on roadway capacity and reliability. Moreover, the prospects of large scale implementation of these systems, stemming from technology assessment and the views of experts in the field (Marchau, 2000) justifies the focus chosen in this article: based on the results of a Delphi study, Marchau (2000) concludes that 82% of the experts expect that before 2005 longitudinal driver assistance systems will be introduced.
More specifically, in the remainder of the article we will consider the following systems:

- Autonomous Intelligent Cruise Control (AICC)
- Intelligent Speed Adaptation (ISA)

1.2 Research objective

The main research objective of the research presented in this article is to assess the impact of ADAS on motorway efficiency in general, and in particular on bottleneck capacity and reliability, traffic safety, and comfort, for a number of representative bottleneck lay-outs, ADAS regimes, and penetration levels.
The ADAS have been implemented in the microscopic simulation model SIMONE, which is a dedicated simulation tool for assisted car driving developed at the Transportation and Traffic Engineering Section of the Faculty of Civil Engineering and Geosciences of the Delft University of Technology. The model output provides data to assess the flow quality in terms of capacity, speeds, comfort and safety.

1.3 Article outline

The article generally follows the different phases in ex-ante assessment life-cycle. The following section sketches the most important characteristics of the ADAS analysed in this article, and discusses the general objectives of longitudinal driver assistance systems. The third section discusses the expected impacts of ADAS in general, and of longitudinal support systems in particular. Based on the application objectives, general assessment objectives are

established that are further specified in terms of Measures of Effectiveness (MoE's) or performance indicators in section 4. Section 5 presents the experimental set-up, while section 6 discusses the results of the model-based assessment study. The final section summarises the research findings and provides the general conclusions and future research directions.

2. Longitudinal Driver Assistance Systems

Driver support systems can support or replace specific driving subtasks. Systems can inform or warn the driver, can be overrulable or non-overrulable. Given the on-going technical improvements and the expected increases in automation levels, Minderhoud (1999) concludes that a useful classification for ADAS is the level of automation. Another classification is based on the driving subtask that is supported or replaced. For instance, ADA systems can provide longitudinal support or lateral support, with respect to other vehicles in the flow or with respect to the roadway. For reasons described in the introduction, the focus of our research will be on systems that support the longitudinal driving sub-task.

2.1 Supported longitudinal driver task

Minderhoud (1999) presents the driving task by using a conceptual feedback control model consisting of state observation and estimation, state prediction and control decision, and control actuation processes. The effects of ADAS pertain to all these components of the control loop, in reducing errors as well as decreasing the response time.
In broad terms, the longitudinal driver tasks consist of two basic elements: car-following and speed-choice. Support systems relating to these processes can be described by longitudinal support with respect to vehicles (e.g. AICC) and longitudinal support with respect to the roadway (for instance ISA).

2.1.1 Autonomous Intelligent Cruise Control

The longitudinal driving task of AICC is performed by making state observations with sensors measuring the distance and relative speed towards the preceding vehicle on the same lane. The control decisions are generally based on car-following algorithms in the AICC system. Other approaches are also possible, for instance using fuzzy logic or self-learning systems. For technical details and details on controller design, we refer to Shaout *et al*. (1997).
Due to the foreseen limitations of the first AICC systems that will be introduced on the market (in terms of acceleration and deceleration boundaries, as well as the supported speed range, see e.g. Benz, 1993), a driver is still responsible for the longitudinal driving task when the system warns that it has reached its operational boundaries. There are also situations in which the driver may intervene, e.g. when a vehicle merges in the gap in front, or when the driver experiences uncomfortable acceleration or deceleration.
The AICC design selected for this study represents the first generation of autonomous in-vehicle longitudinal driver support system. The system allows the driver to intervene at any moment, while it must be reactivated manually after an intervention. Due to the yet expensive techniques and methods for detection of stationary objects, the first generation support systems will operate within a restricted range.

2.1.2 Intelligent Speed Adaptation

ISA is a system that restricts driver behaviour with respect to the driving speed choice. Note that AICC will also restrict the speeds of vehicles (i.e. when another vehicle is followed), but these speeds are not necessarily equal to the prevailing speed limits. Moreover, car drivers will have the opportunity to pass a slower vehicle at a higher speed, assuming that passing opportunities occur. However, compared to AICC, ISA equipped vehicles have little or no possibility to drive at speed higher than the prevailing speed limit, even in case of sufficient passing opportunities. That is, for the ISA systems considered in this paper, speeds higher than the prevailing speed limits are impossible for equipped vehicles. Potential changes in traffic flow operations and safety are mostly determined by the settings of the ISA system. Overruling is generally possible in emergency situations. On the contrary to AICC, the ISA systems considered here are non-autonomous. That is, the speed limits are determined by a central system transmitting prevailing speed limits to the ISA equipped vehicles. In Van der Heijden (1999) an example of an ISA application is presented.

2.2 ADAS objectives

The general objectives of a driver support system will largely depend on the objectives set by the manufacturer and the users of the system, and will represent a trade-off between safety, efficiency, liability, and comfort aspects.

We can perhaps best describe the objectives of AICC systems as: increasing the comfort level of driving and improving the performance by assisting the longitudinal vehicle interaction driving task. From the perspective of the drivers, we can summarise the objectives of ISA systems as: increasing the comfort level of driving and improving the performance by providing longitudinal support with respect to the prevailing speed limits. ISA is however also used by road authorities as an instrument to improve traffic safety, for instance in urban areas.

2.3 ADAS design issues

To implement the systems in a simulation environment, some design issues need to be resolved first. To this end, it was decided to implement ADAS designs that are likely to become available to the market within the next 10 years. For AICC, we have therefore considered overrulable systems with limited speed and acceleration range. ISA will be operationalised by means of roadside transmitters. We will only consider non-overrulable ISA (with the exception of emergency situations, where temporarily exceeding the speed-limit is required to ensure the safety of the driver).

2.3.1 AICC design

First prototypes show a minimal operational speed of approximately 30 km/h. The upper speed boundary is determined by the sensor range and deceleration authority. The value of 170 km/h is an average of maximum speed boundaries. A deceleration authority of –2.5 m/s^2 has been picked as characteristic of the first generation systems. The acceleration level of the support system is restricted as well at a maximum of +4.0 m/s^2. Higher levels are uncomfortable for driver and passengers. Due to the limited support functionality of the system, a driver must take over control of the vehicle when hard braking is required, or the

speed drops below 30 km/h. Driver's intervention means overruling the support system. Reactivation must be carried out by he driver when driving at a supported speed and with a supported acceleration level. This may in practice lead to under-utilisation of the system's vehicle control potentials.

The employed car-following algorithm and sensor characteristics also are important for changes in the traffic flow quality. The distance-gap controller (as a function of speed v) is described by

$$d(v) = z_0 + z_1 v + z_2 v^2 = 3 + z_1 v + 0.01 v^2 \tag{1}$$

In the simulation experiments presented in the ensuing, different AICC controller settings are used. These differ with respect to the vehicles' distance gap parameter settings. Both $z_1 = 0.8$ s and $z_1 = 0.6$ s will be used. At this point, we note that for non-supported driving $z_1 = 0.8$ s holds. This implies that there is no difference between the target distance gap of equipped and non-equipped drivers, unless for $z_1 = 0.6$ s. Possible changes in capacity and safety in the former cases stem from decreased system response times only.

The acceleration and deceleration of supported vehicles stems from a car-following law, aiming to control the gap towards the desired gap determined by the inter-vehicle spacing law.

2.3.2 ISA design

Important ISA design parameters are the prevailing speed limits, the maximum deceleration upon entering the ISA-controlled freeway section. We have chosen a maximum deceleration of 0.5 m/s^2. In general, ISA prevents drivers from driving at a higher speed than the prevailing speed limit under all circumstances. That is, the system interferes whenever a driver attempts to drive at speeds higher than the prevailing speed limits, irrespective of the traffic conditions or driving manoeuvre. When the driver leaves the ISA controlled roadway sections, we assume that manual control is instantaneously returned to the driver. The parameters describing driving behaviour (car-following and gap-acceptance upon lane-changing and overtaking) are equal to the parameters for the non-equipped driver/vehicle combinations.

3. Expected Impacts of ADAS

An essential phase in the assessment of any advanced telematics application is exploring the expected impacts of the system on the relevant processes at hand. This section discusses the results of a qualitative analysis aimed at identifying the impacts of ADAS on traffic flow quality.

Traffic quality can be described from the perspectives of the individual driver (microscopic) as well as from the collective flow (macroscopic). At a microscopic level, traffic quality is determined by travel time (or travel speed), predictability of traffic conditions, and comfort. At the macroscopic level, the capacity is the major indicator of quality. Other quality issues pertain to the stability of the traffic flow and safety. In the remainder, we will distinguish between *efficiency* (travel times and capacity), *stability* (predictability and susceptibility to

shocks) and *safety* (comfort and safety perceived by the driver; number of nearly-accidents) impacts.

3.1 Impact of traffic quality

Figure 1 shows the causal relation between the microscopic level (driving behaviour), ADAS and roadway capacities. The execution of the driving task is in general determined by the characteristics and preferences of the driver and the use of the ADAS (if available).
ADAS is assumed to reduce time delays and errors involved in driving task execution (i.e. state observation and estimation, control decisions, and control actuation). This framework shows how ADAS influences microscopic behaviour. For longitudinal support systems, ADAS deployment will mostly affect the average distance gaps per lane, which in turn effects traffic density, average lane speeds, and thus the (maximum) flow per lane. The latter influences the way in which traffic is distributed across the roadway lanes.

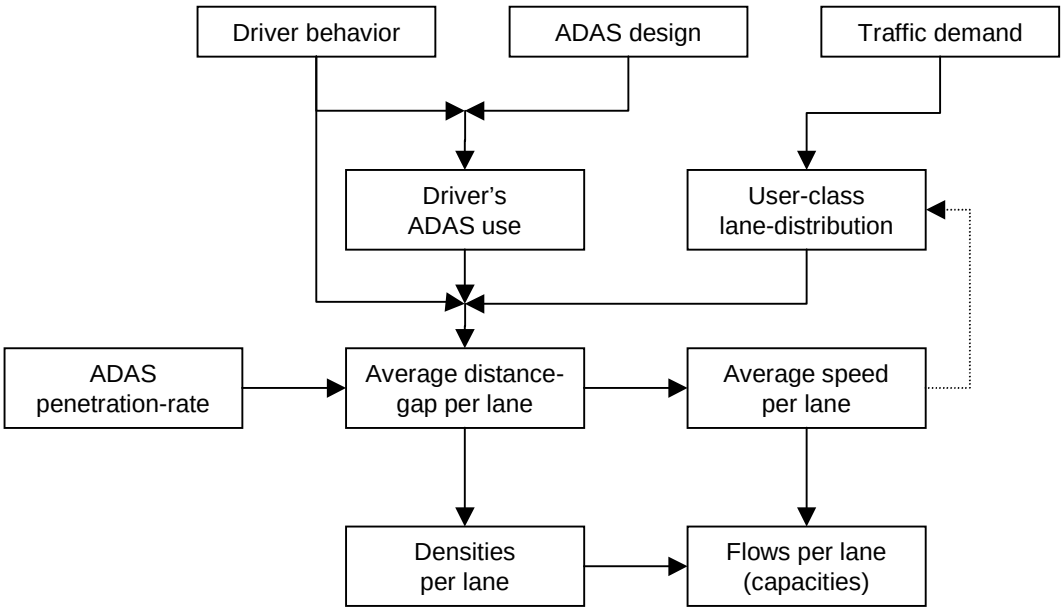

Figure 1. Causal diagram of factors affecting flow levels and flow distribution on motorways (from Minderhoud (1999)).

3.2 Impacts on traffic efficiency

Figure 1 shows how the deployment of ADAS can effect the capacity of the roadway. Different factors determine the capacity of the bottleneck (Figure 2), amongst which are:

1. Vehicle and driver characteristics, and changes herein caused by ADAS systems.
2. Vehicle fleet composition.
3. Driver population and trip purpose.
4. Road configuration.
5. Ambient and weather conditions.

These factors influence different aspects of driving behaviour (lane change desirability, and possibilities, and lane utilisation), which in turn influences the roadway capacity. Additionally, the capacity is also determined by the flow composition, driving speeds, and inter-vehicle gaps directly. In turn, increased capacity will (at least in the short run) decrease congestion levels and thus also improve travel times. Note that these improvements are not experienced solely by equipped drivers, but by all vehicles in the flow. On the contrary, ISA equipped drivers may even experience increased travel times.

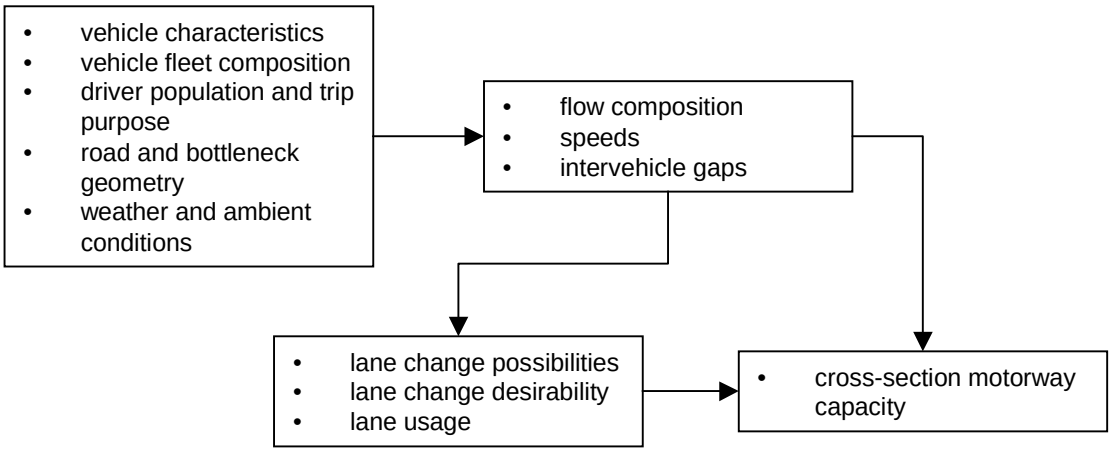

Figure 2. Factors determining changes in road capacity.

Little is know empirically about the impacts of AICC on motorway capacity. Most real-life experiments have focused on driver acceptance of the system and driver behavioural adaptation (Hoedemaeker, 1998). Most of the micro-simulation studies focus on homogeneous roadway stretches, implying that little can be concluded concerning impacts on bottleneck capacity. On the contrary, Minderhoud (1999) presents simulation results pertaining to AICC for a variety of bottleneck layouts (merge, weaving sections, on-ramp) for different AICC penetration levels and designs. For one, it turns out that AICC can have a positive impact on motorway capacity. Among the requirements is that the headways settings lead to headways which on average equal the mean headway on the non-equipped driver population. In this case, a substantial capacity increase is attained by the improved system response time, compared to the driver response time. Clearly, the increases in capacity depends on the AICC penetration level (but not linearly).
ISA is mostly applied to impose speed-limits on traffic in urban or rural areas (see Van der Heijden, 1999 and Lahrmann, 2001. Alkim *et al*. (2000) report the expected impacts of ISA studied by means of microscopic simulation. Only homogeneous roadway stretches are considered, so little can be said about increases in bottleneck capacity.

3.3 Impacts on flow stability and predictability

Stability pertains to the way in which disturbances propagate through the traffic flow. On motorways, shock waves represent unstable behaviour that might result in rear-end collisions. For AICC, stability analysis has focused on analysis of the General Motors model pertaining to particular sensitivity and reaction time settings (Zhang and Jarret,1997): large

reaction times and sensititivies lead to decreased flow stability. When the response time of AICC is smaller than the human response time, positive stability effects can be expected.
Application of linear stability analysis to second-order macroscopic traffic flow models (Leutzbach,1986) reveals the relation between the speed density relation $V = V(k)$ and the wave speed c_0. It turns out that small disturbances grow into a jam when the following condition holds:

$$k\left|\frac{dV}{dk}\right| > c_0 \tag{2}$$

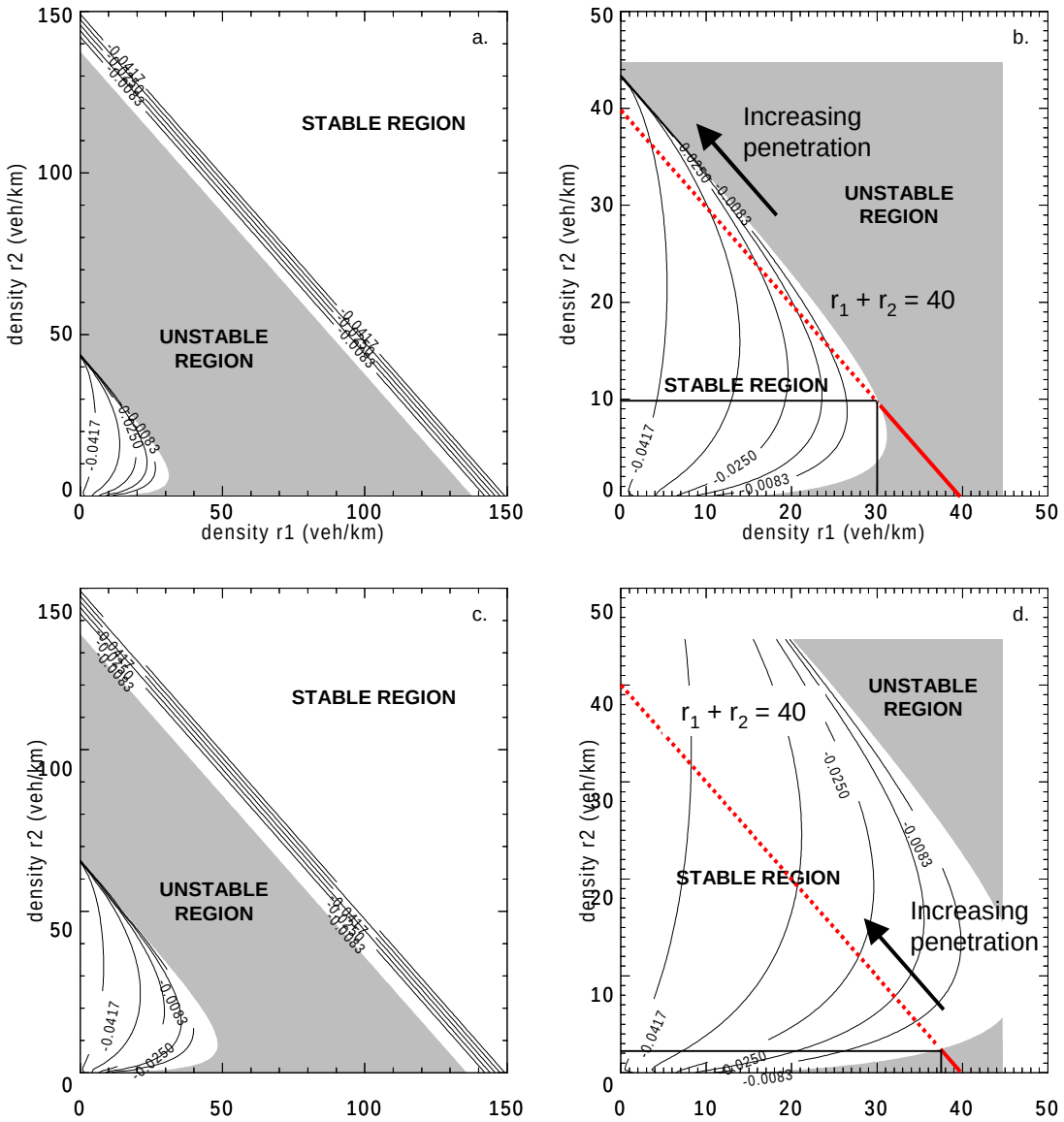

Figure 3. Stable and unstable density regions for ISA speed limits respectively equal to 720 km/h (a,b), and 50 km/h (c,d) (Hoogendoorn, 2001)

Hoogendoorn (2001) presents results of applying linear stability analysis on a multiclass macroscopic model where ISA equipped vehicles are implemented. It turns out that the stable region (in terms of traffic densities) is increased substantially when ISA is implemented. Figure 3 shows the stable and unstable density regions for different ISA speed limits. On the *x*-axis, the figure shows the densities r_1 of the unequipped vehicles; on the *y*-axis, the densities r_2 of the ISA equipped vehicles are shown. In the figures 3b and 3d, we have also indicated iso-total density curves $r = r_1 + r_2$. The points on this line represent different fractions of ISA equipped vehicles. The figure reveals how ISA can improve traffic stability substantially. Consider for instance the total density of $r = 40$ *veh/km*. According to figure 3b, traffic flow is unstable for no or low ISA penetration (i.e. below 25%). When the ISA penetration level increases over 25%, we move along the line $r = 40$ *veh*/*km* into the stable region.

Alkim *et al*. (2000) report the homogenisation of traffic flow operations (decrease in speed variance within and between roadway lanes) due to ISA.

Another interesting issue relating to the stability of the flow operations is the predictability of congestion occurrence. It is generally accepted that capacity is a random variable. This is why congestion may either occur or not under similar circumstances. This article focuses on the latter reliability concept, rather than on traffic flow stability discussed in the previous paragraphs.

3.4 Impacts on traffic safety

With respect to impacts on traffic safety, we can distinguish direct safety benefits (such as enhanced driving performance and mitigation of crash consequences) and indirect safety benefits (e.g. reduced exposure, reduced driver stress and fatigue, reduced conflicts and variance in behaviour). Also, direct safety risks (driver distraction, overload, reduced situation awareness) and indirect safety risks (behavioural adaptation, loss of skill, etc.) can be distinguished. Impacts depend largely on the extent to which the so-called Advance Driver Assistance Systems (ADAS) support drivers needs and are compatible with human capabilities and limitations.

In many cases, direct safety measures such as accident and fatality frequencies can not be obtained, among others due to the fact that ADAS are not yet widespread available. Since empirical collection of accident data is not an option, other methods for safety assessment are needed. Among these are ex ante assessments with which the safety consequences of different vehicle fleet compositions relative to a base (do-nothing) case can be estimated. To this end, microscopic simulation models can be applied. With the application of microscopic simulation tools a variety of traffic safety indicators can be determined, such as the headway distribution, time-to-collision (TTC) distribution, or number and severity of shockwaves.

Minderhoud and Hoogendoorn (2001) have studied the impacts of AICC and ISA on traffic safety, using improved safety measures using vehicle trajectories collected over a specific time horizon for a certain roadway segment, to calculate an overall safety indicator value (Time Exposed Time-to-collision and Time Integrated Time-to-collision). It appears that introducing AICC yields a slight improvement in the proposed safety measures. It is speculated that the threshold value applied in the safety indicator value assessment can be adapted when advanced AICC-systems with safety characteristics are introduced. On the contrary, ISA generally has a negative effect on the safety measures.

4. Towards Performance Indicators for Impact Assessment

The assessment objectives generally stem from the objectives of ADAS, the user-needs, and the requirements of decision-makers and stake holders, i.e. the road authorities. The performance indicators or measures of effectiveness should represent the issues reflected by the assessment objectives. This section discusses both for the ADAS under consideration.

4.1 Assessment objectives

In this article we focus on impacts of ADAS on traffic flow quality. Other important issues, such as impacts on the environment and socio-economic effects, fall outside the scope of the article. More precisely, we will focus on impacts of AICC and ISA on bottleneck capacity, changes in the level of comfort and safety.
With respect to efficiency, the assessment objectives can best be described as follows:

1. What are the expected capacity impacts of AICC and ISA?
2. How do AICC and ISA affect the roadway efficiency of the individual drivers?
3. What are the effects of AICC and ISA deployment on network-wide efficiency?

The remainder of the article will focus on objectives 1 and 2. A methodology to tackle objective 3 is outlined in the remainder of the article as well.
The assessment objectives pertaining to traffic reliability can be expressed as follows:

4. To what extent is the stability of the flow improved by AICC and ISA deployment? (in terms of avalanche-like growth of small perturbations)
5. To what extent will the congestion predictability change due to AICC and ISA?

Flow stability can be studied mathematically by applying linear stability analysis to analytical traffic flow models. Simulation models are generally less suitable to tackle assessment objective 4. In the remainder, we will primarily focus on objective 5.
Regarding safety, we will primarily focus on the effects on subjective safety. Subjective safety describes the extent in which drivers *perceive* traffic flow as unsafe, given the distribution of headways, time-to-collision, etc. On the contrary, objective safety pertains to the average number of accidents per time unit, which cannot be determined using a simulation approach. The assessment objective with respect to comfort and safety is formulated as follows:

6. To which extent do AICC and ISA change the comfort and safety levels?

4.2 Measures of Effectiveness (MoE's)

Estimating and assessing the latent capacity impacts of ADAS is an important subject of research. The capacity estimation method used in our analysis is based on the average queue discharge flow rate which can be measured downstream a bottleneck with congestion upstream the bottleneck, see e.g. Cassidy and Bertini (1999). We assume that congestion occurs when the average velocity is below 70 km/hr.
Capacity estimates are determined by considering the traffic conditions at the upstream traffic detector 2. When congestion occurs at this detector (measured speeds below 70 km/hr), it is assumed that the 5-minute average flow levels measured at the downstream

detector 1 is a good representation of the queue-discharge flow (i.e. bottleneck capacity). In this article only capacity values are presented. We refer to the background report for a more detailed analysis (Hoogendoorn, 2000).

To study the stability and predictability effects we will primarily consider changes in the capacity variability as a consequence of AICC and ISA. Further analysis of traffic flow stability will not be conducted in this study, since the safety analysis will take into account the negative effects of shock waves and flow instability.

The comparison of headway distributions at a cross-section gives an indication about the positive or negative shifts in traffic safety, assuming that small headways are relatively unsafe. Also, a comparison of time-to-collision distributions can be made to evaluate safety changes. Other safety indicators can be used as well, such as the number of shockwaves (e.g., Van Arem *et al.*, 1997), time-to-accident (TTA), post-encroachment-time (PET), deceleration-to-safety-time (DTS), see e.g., Topp *et al*., (1996, 1998). Absolute safety effects are hard to derive with such comparative analyses. It may also be clear that traffic safety analyses with microscopic traffic simulation have a number of restrictions. For instance, driver behaviour in real motorway traffic is more diverse and less predictable than can be implemented within a model. Furthermore, microscopic simulation models mostly neglect parts of the lateral driving tasks, such as keeping the vehicle on the roadway. Despite these limitations, simulation can give valuable insights into relative changes of traffic flow safety.

For sake of assessing the safety impacts of future intelligent in-vehicle devices interacting with the driver, adequate safety indicators should be applied which express the safety notion into a comparative and understandable variable. In the article we will use the new safety measures based on the Time-To-Collision (TTC) notion (Minderhoud and Bovy, 2001). The TTC indicator expresses only indirect safety concerns related with execution of the longitudinal driving task, and should be interpreted with this limitation in mind. Nevertheless, it can be argued that the extent to which a driver perceives a traffic situation as critical is reflected by the TTC values. Several researchers observed the relation between workload and different time-to-event measures (Hancock and Caird, 1993). It turns out that the mental workload increases as the effective time for action decreases (and when the perceived distance to the goal increases), implying that time margins such as the TTC reflect the workload.

The TTC is the time that it takes before a vehicle collide with a vehicle in front, assuming unchanged speeds of both vehicles during this approach. Negative TTC-values imply that the vehicle in front drives faster, i.e. there is no unsafe approach. Only positive TTC-value express a certain ‘approach unsafety’. By assessing TTC-values of a vehicle during his trip, at regular time steps or even in continuous time, a TTC trajectory of a vehicle can be determined. By doing so for all vehicles present on a road segment, we can determine the frequency (or absolutely, the exposure time) of the occurrence of certain TTC values, and by comparing these distributions - or its cumulative counterpart - for different scenarios we can give our judgement about safety changes. The determination of a (cumulative) TTC exposure time distribution is featured in the microscopic simulation model SIMONE, and its output will be used in this article. To analyse the effect of ADAS on traffic safety, in this article only the safety-critical and uncomfortable TTC values (TTC's which are smaller than 1.5 s and 3.0 s respectively) will be considered. In the background report, the headways are also assessed (Hoogendoorn, 2000).

5. Experimental Design

Having established the MoE's for assessing the impacts of AICC and ISA on efficiency, stability, and safety, the experimental design employed in the underlying study is presented in this section. Based on the objectives and MoE's in the previous section, it was decided to apply a microscopic traffic simulation approach.

5.1 Microscopic simulation tool SIMONE

To establish safety and capacity impacts quantitatively, the simulation model SIMONE developed at the Traffic Engineering Section of Delft University of Technology has been applied (Minderhoud and Bovy, 1999). This dedicated simulation model embodies the driver assistance functionalities of the considered Advanced Driver Assistance Systems. The model was calibrated for manual driver behaviour using macroscopic traffic data collected at a three-lane motorway in the Netherlands. The resemblance of the simulated data with practice was satisfactory. Assumptions about the used models for representation of ISA and AICC were based on a literature research.

5.2 Scenarios

The experimental set up used in capacity impact estimation and safety analysis comprises different bottleneck situations (lane drop from 3 to 2 lanes, lane drop from 4 to 3 lanes, and two on-ramp situations (2 + 1 and 3 + 1), and different AICC / ISA penetration levels (0%, 5%, 10%, 25%, 50% and 100%). In case of the lane drop, the dropped left most lane ends at x = 3500 m. In case of the on-ramp, the merging area starts at x = 2000 m, while the on-ramp ends at x = 3000 m.

5.2.1 ADAS settings

Different types of AICC control settings are tested. This pertains mainly to the headway settings of the AICC system (target headway set by z_1 = 0.8 s and z_1 = 0.6 s respectively), see section 2.3.1. With respect to the ISA settings, different prevailing speed limit regimes are tested. That is, in the one case, speed limits are reduced from 120 km/h to 90 km/h (in the bottleneck), while in the other case, speed limits are reduced to from 120 km/h to 70 km/h (given a transition area where the speed limit is equal to 90 km/h).

Table 1 Considered scenarios for ISA impact assessment (figures 4 and 5).

Regime	**Scenario**	
	Lane-drop	**On-ramp**
ISA Regime A	1000 – 3000 : **90 km/h**	800 – 2800 : **90 km/h**
ISA Regime B	1000 – 2000 : **90 km/h**	800 – 1800 : **90 km/h**
	2000 – 3000 : **70 km/h**	1800 – 2800 : **70 km/h**

Other speed regimes, for instance with even lower speeds can be considered as well. However, using lower speeds will negatively effect roadway capacity. Generally, this holds for all speed limits which are smaller than the so-called critical speed (speed at which the

capacity is attained). As a consequence, speed limits that are (somewhat) below the critical velocity should only be used upstream of the bottleneck.

5.2.2 User-classes

For the ISA scenarios, both equipped and unequipped person-cars and trucks are considered. The fraction of vehicles that is equipped varies (0%, 5%, 10%, 25%, 50% and 100%). Moreover, it is assumed that the speed of the vehicles that do not have a variable speed-limiter will also reduce their speed given the prevailing speed limits, albeit not to the same extent as the equipped vehicles. The ISA-equipped vehicles will adhere to the speed-limit precisely.

5.2.3 Traffic demand

A simulation is carried out by gradually increasing traffic demand at the origins from the beginning to the end of the simulation time. For the lane-drop situation, initial traffic demand equals 500 veh/hr/lane. This demand is gradually increased to 1650 veh/hr/lane during the first hour of simulation. For the on-ramp scenarios, traffic demand on all roadway lanes also equals 500 veh/hr/lane; during the first hour of simulation, the traffic volumes are slowly increased to 1750 veh/hr/lane, which was kept constant during the remainder of the simulation period. There are no vehicles generated at the origins if it is physically impossible to place them on the roadway. The simulation duration was set at 2.5 hours, including approximately 1.5 hours of congested traffic flow conditions upstream the bottleneck (congestion onset depends on the experimental scenario). All experiments end in congested conditions.

6. Results of simulation experiments

In this section, we will summarise the results pertaining to the impact assessment of AICC and ISA. To assess the impact of ADAS on motorway efficiency in general, and in particular with respect to bottleneck capacity, speed flow relations, traffic safety, and comfort, for a number of representative bottleneck lay-outs, ADAS regimes, and penetration levels have been studied.

Table 2 provides a summary of the microscopic simulation results, depicting the expected impact of ADAS on bottleneck capacity, reliability, safety, and comfort. It clearly shows the positive impacts that AICC has on the bottleneck capacity.

At all penetration levels, and all bottleneck layouts, it turns out that the impact of AICC on capacity is beneficial. Both the extent of the improvements (columns 'I'), as well as the optimal penetration level (columns 'P'), are dependent on the considered bottleneck layout. Also, the headway control settings play an important role. Note that the bottleneck reliability, expressed in terms of capacity variability, deteriorates in most cases when AICC is introduced.

Table 2 Overview results ADAS on botteneck capacity and reliability, safety, and comfort (I: expected impact, P: optimal penetration level). The plusses and minusses indicate to which extent the results are positive.

Support type	Scenario	Settings / regime	Capacity		Reliability		Safety		Comfort	
			I	P	I	P	I	P	I	P
AICC	3 to 2	$z_1 = 0.8$	+	50%	-	0%	+	100%	-	0%
		$z_1 = 0.6$	++	50%	--	0%	+	100%	-	0%
	4 to 3	$z_1 = 0.8$	+	50%	-	0%	+	100%	-	0%
		$z_1 = 0.6$	++	50%	--	0%	+	100%	-	0%
	2 + 1	$z_1 = 0.8$	++	100%	-	0%	--	0%	--	0%
		$z_1 = 0.6$	++	100%	--	0%	-/+	100%	-	0%
	3 + 1	$z_1 = 0.8$	++	100%	0	n/a	--	0%	--	0%
		$z_1 = 0.6$	++	100%	-	0%	-/+	100%	-	0%
ISA	3 to 2	Regime A	0	N/a	0	n/a	0	n/a	0	n/a
		Regime B	0	N/a	0	n/a	+	50%	+	100%
	4 to 3	Regime A	0	N/a	0	n/a	0	n/a	0	n/a
		Regime B	-	0%	-	0%	+	50%	+	100%
	2 + 1	Regime A	0	N/a	0	n/a	-	0%	-	0%
		Regime B	-	0%	0	n/a	-	0%	-	0%
	3 + 1	Regime A	0	N/a	0	n/a	-	0%	-	0%
		Regime B	-	0%	0	n/a	-	0%	-	0%

It turns out that for the lane-drop scenarios, capacity is not a monotonically increasing function of the AICC penetration level, but rather has an optimal penetration level of 50%. Further analysis showed that that this is mainly caused by shifts in the critical speed (speed at capacity) and changes in the use of the respective roadway lanes.

Given the AICC-induced changes on following behaviour on the main road, it is important to show whether these changes yield differences in how bottleneck capacity is distributed over the main-road and the on-ramp. From the simulation experiments it appears that AICC has no significant influence on how capacity is distributed, and the consequent queue lengths on the main-road and the on-ramp (Hoogendoorn, 2000).

In general, the impact which AICC has on traffic safety is undetermined, while being dependent on the considered bottleneck layout. Based on the cumulative exposure times of uncomfortable TTC values, on average AICC has a negative impact on driver comfort. It should be noted that neither with respect to traffic safety, nor comfort, the additional improvements in traffic safety and comfort due to the driver support system have been considered. For instance, on the one hand, since the AICC system response time is much shorter than the human response time, small TTC values are less dangerous in case of driver support than without. This implies that although TTC exposure time distribution may not have changed, the traffic safety may have improved substantially. On the other hand, changes in driver behaviour (risk substitution, decreasing attention levels) may decrease driving safety in case of supported driving.

The impacts of ISA shown in Table 2 are less profound. From the simulation experiments it turns out that ISA either has no effect on capacity, or a small negative effect, depending mostly on the considered speed-limit regime. Also, no substantial contribution to the

bottleneck reliability could be established. However, it was expected that ISA yield significant safety benefits. Nevertheless, these benefits could generally not be established using the assessment methodology used in this research, i.e. by considering safety-critical TTC exposure times. This holds equally for the impact on driving comfort.

Similar to AICC, it is expected that the induced changes on following behaviour on the main road lead to a different distribution of bottleneck capacity over the main-road and the on-ramp. However, again it that ISA has no significant influence on how capacity is distributed. This implies that congestion propagation in largely independent on the ISA penetration level.

The remainder of this section discusses some of the details of the research. For more background information, we refer to (Hoogendoorn, 2000).

6.1 Changes in capacity due to ADAS

The impact of AICC on bottleneck capacity is substantial for both bottleneck lay-outs. This holds for both AICC controllers (z_1 = 0.8 s and z_1 = 0.6 s). Note that the capacity increase for z_1 = 0.8 s is caused by the reduced response time of the driver-vehicle combination and not by decreased average headways, since the target headways are the same for both equipped and non-equipped drivers.

Another interesting result is the reduced capacity gains for higher AICC penetration levels in case of the lane-drop scenarios (Figure 4a). Minderhoud (1999) hypothesizes that the increasing capacity (critical) speed with a higher AICC penetration causes the capacity reduction (Figure 4b). At first, the overall bottleneck capacity gains from this development. However, the speed increase resulting from large scale AICC deployment eventually leads to a cutback in the capacity growth, since the attractiveness of using the right lane, occupied by relatively slow vehicles such as trucks, decreases. As a consequence, the right lane is not fully utilised, and the capacity of the right roadway lane decreases.

Figure 4a shows that for the on-ramp scenarios, the capacity is a monotonically increasing function of the AICC penetration level. This is caused by the fact that traffic is distributed more efficiently over the roadway lanes compared to the lane-drop case with its attractive right lanes. Rather, the left lane is use more by the merging traffic.

Contrary to AICC, ISA has no considerable impact on the capacities and critical speeds in case of the lane-drop scenarios, at least not for regime A. All capacity estimates are within 0.5% of the zero-ISA penetration case. This also holds for the on-ramp scenarios, where all capacity estimates are within 1.0% of the zero-ISA penetration case. For regime B, a small decrease in the capacity was observed, depending on the ISA penetration level.

Given the AICC induced changes on following behaviour on the main road, it is important to show whether these yield changes in how bottleneck capacity is distributed over the main-road and the on-ramp. From the simulation experiments it appears that AICC has no significant influence on how capacity is distributed, and therefor also not on the relative queue lengths on on-ramp compared to the main-road. Also ISA has no significant influence on how capacity is distributed.

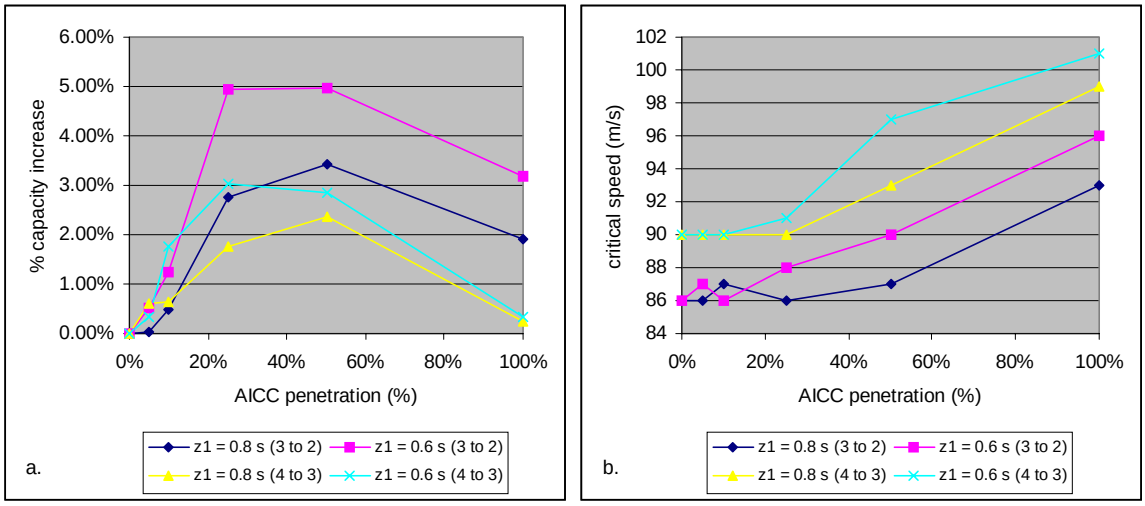

Figure 4 a) Relative change in capacities and b) increases in critical speeds for lane-drop scenarios with different AICC settings. The legends indicate the different AICC scenarios (headway setting z_1 *and bottleneck (3 to 2 lane drop or 4 to 3 lane drop).*

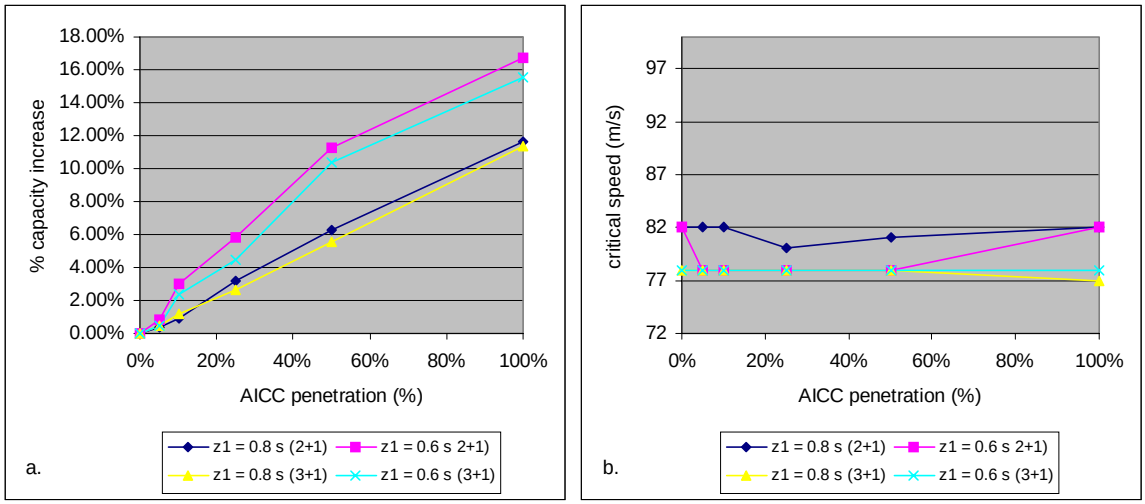

Figure 5 a) Relative change in capacities and b) increases in critical speeds for on-ramp scenarios with different AICC settings. The legends indicate the different AICC scenarios (headway setting z_1 *and bottleneck (2+1 on-ramp or 3+1 on-ramp).*

6.2 Impacts on bottleneck reliability

Figure 6a and b show how the variability of the bottleneck capacity increases with increasing AICC penetration levels. This pertains especially to the z_1 = 0.6 s headway settings. As a consequence, it is expected that the bottlenecks reliability is reduced due to AICC supported driving. In other words, the occurrence of congestion under seemingly similar conditions becomes less predictable. Note that compared to AICC, ISA has little or no effect on bottleneck reliability.

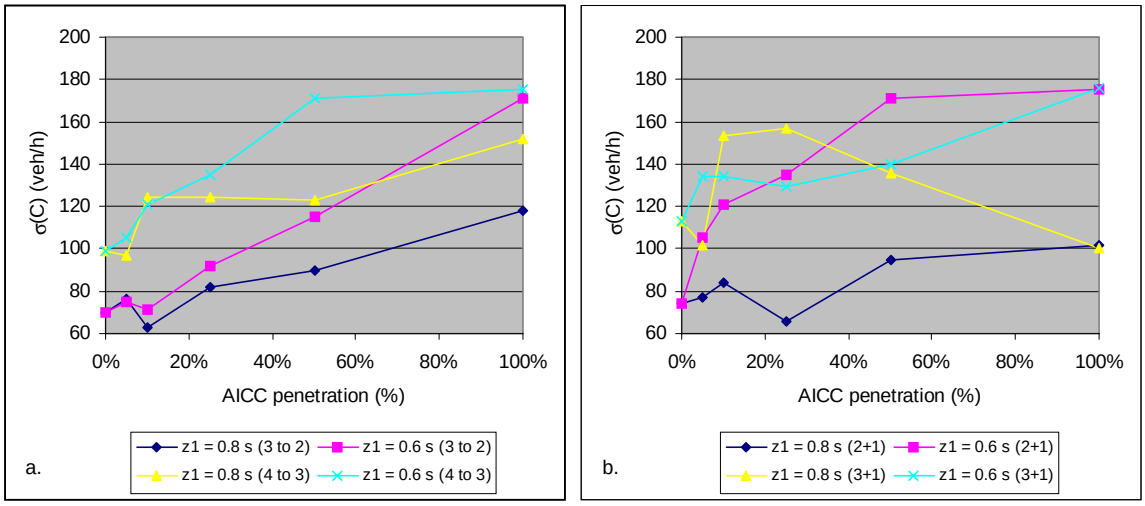

Figure 6 Bottleneck variability for a) lane-drop scenarios and b) on-ramp scenarios for AICC supported driving. The legends indicate the different AICC scenarios (headway setting z_1 and bottleneck (3 to 2 lane drop, 4 to 3 lane drop, 2+1 on-ramp or 3+1 on-ramp).

6.3 Time-to-Collision and safety

Table 3 shows the cumulative exposure times for different penetration rates for both TTC values smaller than 1.5 s (indicating safety) and smaller than 3.0 s (indicating comfort). When the AICC penetration increases, the frequency at which dangerous TTC values are experienced decreases, albeit not considerably. However, this does not hold for uncomfortable TTC values (smaller than 3.0 s), which frequencies appear to increase with increasing AICC penetration rates.

For the on-ramp scenarios, different conclusions are drawn regarding safety and comfort. In illustration, Table 3 shows the different levels of AICC penetration on the safety-critical and uncomfortable exposure times smaller than 1.5 and 3.0 seconds respectively, for $z_1 = 0.8$ *s*. The table shows how small TTC values on the on-ramp decrease with increasing AICC penetration rates. This improvement is mainly due to the fact that while no vehicle change lanes to the on-ramp, the increase in the number of AICC supported drivers on the on-ramp yields improved driving behaviour (e.g. due to smaller response times).

However, Table 3 also shows how on the right lane, the safety critical exposure times increase substantially. This increase can be explained, by considering the fact that due to AICC control, the average number of large gaps will decrease (variance in gap lengths will decrease) due to more efficient car-following of the supported vehicles. As a consequence, drivers from the on-ramp may occasionally need to accept a smaller gap (so-called mandatory lane-change), to be able to perform the merging manoeuvre, which may result in a small TTC value for either the merging vehicle, the vehicle that is behind the merging vehicle after the lane-change, or both. For full AICC penetration, Table 3 shows that the frequency at which safety critical TTC's occur in the on-ramp case reduce substantially with respect to 25% AICC penetration. This effect is even more profound for $z_1 = 0.6$ s, where the full AICC deployment case is perceived safer that the 0% penetration case.

Table 3 Impacts of ADAS on TTC distribution for different scenarios. The figures indicate the Time Exposure Time-to-collision (in seconds), i.e. the total time drivers experience safety-critical or uncomfortable TTC's (for the left, middle, or right lane, or all lanes together).

		--- Penetration ---								
		0%			25%			100%		
		--- Lane ---			--- Lane ---			--- Lane ---		
Case	**TTC smaller than**	**Left**	**Middle**	**Right**	**Left**	**Middle**	**Right**	**Left**	**Middle**	**Right**
3 to 2	1.5	0.3	2.1	11.5	0.3	1.4	10.9	0.4	1.1	9.3
AICC			13.9			12.6			10.8	
z_1 = 0.8 s	3.0	3.0	8.2	18.2	3.9	8.3	19.1	6.9	9.2	19.8
			29.3			31.2			35.8	
2 + 1	1.5	0.0	3.0	8.2	0.0	17.7	6.5	0.0	7.5	9.3
AICC			11.3			24.2			12.3	
z_1 = 0.8 s	3.0	0.5	9.8	11.2	0.4	25.5	9.5	0.1	14.3	19.8
			21.4			35.4			23.1	
3 to 2	1.5	0.3	2.6	11.3	0.4	2.1	13.3	0.1	1.6	11.7
ISA			14.1			15.8			13.4	
regime A	3.0	3.2	10.1	22.5	5.2	12.4	22.1	2.8	7.4	21.5
			35.7			39.7			31.7	
2 + 1	1.5	0.0	3.8	8.6	0.0	12.9	6.7	0.0	15.8	6.7
ISA			12.4			19.5			22.5	
regime A	3.0	0.6	11.6	12.1	0.3	20.5	9.4	0.6	23.8	10.3
			24.2			30.3			34.7	

Either way, we have to keep in mind that although small TTC values may be perceived as being unsafe or uncomfortable, the small response time of AICC may in the end yield safer traffic flow operations: a TTC that is unsafe given the long response time of the driver may not be unsafe for the timely responding AICC system.

For ISA, Table 3 shows the simulation results for regime A (3 to 2 lane drop) for different ISA penetration rates. It is astonishing to see that while for smaller ISA penetration levels the safety-critical exposure times are slight decreased, for higher ISA penetration levels, these exposure time tend to increase substantially. An explanation for this are the high speed differentials at the transitions areas between the non-ISA controlled and ISA-controlled areas: when driving into the ISA-controlled scenario, ISA controlled vehicles will adopt the velocity to the prevailing speed limits. The resulting speed drop can be both substantial and instantaneous, yielding small TTC values for the vehicles right upstream of the ISA controlled area.

For regime B, it appears that ISA has a positive effect on the TTC distribution, in that the fraction of very small TTC values (below 1.5 s) reduces with increasing penetration rates of ISA supported vehicles, compared to the 0% penetration level. However, compared to 25% percent ISA penetration, the exposure time to safety critical TTC values (smaller than 1.5 s) increases slightly. This observation supports the hypothesis that ISA reduces the average workload due to driving. Note that on the median lane, being the lane that is dropped, the reduction in the total TTC exposure time is not as substantial.

On the contrary to the neutral / positive effects of ISA on safety observed in case of a lane-drop scenario, it turns out that the safety-critical TTC exposure times on the on-ramp increase, while on the middle lane they increase (Table 3). The table also shows that the gross effect is negative, in that the cross-lane safety critical TTC exposure times increase substantially increasing ISA penetration levels (for speed-limit regime A). For the comfort-critical TTC value exposure times, the same applies. Similar results are obtained from regime B. Assuming that TTC values provide some indication in shifts in traffic safety, it appears that ISA yields no improvement in traffic safety or comfort for the on-ramp scenarios.

7. Conclusions and recommendations

This article discusses a methodology for ADAS impact assessment. By establishing the assessment objectives for the considered ADAS (i.e. AICC and ISA), we derived performance indicators describing impacts with respect to efficiency, bottleneck reliability, comfort and safety. The performance indicators have been determined by micro-simulation using the model SIMONE for a number of bottleneck scenarios and different ADAS penetration levels.

The research results clearly show the positive effects that AICC is expected to have on the bottleneck capacity. At all penetration levels, and all bottleneck layouts, it turns out that the impact of AICC on capacity is beneficial. Both the extent of the improvements, as well as the optimal penetration level, are dependent on the considered bottleneck layout. Also, the headway control settings play an important role. Note that the bottleneck reliability, expressed in terms of capacity variability, deteriorates in most cases when AICC is introduced. For the lane-drop scenarios, capacity is not a monotonically increasing function of the AICC penetration level, but rather has an optimal penetration level of 50%. Further analysis showed that that this is mainly caused by shifts in the critical speed (speed at capacity) and changes in the use of the respective roadway lanes. In general, the impact of AICC on traffic safety is undetermined, while its impact depends on the considered bottleneck layout. Based on the cumulative exposure times of uncomfortable TTC values, AICC has a negative impact on driver comfort. Neither with respect to traffic safety, nor comfort, we have considered the additional improvements in traffic safety and comfort due to the driver support system itself.

The impacts of ISA are less profound. From the simulation experiments it turns out that ISA either has either no effect on capacity, or a small negative effect, depending mostly on the considered speed-limit regime. Also, no substantial contribution to the bottleneck reliability could be established. It was expected that ISA would yield significant safety benefits. However, these benefits could generally not be established using the assessment methodology applied in this research, i.e. by considering safety-critical Time-To-Collision exposure times. The results imply that an active policy that stimulates the development and deployment of AICC-systems is more beneficial than stimulation of ISA systems with respect to efficiency improvements on motorways.

Acknowledgements

This research has been performed within the framework of the EC-funded project ADVISORS. The author is very grateful for the constructive suggestions and critical comments of the anonymous reviewers.

References

Alkim, T., H. Schuurman, and C. Tampere (2000). Effects of External Cruise Control and Co-operative Following on Highways: an Analysis with the MIXIC Traffic Simulation Model. *Proceedings of the 2000 Intelligent Vehicles Conference*.

Benz, T. (1991), *Traffic flow effects of Intelligent Cruise Control*, In: Proceedings of the ISATA conference, pp 755-760.

Broqua, F., Lerner, G., and V. Maro (1991), *Cooperative driving: Basic concepts and first assessment of Intelligent Cruise Control strategies*, In: Proceedings of DRIVE conference, Vol. 2, project V1048, Brussels.

Cassidy, M.J. and R.L. Bertini (1999), *Some traffic features at freeway bottlenecks*, In: Transportation Research B, No.33.

Hancock, P.A. and J.K. Caird (1993*), Experimental evaluation of a model of mental workload*, Human factors 35, pp 413 - 429

Heijden, R. Van der, and M. Wiethoff (1999), *Automation of Car Driving*, TRAIL Studies in Transportation Science, S99/4, Delft University Press, Delft, The Netherlands.

Hoedemaeker, M. and K.A. Brookhuis (1998*), Behavioural adaptation to driving with an adaptive cruise control*, Transportation Research Part F, pp 95-106.

Hoogendoorn, S.P. (2000), *Advanced Driver Assist Systems: Traffic Impacts Assessed by Microscopic Simulation*, ADVISORS task 4.5, Transportation and Traffic Engineering Section, Delft.

Hoogendoorn, S.P., and P.H.L. Bovy (2001). Model Assessment of Dynamic Speed Limit Control. *Proceedings of the 2001 World Conference on Tranportation Research*, Seoul, Korea.

Lahrmann, H., Madsen, J.M, and Boroch, T. (2001), *Intelligent Speed Adaptation – Development of a GPS based ISA-system and Field trial*, In: Proceedings of the 8th ITS congress, Sydney.

Leutzbach, W. (1988), *An introduction to the theory of traffic flow*, Springer-Verlag, Berlin.

Minderhoud, M. and S. Hoogendoorn (2001). Extended Time-to-Collision Safety Measures for ADAS Safety Assessment. *Proceedings of Critical Infrastructures Delft 2001*.

Minderhoud, M.M. (1999), *Supported Driving: Impacts on Motorway Traffic Flow*, TRAIL Thesis Series T99/4, Delft.

Minderhoud, M., and P.H.L. Bovy (1999). *Modelling Driver Behavior on Motorways – Description of the SIMONE model*. Report VK22206.302, Delft University of Technology, Transportation and Traffic Engineering Section.

Minderhoud, M.M. and P.H.L. Bovy (2001), *Extended time-to-collision measures for road traffic safety*, In: Accident Analysis and Prevention 3, pp 89-97.

Shaout, A. and M.A. Jarrah (1997). Cruise Control Technology Review. *Computers Electronic Engineering* 23(4), pp 259-271.

Topp, H.H. (Ed.) (1998), *Viva traffic: video verkehrs analyse in der praxis*, University of Kaiserslautern, Transportation Department, Green series No. 43.

Van Arem, B. & De Vos, A.P. (1997*), The effect of a special lane for intelligent vehicles on traffic flow*, TNO-INRO Report 1997-02a, Delft.

Zhang, X, and D.G. Jarret (1997). Stability Analysis of the Classical Car-Following Model. *Transportation Research B* 31(6), pp. 441-462.