Advanced Driver Assistance Systems: Traffic Impacts Assessed by Micro-simulation

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    This report presents results of research carried out in the ADVISORS project. The objective of this research is to develop a methodology to assess road traffic efficiency and environmental impacts of Advanced Driver Assistance Systems (ADAS) at both the microscopic and the network level.

    The results discussed in this report pertain to the microscopic analysis, in showing the impact of ADAS on bottleneck capacity and capacity distribution among the main-road and the on-ramps (if applicable) for both Autonomous Intelligent Cruise Control (AICC) as well as Intelligent Speed Adaptation (ISA). Moreover, impact on traffic safety and driving comfort are studied indirectly, by considering cumulative exposure times to Time-To-Collision values that can be considered to be either unsafe and uncomfortable. This impact analysis is carried out using the microscopic simulation model SIMONE, developed by Delft University of Technology.

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Preface

This report presents results of research into the impacts of ADAS on traffic flow efficiency and safety, carried out within the ADVISORS project. The objective of this research is to develop a methodology to assess road network efficiency and environmental impacts of Advanced Driver Assistance Systems (ADAS) at both the microscopic and the network level.

The results discussed in this report pertain to the microscopic analysis, in showing the impact of ADAS on bottleneck capacity and capacity distribution among the main-road and the on-ramps (if applicable) for both Autonomous Intelligent Cruise Control (AICC) as well as Intelligent Speed Adaptation (ISA). Moreover, impact on traffic safety and driving comfort are studied indirectly, by considering cumulative exposure times to Time-To-Collision values that can be considered to be either unsafe and uncomfortable. This impact analysis is carried out using the microscopic simulation model SIMONE, which has been developed at the Delft University of Technology.

This report has been done by the Transportation and Traffic Engineering Section of the Faculty of Civil Engineering and Geosciences of the Delft University of Technology. The Transportation and Traffic Engineering Section acts as one of the TRAIL partners participating in the ADVISORS project. During the past ten years, a group of TRAIL researchers have been studying expected impacts of ADAS on driver behaviour and traffic operations, as well as market assessment and legal matters. The main results of this programme are described in Van der Heijden en Wiethoff (1999).

Delft, Wednesday, March 21, 2001
Summary

This report discusses the results of the microscopic analysis of Advanced Driver Assistance Systems (ADAS) and their impacts on motorway efficiency and safety. This summary discusses problem analysis, research objective and approach, and the main results of the microscopic analysis of the impacts of ADAS on traffic operations on motorway bottlenecks.

S.1 Problem analysis

The research is part of the ADVISORS project, pertaining to methodology development to assess the impacts on network-level efficiency and environmental impacts of ADAS. To assess the impact of network efficiency, among other things, unifying insights into the impacts of ADAS on bottleneck capacities are required. Currently, these insights are lacking. This holds equally for knowledge concerning changes in the fundamental relation between flow and speed, as well as the impacts of ADAS on traffic safety and comfort.

S.2 Research objective

The main objective of the reported research is as follows.

To assess the impact of ADAS on motorway efficiency in general, and in particular with respect to bottleneck capacity, speed flow relations, (subjective) traffic safety, and comfort, for a number of representative bottleneck lay-outs, ADAS regimes, and penetration levels.

S.3 Research approach

To meet this research objective the instruments Autonomous Intelligent Cruise Control (AICC) and Intelligent Speed Adaptation (ISA) systems have been chosen to exemplify. These instruments have been implemented in the microscopic simulation model SIMONE. SIMONE is a dedicated tool developed at the Transportation and Traffic Engineering Section of the Faculty of Civil Engineering and Geosciences of the Delft University of Technology to assess the flow quality in terms of capacity, speeds, comfort and safety. This model is especially suited to deal with partly or fully automated vehicles.

S.3.1 Considered bottleneck layouts, control regimes and penetration levels

For analysing both AICC and ISA impacts, four bottleneck layouts have been considered, namely the 3 to 2 lane-drop, the 4 to 3 lane-drop, the 2 + 1 on-ramp, and finally the 3 + 1 on-ramp. The research has focused on bottlenecks, since these are the main cause for congestion in traffic networks, and therefore constitute the main cause for travel time losses, decreases in traffic safety and comfort, and increases in fuel consumption and emissions on a network scale, both directly (drivers queuing) as well as indirectly (for instance due to drivers re-routing to avoid congestion, thereby
increasing the distance they travel). For each scenario, several levels of ADAS penetration (0%, 5%, 10%, 25%, 50%, and full penetration) are considered.

Finally, different ADAS control settings are compared. For AICC, different headway settings are considered. For ISA, different speed-limit regimes are compared.

**S.3.2 Measures of Effectiveness and calculation approach**

To assess the impact of ADAS, Measures of Effectiveness (MoEs) are established to quantify the assessment objectives. With respect to the impact of ADAS on bottleneck efficiency, the most important MoE is bottleneck capacity. This capacity, defined by the *queue discharge rate*, equals the *maximum bottleneck throughput in vehicles per hour* in case congestion has occurred due to oversaturation of the bottleneck in question. The capacity can be measured by detecting when congestion occurs at a detector location *upstream* of the bottleneck. The flow-rates measured *downstream* of the bottleneck subsequently serve as an observation of capacity flow. Collecting a sufficient number of capacity observations, the mean and variance of the capacity can be estimated. In doing so, for each scenario, relations between capacities and the penetration rates are determined. This holds equally for the critical speed (average traffic speed at capacity conditions).

Furthermore, relations between flow and speed, and the resulting changes due to ADAS are discussed. At this point, let us note that using estimates for the capacity, critical speed, and the free speed, expressions describing the relation between speed and flow can also be determined for macroscopic analysis (e.g. to determine travel time functions in assignment modelling, or fundamental diagrams in macroscopic network simulation models).

In microscopic simulation models, the frequency at which accidents occur (*if they occur at all*) can generally not be used as a representative indicator for traffic safety. Therefore, indirect measures, namely headways and Time-To-Collision (TTC) cumulative exposure times are considered and compared for the different cases. The TTC's are also used to address changes in driving comfort.

**S.4 Overview of results**

Table S-1 summarises the microscopic simulation results described in detail in the remainder of this report, by depicting the expected impact of ADAS on bottleneck capacity, reliability, safety, and driving comfort.

**S.4.1 Expected impacts of AICC**

Table S-1 clearly shows 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.
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 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 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 therefore also not on the relative queue lengths on on-ramp compared to the main-road.

In general, the impact of AICC on (subjective) traffic safety is undetermined, while its impact depends 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. 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. For instance, 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.

<table>
<thead>
<tr>
<th>Support type</th>
<th>Scenario</th>
<th>Settings / regime</th>
<th>Capacity</th>
<th>Reliability</th>
<th>Safety</th>
<th>Comfort</th>
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<tr>
<td></td>
<td>3 to 2</td>
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<td>3 + 1</td>
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<td>4 to 3</td>
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Table S-1 Overview results ADAS on bottleneck capacity and reliability, safety, and comfort (I: expected impact, P: optimal penetration level).

Finally, from the simulation experiments it is observed that AICC has no impact on the free-speed of traffic.
S.4.2 Expected impacts of ISA

The impacts of ISA shown in Table S-1 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. This holds equally for the impacts 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 in case of ISA supported driving, congestion propagates through the network in the same way as without driving support.

With respect to the free-speed, it is observed that the free-speed is a linear function of the ISA penetration level, which varies from the free-speed of unequipped drivers (in case of 0% ISA penetration), to the prevailing speed-limits adhered to by the ISA systems (for full ISA penetration).
The introduction of ADAS will change the traffic flow quality at different descriptive levels of traffic flow operations, namely:

1. The microscopic level (individual drivers),
2. The mesoscopic level (groups of drivers), and at
3. The macroscopic level for the total flow.

In the remainder of this report, we will first identify possible changes due to ADAS qualitatively. Moreover, we will show the impacts of a few particular forms of ADAS, such as AICC (Autonomous Intelligent Cruise Control), and ISA (Intelligent Speed Adaptation), on traffic flow operations and traffic safety. These systems have been chosen due to their prospects for implementation of these systems on a large scale (see Marchau (2000)), and the expected impacts on traffic (Minderhoud (1999)).

To this end, we will mainly focus on the impacts of these ADAS systems on bottleneck capacity, speed-flow relations, headway and Time-To-Collision (TTC) distributions. Let us first discuss how individual driving behavior affects traffic flow operations.

### Table 1-1 Microscopic and macroscopic aspects of traffic flow quality

<table>
<thead>
<tr>
<th>Microscopic</th>
<th>Macroscopic</th>
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<td>Travel speed (travel time)</td>
<td>Capacity</td>
</tr>
<tr>
<td>Predictability</td>
<td>Flow stability (sensitivity to shockwaves)</td>
</tr>
<tr>
<td>Smoothness, subjective safety,</td>
<td>Objective safety (accidents)</td>
</tr>
<tr>
<td>and driving comfort</td>
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### 1.1 Microscopic behavior and bottleneck capacity

One of the main interests from the viewpoint of ADAS impact assessment are the incurred changes on bottleneck capacity. Especially from the viewpoint of network wide assessment of ADAS impacts, insights into the changes in bottleneck capacity are essential, since these modified capacities will mostly determine travel times and congestion experienced in the considered network.

Different factors affect the capacity of the bottleneck (Figure 1-1), amongst which are the following:

1. Vehicle and driver characteristics, and changes herein caused by ADAS systems.
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.

- vehicle characteristics
- vehicle fleet composition
- driver population and trip purpose
- road and bottleneck geometry
- weather and ambient conditions
- flow composition
- speeds
- intervehicle gaps
- lane change possibilities
- lane change desirability
- lane usage
- cross-section motorway capacity

Figure 1-1 Factors determining changes in road capacity.

ADAS affects the characteristics of the driver vehicle combination. Figure 1-2 shows the causal relation between ADAS and roadway capacities. The execution of the longitudinal driving task is in general determined by the characteristics and preferences of the driver. Drivers have different free speeds, and desired distance gaps, and react differently to similar stimuli.

Depending of the type of ADAS system, these driving characteristics and reactions to stimuli is determined by the settings of the driver support systems. For instance, in case of AICC, the choice in distance gaps, as well as the reaction to downstream vehicles stimuli, this behaviour is prescribed by the system’s settings. On the contrary, in case of ISA, the speed choice is limited by the prevailing speed limits.
Besides these functional characteristics, the impact on traffic flow will depend on how drivers will use the system. While some of the systems cannot be overruled (such as ISA), others can be turned off. In turn, this utilisation depends on how the driver perceives the traffic situation. In other words, driver characteristics, objectives and preferences, the experienced traffic conditions, and the ADAS system's characteristics (e.g. supported speed range, supported acceleration range, prevailing speed limits) will influence the moments a driver will overrule and / or reactivate the system.

The resulting average gap distances per lane affect the average speeds and densities on a motorway lane. In addition, the minimum time headways drivers want to maintain determines the lane capacity. Changes in the average gap distance (per vehicle) per lane depend on many factors which we will discuss in the following.

The traffic demand (inflow of vehicles in a motorway section) determines to a large extent the average gap distances which can be observed on a motorway lane. Vehicles will usually drive at relatively large distances from each other if the traffic demand is low. The user class distribution (proportion of passenger cars, trucks, etc. in the traffic flow) affects the average gap distance per lane by influencing the lane change opportunities and decisions.

For instance, if drivers supported with AICC select higher or lower desired speeds this will introduce a user class with a deviating desired speed distribution, and might affect the average speed per lane. Some studies report a decrease of the desired speed when drivers are using an AICC-system.

1.2 Considered systems

In this study, the followings ADAS systems are considered:

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

These systems have been chosen due to prospects of large scale implementation on the one hand, and on the other hand (see Marchau (2000)), their anticipated impacts on traffic safety and comfort (see Minderhoud (1999)). In the remainder on this introduction, the different systems are discussed in some detail.

1.3 AICC design and use

The AICC system design and driver's AICC use determine the potential changes in the average gap distance per lane. Important AICC design variables are for example the supported speed range, supported acceleration level, the reactivation method, and the headway setting. The employed car-following algorithm and sensor characteristics also are important for changes in the traffic flow quality. Let us describe the impacts of these design issues on expected changes in the gap distances in more detail.
1.3.1 Supported speed and acceleration range

The supported speed range determines the traffic flow conditions in which the system can support the driver. For example, if speeds below 30 km/h are not supported, the system is not useful in heavily congested traffic and thus will not change the traffic flow characteristics in these cases. More precisely, the average gap distance will not change in flow conditions with speeds below 30 km/h, compared to a reference situation without such AICC system.

The supported acceleration range, and especially the deceleration authority, determines the number of interventions per unit time needed to execute the longitudinal driving task correctly and comfortably. It is reported that a system with a maximum supported deceleration of 0.1g will be overruled more often than a system with 0.2g deceleration authority. Intervention implies manual vehicle control, and consequently, it will take some time until the driver or system reactivates the assistance system. We expect that when a system is used more often and for a longer time, the car will drive for a longer time at the target headway setting, and approaches the desired speed closer. This affects the average distance gap positively (smaller distances).

1.3.2 Reactivation method

The reactivation method determines also the time a driver drives without the support functions of the system. The manual reactivation type will give full authorization to the driver to reactivate the AICC. This will probably lead to a loss in the total time the system is actually in the support mode, compared to the automatic reactivation type. Since the automatic reactivation type starts the reactivation automatically after driver intervention has stopped, we expect that this AICC design will maximize the time the system is activated.

1.3.3 Headway settings and longitudinal control

An important design variable of an AICC, directly affecting the average gap distance per lane, is the (time-) headway setting (the gap distance expressed in a time unit). Small headway settings of AICC systems will automatically result in small average gap distances and high capacities. Furthermore, we expect that the deployment of AICC systems contribute to a considerable reduction of variation in gap distances compared to a situation without supported driving. Although capacity is not affected when the average gap distance remains equal, homogenization may increase the safety and stability of the traffic flow. The adopted longitudinal car-following model defines the control actions of the vehicle in response to observed stimuli by the sensor in front of the vehicle.

1.3.4 Response time

By selecting appropriate values for the parameters, the behavior of an equipped vehicle can be improved compared to an average driver. An AICC sensor can observe stimuli (distance, speed) at small regular intervals, and make a control decision and perform the control action in a considerable shorter time than a driver. The resulting
reduction of the overall time delay $\delta$ between observation and control action performance, the resulting reduction of the observation, estimation, decision, and control action errors, and less variance in these error distributions, are relevant for an adequate and alert execution of the longitudinal driving task.

Drivers have sometimes a very slow response on accelerations of a vehicle in front. When a AICC-equipped vehicle is following a vehicle in front, the needed time and space to respond to the leader’s acceleration is less than without a support system. This implies shorter gaps as well as higher speeds.

1.3.5 Homogeneity of driver population

Furthermore, since the longitudinal behavior of AICC-systems is universal (given a specific type) differences in car-following behavior between drivers will disappear, while varying car-following behavior of a driver when following a vehicle in front will also disappear, assuming that drivers do not overrule their system. This will all lead to more homogeneous driving conditions and higher predictability of these conditions, to the benefit of the performance of the driver. The characteristics of a well-designed AICC longitudinal controller, compared to varying human car-following behavior, will probably lead to a reduced average gap distance per lane, and higher speeds on average. At the end, a higher capacity may be hypothesized, even with unchanged minimum gap settings.

1.3.6 AICC penetration rate

The equipment penetration rate of AICC systems determines the proportion of vehicles in the flow that can use the support functions of this device. The penetration rate will affect the average gap distance per lane, but this will depend on the AICC design and the AICC use by the drivers.

1.4 ISA design and use

Compared to AICC, Intelligent Speed Adaptation (ISA – or interurban variable speed-limiter) is more mandatory by its nature. That is, potential changes in traffic flow operations and safety are mostly determined by the settings of the ISA system. Important ISA design parameters are the prevailing speed limits, the maximum deceleration upon entering the ISA-controlled freeway section.

In the remainder of this report, we assume that prevailing speed-limits used for ISA are non-traffic responsive. Rather, the speed-limits are fixed for specific roadway segments, and are equal to the speed-limits depicted on the road-signs (e.g. 120 km/h, 100 km/h, 90 km/h).

1.4.1 Supported traffic conditions and overruling possibilities

In general, ISA prevents drivers from driving at a higher speed than the prevailing speed limit under all circumstances. That is, the system kicks in whenever a driver attempts to drive at speeds higher than the prevailing speed limits, irrespective of the
traffic conditions or driving maneuver. We assume that the driver has no option to overrule the system.

1.4.2 Reactivation method

Similar to AICC, the reactivation method determines when the driver will stop being supported by the system. Clearly, this occurs when the driving speed is below the prevailing speed limit. When the driver leaves the ISA controlled roadway sections, we assume that manual support is instantaneously returned to the driver.

1.4.3 Control settings

The main control parameter relevant for ISA is the maximum deceleration upon entering a roadway section of which the prevailing speed-limit is below the speed of the vehicle. Since bottleneck capacity (queue discharge rate) is mainly determined by the acceleration time upon leaving a jam, and the reaction time of drivers, it is not likely that this deceleration parameter will affect the bottleneck capacity. However, it may play a significant role in traffic safety (shockwaves, etc.). Nevertheless, in the remainder we assume that the maximum deceleration equals 0.5 m/s².

1.4.4 Homogeneity of driver population

One of the main effects of ISA will be that differences in driving speeds are reduced. In turn, it is assumed that this will yield more homogeneous and stable traffic condition. Consequently, although the capacity of the bottleneck may not be increased, the probability of traffic breakdown may be reduced substantially. Moreover, reducing speed variance will generally improve (subjective) traffic safety.

1.4.5 ISA penetration rate

The equipment penetration rate of ISA systems determines the proportion of vehicles in the flow that can use the support functions of this device. In this respect, it is noteworthy that it is generally believed when the ISA penetration rate is high enough, the average velocity of the non-equipped vehicles will also reduce, further reducing speed variances and further improving homogeneity, stability, and safety of the flow.

1.5 Research objectives and approach

The main research objective is:

To assess the impact of ADAS on motorway efficiency in general, and in particular with respect to bottleneck capacity, speed flow relations, (subjective) traffic safety, and comfort, for a number of representative bottleneck lay-outs, ADAS regimes, and penetration levels.

To meet this research objective the instruments Autonomous Intelligent Cruise Control (AICC) and Intelligent Speed Adaptation (ISA) systems have been chosen to exemplify the impacts of ADAS on traffic operations. These instruments have been implemented in the microscopic simulation model SIMONE, which is a dedicated...
simulation tool developed at the Transportation and Traffic Engineering Section of the Faculty of Civil Engineering and Geosciences of the Delft University of Technology to assess the flow quality in terms of capacity, speeds, comfort and safety.

1.6 Overview of report

In the remainder of this report, the results of the simulation experiments with SIMONE are presented. To this end, the following chapter discusses experimental design for the different ADAS systems considered in this research. Chapter 3 and 4 discusses the simulation results for the AICC systems. Chapters 5 and 6 present the results of ISA. Finally, chapter 7 provides a synthesis of the results.
2 Experimental Design

This report discusses impact assessment of Advanced Driver Assistance Systems by means of microscopic simulation. To establish these impacts quantitatively, the simulation model SIMüNE developed at the Traffic Engineering Section of Delft University of Technology has been applied. This dedicated simulation model embodies the driver assistance functionalities of the considered Advanced Driver Assistance Systems. For a description of the SIMüNE model, see Minderhoud and Bovy (1999).

Besides impacts on traffic safety and driving comfort, estimating and assessing both 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). To this end, we assume that capacity occurs when the average velocity is below 70 km/hr.

However, not only the bottleneck capacity is a research topic. Also safety effects will be considered in the simulation study. Although in principle, it is possible to simulate actual accidents, we will study the effects on traffic safety indirectly. This is mainly done by considering the Time-to-Collision distribution, or rather, the cumulative TTC exposure times. The latter is defined by the total time at which vehicles have a smaller TTC than some critical value (e.g. 1.5 s or 3.0 s).

In this chapter, we discuss the experimental design of the simulation study. That is, we discuss the considered roadway geometries, the ADAS systems' settings, etc.

2.1 Considered scenarios

The experimental setup used in capacity impact estimation and safety analysis comprises different bottleneck situations (lane drop from 3 to 2 lanes (see Figure 2-1), lane drop from 4 to 3 lanes, and two on-ramp situations (2 + 1 and 3 + 1 (see Figure 2-2))), and different AICC / ISA penetration levels (0%, 5%, 10%, 25%, 50% and 100%).

Different types of AICC control settings are tested. This pertains mainly to the headway settings of the AICC system. 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).

2.2 AICC scenarios

For AICC, the considered cases consist of motorways where the speed limit equals 120 km/hr. In all cases, driver-on-the-right overtake-on-the-left regulation is adhered
to. This implies that unless traffic is congested, drivers may not overtake a slower vehicle on the right.

For ISA impact assessment, the same roadway geometries are considered as for AICC impact assessment. However, rather than considering different ISA system settings, different speed-limit strategies are considered. In the first case, a speed-limit of 90 km/h prevails for the region upstream of the bottleneck locations, i.e. at $x = 3500$ m for the lane-drop, and at $x = 3000$ m for the on-ramp scenarios.
respective). Downstream of the bottleneck, no speed limits are present. In the second case, speed-limits are progressive, i.e. it reduces with increasing $x$. For the lane-drop scenario, a speed-limit of 90 km/h is active for the interval $x = [1500 \text{ m}, 2500 \text{ m})$, while for $x = [2500 \text{ m}, 3500 \text{ m})$ a speed-limit of 70 km/h prevails. For the on-ramp scenarios, we use the intervals $x = [1000 \text{ m}, 2000 \text{ m})$ and $x = [2000 \text{ m}, 3500 \text{ m})$ for the 90 km/h and 70 km/h regimes respectively.

2.2.1 User-classes

Two user classes are distinguished, namely person-cars and trucks. These user-classes are different with respect to the parameter settings for speed-choice, vehicle parameters (length, maximum speed, acceleration and braking capabilities), car-following and lane-changing. Figure 2-3 and Figure 2-5 show the parameter settings describing both the characteristics of cars and trucks, as well as their drivers. In the considered test-cases, the fraction of trucks is equal to 10% of the total traffic demand. Trucks will mainly use the right roadway lane.

2.2.2 AICC system settings

Both person-cars and trucks can be equipped with AICC systems. Figure 2-4 and Figure 2-6 show the different AICC controllers for both person-cars and trucks used in the simulation experiments. Note that a the distance-gap controller (as a function of speed $v$) is described by $d(v) = z_0 + z_1v + z_2v^2 = 3 + 0.8v + 0.01v^2$. Note that this distance keeping law largely affects the capacity impacts of the AICC system. Moreover, for the default controller, the control laws of both the driver and the AICC controller are similar, implying that the capacity is only affected by reductions in reaction times, e.g. due to drivers accelerating faster from congestion). When the parameters of the distance gap controller law are changed, more substantial changes in roadway capacity are expected.

The ‘Normal AICC’ design represents the first generation of autonomous in-vehicle longitudinal driver support system. The system allows the driver to intervene at any moment. The support system must be reactivated manually after an intervention. Due to the yet expensive techniques and methods for detection of stationary objects, this first generation support systems will operate within a restricted range. 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.
### Figure 2-3 Car and car-driver behavioral parameters used in microscopic impact assessment.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td>5 m</td>
</tr>
<tr>
<td>Max Acceleration</td>
<td>2.5 m/s²</td>
</tr>
<tr>
<td>Min Acceleration</td>
<td>-1 m/s²</td>
</tr>
<tr>
<td>Mean Desired Speed</td>
<td>115 km/h</td>
</tr>
<tr>
<td>St. Deviation Speed</td>
<td>6 km/h</td>
</tr>
<tr>
<td>Lane Change TTC</td>
<td>7 s</td>
</tr>
<tr>
<td>z1 Parameter</td>
<td>0.3</td>
</tr>
<tr>
<td>Safety Time</td>
<td>0.45 s</td>
</tr>
<tr>
<td>Delay Time</td>
<td>0.1 s</td>
</tr>
<tr>
<td>Perceived Time</td>
<td>0.1 s</td>
</tr>
<tr>
<td>TTC Right Lane Accept</td>
<td>130 m</td>
</tr>
<tr>
<td>St. Deviation Delay</td>
<td>0.1 s</td>
</tr>
<tr>
<td>Perception Interval Time</td>
<td>0.3 s</td>
</tr>
<tr>
<td>Visibility Range</td>
<td>400 m</td>
</tr>
</tbody>
</table>

**Driver car-following law**
- Linear Controller: [0.3, 1.7, 1.8]
- Perception Boundary: 0.5
- Time To Collision: 0
- Safe Distance Controller: [0.3, 1.7, 1.8]

**Driver spacing law**
- Minimum Value: [0.8, 1.4, 3, 0.01]
- Speed Control Device: Not equipped

### Figure 2-4 AICC car-controller used in simulation experiments.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Actuator Delay</td>
<td>0.1 s</td>
</tr>
<tr>
<td>System Delay</td>
<td>0.1 s</td>
</tr>
<tr>
<td>Refresh Interval Time</td>
<td>0.1 s</td>
</tr>
<tr>
<td>Lowest Speed Supported</td>
<td>30 km/h</td>
</tr>
<tr>
<td>Highest Speed Supported</td>
<td>170 km/h</td>
</tr>
<tr>
<td>Linear Controller: [0.3, 1.7, 1.8]</td>
<td></td>
</tr>
<tr>
<td>Perception Boundary: [0.3, 1.7, 1.8]</td>
<td></td>
</tr>
<tr>
<td>Time To Collision: [0.3, 1.7, 1.8]</td>
<td></td>
</tr>
<tr>
<td>Safe Distance Controller: [0.3, 1.7, 1.8]</td>
<td></td>
</tr>
</tbody>
</table>

**Lateral support system characteristics**
- TTC Right Lane Accept: 1 s
- Overrule property: Automatic Re-engage
Figure 2-5 Truck and truck-driver behavioral parameters used in microscopic impact assessment.

Figure 2-6 AICC truck-controller used in simulation experiments.
The proposed 'Normal AICC' has also the restriction of supported deceleration levels. A deceleration authority of \(-2.5 \text{ m/s}^2\) has been picked as characteristic of the first generation AICC systems. The acceleration level of the support system is restricted as well at a maximum of \(+4.0 \text{ m/s}^2\). 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 implies overruling the support system. Reactivation must be carried out by the driver when driving at a supported speed and with a supported acceleration level. This may in practice lead to underutilization of the system’s vehicle control potentials.

In the simulation experiments, different AICC controller settings are used. These differ with respect to the following vehicle spacing control parameter settings. Both \(z_1 = 0.8 \text{ s}\) and \(z_1 = 0.6 \text{ s}\) will be used (see Figure 2-7). 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 spacing lay. The considered AICC systems comprise a linear control law.

![Figure 2-7 Gross time headways following from AICC spacing law for different \(z_1\) parameter settings (car-following distance setting).](image)

In all cases, only overrable AICC with manual reactivation is considered. The speed range in which the AICC systems are active is between 30 km/hr and 170 km/hr. The maximum acceleration equal 4 m/s, while the maximum deceleration equals 2.5 m/s.

### 2.3 ISA scenarios

The scenarios considered for testing the effect of ISA on capacity and safety are similar to the AICC scenarios. That is, two lane-drop scenarios (3 to 2 and 4 to 3 lanes) and two on-ramp scenarios (2 + 1 and 3 + 1) are considered. However, rather than considering different AICC settings, different speed-limit regimes are tested.
2.3.1 Speed-limit regimes

For both the lane-drop and the on-ramp scenarios, two speed-limit regimes are considered. These are indicated in Table 2-1. Note that the roadway geometries are equal to those described for the AICC system evaluation.

Table 2-1 Considered scenarios for ISA impact assessment.

<table>
<thead>
<tr>
<th>REGIME</th>
<th>SCENARIO</th>
<th>lane-drop</th>
<th>on-ramp</th>
</tr>
</thead>
<tbody>
<tr>
<td>regime 1</td>
<td>1000 - 3000 : 90 km/h</td>
<td>800 - 2800 : 90 km/h</td>
<td></td>
</tr>
<tr>
<td>regime 2</td>
<td>1000 - 2000 : 90 km/h 2000 - 3000 : 70 km/h</td>
<td>800 - 1800 : 90 km/h 1800 - 2800 : 70 km/h</td>
<td></td>
</tr>
</tbody>
</table>

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

2.3.2 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 latter will adhere to the speed-limit precisely.

2.3.3 ISA system settings

The main parameter that is of influence for the ISA equipped vehicles are the maximum deceleration upon entering the roadway section where a certain speed limit prevails. We have chosen a maximum deceleration of $2.5 \, \text{m}^2/\text{s}^2$.

The parameters describing driving behavior (car-following and gap-acceptance upon lane-changing and overtaking) are equal to the parameters for the non-equipped case, described in section 2.2.2.

2.4 Capacity and safety impacts

Both the impacts on roadway capacity, as well as on roadway safety will be studied for both AICC and ISA. Let us briefly discuss how the cross-section bottleneck capacity is determined from the simulation results.
2.4.1 Approach to determine roadway capacity

To determine the roadway capacity, the upstream traffic flow conditions are considered (detector 2 in Figure 2-1). When traffic conditions become congested, the queue discharge rate is measured at the downstream detector 1.

For a correct data interpretation, it is also needed to collect flow rates independently drawn from an identical distribution. We used a five-minute time interval as aggregation period instead of 1-minute intervals adopted in past research, since larger time intervals obey the requirement of independent, uncorrelated flow data better than small intervals.

A simulation is carried out by gradually increasing the 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 was gradually increased to 1650 veh/hr/lane during the first hour of simulation. For the on-ramp scenarios, traffic demand on all the 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 this is physically impossible. 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. 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).

Capacity estimates are determined for the different ADAS regimes, and scenarios. For each of these cases, expressions are determined describing the capacity \( C(p) \) as a function of the penetration rate \( p \). These expressions can serve as an input for the network analysis performed in the ensuing of the ADVISORS WP 4.5 research. This is also done for the critical speed \( V_{\text{crit}}(p) \) at capacity.

In most macroscopic models, traffic flow operations are described in terms of speed-density functions \( V(\rho) \), describing the average flow speed as a function of the traffic density. In illustration, we can use the following function

\[
V(\rho) = V_o \exp\left(-\frac{1}{\alpha}\frac{\rho}{\rho_{\text{crit}}}\right)
\]  

(2-1)

where \( V_o \) is the free-speed of the traffic, \( \rho_{\text{crit}} = C/V_{\text{crit}} \) is the critical density, and \( \alpha \) is some parameter, defined by

\[
\alpha = 1/\ln(V_{\text{crit}}/V_o)
\]  

(2-2)

In this case, estimates for the critical speed \( V_{\text{crit}}(p) \), the capacity \( C(p) \), and the free-speed \( V_o \) can be used to establish the speed-density relation (2-1). This holds equally for the travel time functions.
2.4.2 Impacts on bottleneck reliability

In addition to considering the average bottleneck performance, also the bottleneck reliability is considered. The reliability pertains to the variability of bottleneck capacity and described the predictability of congestion occurrence under given traffic conditions. When the capacity variability is small, the conditions under which congestion occurs can be described with reasonable accuracy. On the contrary, when capacity variability is large, the instant congestion occurs cannot be predicted accurately (only in terms of probabilities). To this end, we also consider the variability of bottleneck capacity.

2.4.3 Maximum lane-flows during congestion

For the on-ramp scenarios, insight into the distribution of the cross-section bottleneck capacity among the main-road and the on-ramp is important, since this will to a large extent, determine the location and length of the queues. For instance, will the queues appear mostly on the main-road (due to merge-give-way behaviour), or will queues be equally distributed among the main-road and the on-ramps?

To study these effects, maximum lane-flows are determined during congested conditions, on a location upstream of the head of the queue (detector 2). In doing so, we can determine how many vehicles can enter the main-road per hour, assuming that traffic conditions are congested.

2.4.4 Safety analysis and cumulative exposure times

To analyse the effect of ADAS on traffic safety, both headway distributions as well as the safety-critical and uncomfortable TTC exposure times (TTC’s which are smaller than 1.5 s and 3.0 s respectively) will be considered. On the contrary to the headways, which are collected at the detector locations, the TTC’s are determined for all locations. More precisely, for each simulation period, the TTC values for all vehicles that are present are calculated. Using these TTC values, a TTC distribution is determined for this specific simulation period. These distributions are subsequently aggregated for the entire simulation period. For more detailed information, we refer to Minderhoud and Bovy (2001).

2.5 Overview

Table 2-2 presents an overview of the characteristics of the selected support systems to be analysed, the roadway geometries that are considered, and the chapters where these scenarios are discussed.
### Table 2-2 Overview of considered test-case scenarios.

<table>
<thead>
<tr>
<th>ADAS system</th>
<th>Chapter</th>
<th>Situation</th>
<th>Penetration</th>
<th>Speed range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal AICC</td>
<td>manual</td>
<td>3</td>
<td>3 → 2</td>
<td>30 km/hr</td>
</tr>
<tr>
<td>($z_1 = 0.8$)</td>
<td>reactivation</td>
<td>4</td>
<td>4 → 3, 2 + 1 → 2</td>
<td>170 km/hr</td>
</tr>
<tr>
<td>ISA regime 1</td>
<td>5</td>
<td>3 + 1 → 3</td>
<td>0%, 5%, 10%, 25%, 50%, 100%</td>
<td>N/R</td>
</tr>
<tr>
<td>ISA regime 2</td>
<td>6</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

ADAS Impacts on Flow Operations using SIMONE  21-3-01  Page 28/73
3 Results for lane-drop scenarios with AICC

In the remainder of this report, we will discuss the results of the simulation experiments for the lane-drop and on-ramp scenarios discussed in the experimental set-up. In this chapter, we will consider the expected impacts with respect to bottleneck capacity, speed-flow relations, traffic safety, and comfort, of AICC in case of the lane-drop scenarios.

3.1 Capacities for different penetration rates

To determine the capacity, the traffic demand upstream of the merge was increased until congested occurs (i.e. speeds upstream of the bottleneck are below 70 km/hr). In the following, both results for the AICC as well as for ISA are discussed.

3.1.1 Cross-section capacities for 3 to 2 lane drop

Figure 3-1 shows the results from the simulation experiments for the 3 to 2 lane drop bottleneck scenarios for different distance-gap controller settings and penetration rates. The figure clearly shows that at first, the bottleneck capacity increases with increasing penetration rate. Clearly, the capacity increase is more profound for the $z_1 = 0.6$ s than for $z_1 = 0.8$ s control setting. The capacity increases are caused mainly by the improved car-following caused by the AICC system. Moreover, for $z_1 = 0.6$ s, additional capacity increases are due to smaller target time headways maintained by the AICC system.

![Figure 3-1 Bottleneck capacity for different penetration rates, and different distance control settings.](image)

Figure 3-1 shows that capacity increases result until a penetration of 50% is attained, for both distance-gap control laws. When the penetration rate increases beyond 50%, it turns out that the capacity reduces substantially. In Minderhoud (1999) it is hypothesized that this capacity reduction is caused by the increased use of the left
roadway lane in case of AICC support. It turns out that as the penetration rate increases, utilization of the left lane increases as well, at the expense of utilization of the right lane. The same holds for the roadway lane capacity estimates. Nevertheless, the capacity of the cross-section increases with increasing penetration rates, until 50% penetration. For additional information, we refer to section 4.5.

We have fitted several curves describing the relation between the capacity and the fraction of equipped vehicles. It turns out that $z_1 = 0.8$ s, the capacity relates approximately to the capacity by the following second-order relation ($R^2 = 0.95$):

$$C(p) = 1912 + 257p - 215p^2 \quad \text{where} \quad 0 \leq p \leq 1$$  \hspace{1cm} (3-1)

In case $z_2 = 0.6$ s, the relation between the capacity and the fraction of equipped vehicles could not be adequately approximated by a second-order polynomial. However, using the following polynomial of third order yields an adequate result ($R^2 = 0.94$):

$$C(p) = 1908 + 562p - 878p^2 + 387p^3 \quad \text{where} \quad 0 \leq p \leq 1$$  \hspace{1cm} (3-2)

Considering the speed-flow relation, capacity increases can be explained by the observed increases in the speed at capacity flow (see Figure 3-2): when the fraction of equipped vehicles increases, so does the speed at capacity flow (the so-called critical speed). It turns out that the critical density (density at capacity flow operations) on the left lane increases as well (not shown). However, the critical density on the right lane decreases.

![Figure 3-2 Increasing speeds at capacity flow (collected at downstream detector 1) for considered distance-gap control laws.](image)

For $z_1 = 0.8$ and $z_1 = 0.6$, the critical speed $V_{crit}$ relates to the penetration rate $p$ according to the following expressions

$$V_{crit}(p) = 86.4 - 3.4p + 10.0p^2 \quad \text{where} \quad 0 \leq p \leq 1$$  \hspace{1cm} (3-3)

with $R^2 = 0.83$ and

$$V_{crit}(p) = 85.7 + 9.9p \quad \text{where} \quad 0 \leq p \leq 1$$  \hspace{1cm} (3-4)

with $R^2 = 0.97$ respectively.
<table>
<thead>
<tr>
<th>Penetration</th>
<th>( z_1 = 0.8 ) s</th>
<th>( z_1 = 0.6 ) s</th>
</tr>
</thead>
<tbody>
<tr>
<td>E(C)</td>
<td>% var(C) Vcrit</td>
<td>E(C) % var(C) Vcrit</td>
</tr>
<tr>
<td>0%</td>
<td>1918 0.00% 70</td>
<td>1918 0.00% 70</td>
</tr>
<tr>
<td>5%</td>
<td>1919 0.03% 76</td>
<td>1928 0.52% 75</td>
</tr>
<tr>
<td>10%</td>
<td>1928 0.50% 63</td>
<td>1942 1.23% 71</td>
</tr>
<tr>
<td>25%</td>
<td>1971 2.76% 82</td>
<td>2013 4.93% 92</td>
</tr>
<tr>
<td>50%</td>
<td>1984 3.42% 90</td>
<td>2014 4.98% 115</td>
</tr>
<tr>
<td>100%</td>
<td>1955 1.90% 118</td>
<td>1979 3.18% 171</td>
</tr>
</tbody>
</table>

Table 3-1 Simulation results for lane drop scenario for 3 to 2 lanes and different car-following controllers.

Minderhoud (1999) hypothesizes that the increasing capacity speed with a higher AICC penetration causes the capacity reduction. 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.

3.1.2 Cross-section capacities for 4 to 3 lane drop

Figure 3-3 shows the average capacity per lane for a 4 to 3 lane drop bottleneck situation, for different AICC penetration rates and control settings. Similar to the case described in the previous section, the truck fraction is equal to 10%. The relative lane-capacity increases are similar to the 3 to 2 lane drop bottleneck situations. Clearly, capacity increases very profoundly from small penetration rate, having a peak somewhere between 25% and 50% AICC penetration. Beyond these critical penetration rates, capacity tends to decrease again, due to the underutilization of the right roadway lanes.

By regression analysis, it turns out that \( z_1 = 0.8 \) s, the capacity relates approximately to the capacity by the following second-order relation \( R^2 = 0.99 \):

\[
C(p) = 1758 + 160p - 156p^2 \quad \text{where} \quad 0 \leq p \leq 1 \tag{3-5}
\]

In case \( z_2 = 0.6 \) s, the relation between the capacity and the fraction of equipped vehicles could not be adequately approximated by a second-order polynomial. However, using the following polynomial of third order yields an adequate result \( R^2 = 0.97 \):

\[
C(p) = 1754 + 380p - 713p^2 + 342p^3 \quad \text{where} \quad 0 \leq p \leq 1 \tag{3-6}
\]

Note that in this 4 to 3 lane-drop case, the capacity per lane is somewhat smaller than in case of a 3 to 2 lane drop. This is mainly caused by the fact that the middle and the right lane are not efficiently utilised. Among the reasons for this under-utilisation is the fact that congestion occurs on the left-lane first, since this lane has to be used by all traffic on the dropped lane. Note that in most European countries, overtaking on the left is prohibited (as long as traffic is not congested).
Figure 3-3 Bottleneck capacity for different penetration rates, and different distance control settings.

Table 3-2 provides an overview of all simulation results. Again, increases in the critical velocity can be observed with increasing penetration rates.

<table>
<thead>
<tr>
<th>Penetration</th>
<th>z1 = 0.8 s</th>
<th>z1 = 0.6 s</th>
</tr>
</thead>
<tbody>
<tr>
<td>E(C)</td>
<td>%</td>
<td>σ(C)</td>
</tr>
<tr>
<td>0%</td>
<td>1757</td>
<td>0.00%</td>
</tr>
<tr>
<td>5%</td>
<td>1768</td>
<td>0.61%</td>
</tr>
<tr>
<td>10%</td>
<td>1769</td>
<td>0.64%</td>
</tr>
<tr>
<td>25%</td>
<td>1788</td>
<td>1.76%</td>
</tr>
<tr>
<td>50%</td>
<td>1799</td>
<td>2.37%</td>
</tr>
<tr>
<td>100%</td>
<td>1762</td>
<td>0.25%</td>
</tr>
</tbody>
</table>

Table 3-2 Simulation results for lane drop scenario for 4 to 3 lanes and different car-following controllers.

Finally, we have determined that for $z_1 = 0.8$ and $z_1 = 0.6$, the critical speed $V_{crit}$ relates to the penetration rate $p$ according to the following expressions

$$V_{crit}(p) = 89.1 + 9.3p \quad \text{where } 0 \leq p \leq 1$$

with $R^2 = 0.95$ and

$$V_{crit}(p) = 89.3 + 12.1p \quad \text{where } 0 \leq p \leq 1$$

with $R^2 = 0.97$ respectively

3.2 Speed-flow curves

Figure 3-4 and Figure 3-5 show the speed-flow curves for detectors 1 and 2 respectively, for 0% and 50% AICC penetration rates for the 3 to 2 lane drop scenario, and the 4 to 3 lane drop scenario.
For high velocities and low traffic volumes, changes caused by AICC are hardly noticeable. Among other things, this implies that the free speed in unaffected by the introduction of AICC systems.

As traffic volume increases, the speed drops less profoundly in case of supported driving. Moreover, the capacity and the speed at capacity (so-called critical speed) are both higher for the AICC case than for the reference case.

From the speed-flow curves collected at the cross-section upstream of the bottleneck (detector 2), it turns out that the speed within the congested region is on average **below 30 km/hr**, which implies that within the queue, the AICC driving support systems are **not operational in most cases**. This has a negative effect on the queue-discharge rate. At this point, let us note that for the on-ramp cases, the speed within the congestion is **above 30 km/hr** (see section 4.2), implying that the driver-support systems are mostly turned on in the congested area. As a consequence, it will be shown that the capacities of the on-ramp bottlenecks are substantially higher than in case of the lane-drop scenario.

![Figure 3-4 Speed-flow relation determined from measurements at detectors 1 and 2 for reference situation and 50% penetration rate, for 3 to 2 lane drop scenario.](image)

![Figure 3-5 Speed-flow relation determined from measurements at detectors 1 and 2 for reference situation and 50% penetration rate, for 4 to 3 lane drop scenario.](image)
As a final note, observe that AICC has no impact on the free-speed $V_0$ of the drivers, for neither of the lane-drop scenarios.

### 3.3 Impacts on bottleneck reliability

The results in Table 3-1 and Table 3-2 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.

### 3.4 Headway distribution

In safety analysis, the headway gaps are sometimes used to indicate the (subjective) safety of the traffic flow operations. Moreover, the average headways determine the roadway capacity. It is expected that AICC systems yield a substantial change in the headway distribution.

We have analysed the changes by considering the lane-specific headway distribution for the downstream measurement location. Both the reference case (0% penetration), 25% AICC penetration, and full AICC penetration have been compared (Figure 3-6, Figure 3-7, and Figure 3-8 respectively). At this point, let us emphasise that the results obtained from the lane-drop scenarios are representative for all AICC cases considered in this report. As a result, the headway distributions are not explicitly discussed for the other scenarios.

![Figure 3-6 Headway distribution for left and right lane at downstream detector 1 for reference case (0% penetration)](image)

1 Note that the headways depicted in this figure are the net time headways (excluding vehicle lengths). On the contrary, Figure 2-7 shows the gross time headways (including vehicle lengths).
In comparing the headway distributions, it turns out that the headway distribution is more uniform at higher AICC penetration levels. Note that the average headway is approximately the same for all considered scenarios, since the average flow rate was equal for all cases (for the case where $z_1 = 0.8$ s).

3.5 **Time-to-Collision and subjective safety**

Although the correlation between the Time-To-Collision (TTC) and the probability that an accident occurs may not be clear for motorways, it can be argued that the extent to which a driver perceives a traffic situation as critical (subjective safety) is reflected by the TTC values. Several researchers observed the relation between workload and different time-to-event measures (e.g. 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 can be seen as reflecting the workload. In this respect, we assume that TTC values below 3 s are perceived as uncomfortable; values below 1.5 s are considered dangerous TTC values.

3.5.1 TTC cumulative exposure times for headway setting A

Let us now consider the effect of AICC on the TTC distribution for the 3 to 2 lane drop scenario. To reduce the impact of randomness in the simulation results and get an representative view of the impact of AICC on the exposure times, the following results have been established by applying five simulation runs with different random seeds, for each considered scenario (0%, 25%, and 100% penetration).

Figure 3-9, Figure 3-10, and Figure 3-11 show the exposure times, defined by the total time during which vehicles experience TTC values that are in a specific interval, for the reference case, 25% penetration, and full penetration, for the different motorway lanes.

![Figure 3-9 Exposure times for different TTC intervals for reference case. Lanes 2, 3 and 4 respectively refer to the left, the middle, and the right motorway lane.](image-url)
Figure 3-10 Exposure times for different TTC intervals for 25% AICC penetration rate. Lanes 2, 3 and 4 respectively refer to the left, the middle, and the right motorway lane.

Figure 3-11 Exposure times for different TTC intervals for 100% penetration rate. Lanes 2, 3 and 4 respectively refer to the left, the middle, and the right motorway lane.

Table 3-3 shows the *cumulative exposure times* for different penetration rates for both TTC values smaller than 1.5 s and smaller than 3.0 s. Clearly, 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.

**Table 3-3 Impact of AICC (\(z_r = 0.8\) s) on TTC distribution for 3 to 2 on-ramp scenario. Note that the left-lane is dropped.**

<table>
<thead>
<tr>
<th>Penetration</th>
<th>0%</th>
<th>25%</th>
<th>100%</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>left</td>
<td>middle</td>
<td>right</td>
</tr>
<tr>
<td>TTC &lt; 1.5</td>
<td>0.3</td>
<td>2.1</td>
<td>11.5</td>
</tr>
<tr>
<td></td>
<td>13.9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TTC &lt; 3.0</td>
<td>3.0</td>
<td>8.2</td>
<td>18.2</td>
</tr>
<tr>
<td></td>
<td>29.3</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Let us finally note that, although the TTC values provide some indication of expected changes in roadway safety caused by AICC systems, it provides no conclusive results. Clearly, small TTC values can be considered dangerous for non-supported driving: when the TTC is smaller than the reaction time of a driver, and the driver has not anticipated on the event causing the small TTC value, a collision will generally result. However, since AICC systems have very small response times, small TTC values are not necessarily unsafe. However, even the supported driver may consider small TTC values as unpleasant.

In this respect, a complicating factor is caused by the AICC controlled vehicles. Clearly, as long as the AICC system is active (i.e. speeds are within the supported range and the system is not overruled by the driver), small TTC values will not necessarily yield unsafe situations, since the AICC system itself is in control of the longitudinal driving task, while having a system response time that is much smaller than that of a driver. However, when prevailing speeds are not in the supported range (i.e. are below 30 km/h), the (unaware) driver may be caught off-guard and suddenly face a very small TTC value.

3.5.2 TTC cumulative exposure times for headway setting B

The same analysis has been performed for AICC headway settings $z_1 = 0.6$ s. Figure 3-9, Figure 3-12, and Figure 3-13 respectively show the TTC exposure times for 0%, 25%, and 100% AICC penetration respectively. Clearly, the TTC distribution changes substantially.

![Figure 3-12 Exposure time distribution for 3 to 2 lane-drop scenario and AICC headway setting $z_1 = 0.6$ s, for 25% AICC penetration.](image-url)
Figure 3-13 Exposure time distribution for 3 to 2 lane-drop scenario and AICC headway setting \( z_1 = 0.6 \text{ s} \), for 100% AICC penetration.

Table 3-4 shows the cumulative exposure times for safety-critical TTC values (smaller than 1.5 s), and TTC values which are assumed to be perceived as uncomfortable. Clearly, the drivers exposure to safety-critical TTC values decreases with increasing penetration of AICC equipped vehicles. However, as can be observed from Figure 3-12, and Figure 3-13 as well, Table 3-4 also shows that the drivers' exposure to TTC values that are uncomfortable increases with increasing AICC penetration.

Table 3-4 Impact of AICC \((z_1 = 0.6 \text{ s})\) on TTC distribution for 3 to 2 lane-drop scenario. Note that the left lane is dropped.

<table>
<thead>
<tr>
<th>Penetration</th>
<th>0%</th>
<th>25%</th>
<th>100%</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>left</td>
<td>middle</td>
<td>right</td>
</tr>
<tr>
<td>TTC &lt; 1.5</td>
<td>0.3</td>
<td>2.1</td>
<td>11.5</td>
</tr>
<tr>
<td>TTC &lt; 3.0</td>
<td>3.0</td>
<td>8.2</td>
<td>18.2</td>
</tr>
</tbody>
</table>

If we cross-compare the results depicted in Table 3-3 and Table 3-4, we observe that the different AICC settings have a different effect on perceived safety and comfort: while the cumulative safety-critical TTC exposure times are smaller for the case \( z_1 = 0.6 \) compared to \( z_1 = 0.8 \), uncomfortable TTC exposure times are generally larger.

3.6 Summary

Summarising, for the lane-drop scenarios it can be concluded that AICC generally improves the bottleneck capacity. The extent to which depends on among other things the settings of the AICC controller.

The capacity is however not a monotonically increasing function of the AICC penetration rate. Rather, the maximum capacity is reached at 50% AICC penetration. The speed at capacity increases monotonically, irrespective of the considered AICC...
headway settings. Bottleneck reliability, in terms of capacity variability, tends to deteriorate with increasing AICC penetration levels. The free-speeds of traffic is not influenced by the introduction of AICC.

Based on studying the cumulative exposure times to both safety-critical and uncomfortable TTC values, the (subjective) safety of the traffic flow tends to increase, while the comfort level tends to decrease, with increasing AICC penetration levels.
4 Results for on-ramp scenarios with AICC

For the on-ramp scenarios, a similar approach has been taken as for the lane-drop experiments. However, it turns out that the simulation results are remarkably different, especially with respect to the capacity estimates.

4.1 Capacities estimates

In this section, capacity estimates for both the 2+1 and 3+1 on-ramp scenarios are determined. Also functional expressions for the bottleneck capacity and the critical speed as function of the AICC penetration level are determined.<

4.1.1 Bottleneck capacity for 2+1 on-ramp scenario

Figure 4-1 depicts the bottleneck capacity for different AICC penetration rates for the 2+1 on-ramp scenario. It turns out that the capacity increases monotonically with increasing AICC penetration, for all AICC gap-distance control-settings. The capacity increase depends on the headway settings of the AICC controller. For $z_1 = 0.8$ s, the capacity relates approximately to the capacity by the following linear relation ($R^2 = 1.00$):

$$C(p) = 2109 + 251p \text{ where } 0 \leq p \leq 1$$

(4-1)

implying that for each additional 10% of AICC equipped vehicles, the capacity per lane increases by 25 veh/h.

In case $z_2 = 0.6$ s, the relation between the capacity and the fraction of equipped vehicles is clearly non-linear. It turns out that the following polynomial relation expresses adequately the relation between the capacity $C$ and the fraction of equipped vehicles $p$ ($R^2 = 1.00$):

$$C(p) = 2106 + 597p - 240p^2 \text{ where } 0 \leq p \leq 1$$

(4-2)

This result is clearly different from the lane drop from 3 to 2 lanes. Moreover, if we consider the other estimates (depicted in Table 4-1), it turns out that the critical speed does not increase substantially with increasing AICC penetration rate.
Figure 4-1 On-ramp scenario (2+1) for different AICC penetration rates.

<table>
<thead>
<tr>
<th>Penetration</th>
<th>z1 = 0.8 s</th>
<th>z1 = 0.6 s</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>E(C)</td>
<td>var(C)</td>
</tr>
<tr>
<td>0%</td>
<td>2110</td>
<td>0.00%</td>
</tr>
<tr>
<td>5%</td>
<td>2118</td>
<td>0.36%</td>
</tr>
<tr>
<td>10%</td>
<td>2130</td>
<td>0.92%</td>
</tr>
<tr>
<td>25%</td>
<td>2178</td>
<td>3.22%</td>
</tr>
<tr>
<td>50%</td>
<td>2243</td>
<td>6.30%</td>
</tr>
<tr>
<td>100%</td>
<td>2356</td>
<td>11.66%</td>
</tr>
</tbody>
</table>

Table 4-1 Simulation results for 2+1 on-ramp scenario and different car-following controllers.

We have again determined expressions describing changes in the critical speed. In this case, it turns out that the critical speeds are statistically independent on the penetration rate. In other words, for both AICC control regimes, the average critical speed for all penetration rates can be considered (i.e. $V_{crit} = 81.5$ and $79.3$ km/h for the respective headway settings).

4.1.2 Bottleneck capacity for 3+1 on-ramp scenarios

Figure 4-2 depicts the bottleneck capacity for different AICC penetration rates for the 3+1 on-ramp scenario. It turns out that the capacity increases monotonically with increasing AICC penetration, for all AICC gap-distance control settings (similar to the 2+1 on-ramp scenario). This result is clearly different from the lane drop from 4 to 3 lanes. Moreover, if we consider the other estimates (depicted in Table 4-2), it turns out that the critical speed does not increase substantially with increasing AICC penetration rate.
Figure 4-2 On-ramp scenario (3+1) for different AICC penetration rates.

In this case, we can establish the following relations between the capacity and the penetration rate. For $z_1 = 0.8$ s, the capacity relates approximately to the capacity by the following linear relation ($R^2 = 1.00$):

$$C(p) = 2028 + 232p \quad \text{where } 0 \leq p \leq 1$$

(4-3)

implying that for each additional 10% of AICC equipped vehicles, the capacity per lane increases by 23 veh/h. In case $z_2 = 0.6$ s, the relation between the capacity and the fraction of equipped vehicles is clearly non-linear. It turns out that the following polynomial relation expresses correctly the relation between the capacity and the fraction of equipped vehicles ($R^2 = 0.99$):

$$C(p) = 2022 + 500p - 175p^2 \quad \text{where } 0 \leq p \leq 1$$

(4-4)

<table>
<thead>
<tr>
<th>Penetration</th>
<th>$z_1 = 0.8$ s</th>
<th>$z_1 = 0.6$ s</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>E(C)</td>
<td>% var(C)</td>
</tr>
<tr>
<td>0%</td>
<td>2030</td>
<td>0.00%</td>
</tr>
<tr>
<td>5%</td>
<td>2039</td>
<td>0.43%</td>
</tr>
<tr>
<td>10%</td>
<td>2053</td>
<td>1.15%</td>
</tr>
<tr>
<td>25%</td>
<td>2084</td>
<td>2.66%</td>
</tr>
<tr>
<td>50%</td>
<td>2143</td>
<td>5.55%</td>
</tr>
<tr>
<td>100%</td>
<td>2261</td>
<td>11.36%</td>
</tr>
</tbody>
</table>

Table 4-2 Simulation results for 3+1 on-ramp scenario and different car-following controllers.

Note that from the results depicted in Table 4-2, it can be concluded that the critical speeds are in this case independent on the AICC penetration level, and are on average equal to 77.8 km/h and 78.0 km/h respectively).
4.2 Speed-flow curves

Figure 4-3 shows the speed-flow relations collected at detectors 1 and 2 for 0% and 50% AICC penetration. The figures clearly show that for non-congested traffic flow conditions, the effect of introduction of AICC is not significant. However, for saturated and oversaturated traffic flow conditions, a substantial difference exists between the 0% and 50% penetration rate.

At this point, we note that compared to the 3 to 2 lane drop scenario (see Figure 3-4), the speed within the congested area is below 30 km/hr, implying that drivers within the congested area drive unsupported. This implies that upon leaving the queue at the bottleneck, it will take some time before the driver reactivates the driving support. In turn, this will have a negative effect on the bottleneck capacity. Conversely, the speed of the queuing vehicles in the 2+1 on-ramp scenario (Figure 4-3) is substantially higher, and at least some of the drivers will be supported during queuing, which in turn will have a positive effect on the bottleneck capacity. This difference is one of the factors causing the differences in capacities in for the considered test cases.

Figure 4-3 Speed-flow relation collected at detectors 1 and 2 for 0% and 50% AICC penetration, for the 2+1 on-ramp scenario.

Another important aspect is the influence of driving regulation. In opposition to American driving regulation, European regulation prohibits overtaking on the left for uncongested conditions. This implies that faster drivers will always have to make use of the left lane upon overtaking a slower vehicle. Moreover, the velocity on the left roadway lane provides an upperbound for the speeds on the other lane(s). Since in the lane-drop scenario's, traffic demand on the left lane is relatively high (due to the lane-drop), the speed reduces on both the left and the right lane. Moreover, drivers on the right lane cannot accelerate and reduce their time headway, due to traffic regulation.
Figure 4-4 Speed-flow relation collected at detectors 1 and 2 for 0% and 50% AICC penetration, for the 3+1 on-ramp scenario.

Similar results hold for the 3+1 on-ramp scenario. Figure 4-4 shows the speed-flow relations for 0% and 50% AICC penetration rates for detectors 1 and 2 respectively. Clearly, uncongested branch of the speed-flow relation is independent of the presence of AICC supported drivers. However, the changes in capacity are clear, as are the congested branch of the speed-flow curve. Again, note the difference in the within queue speed for the 4 to 3 lane drop scenario (see Figure 3-5) and the 3+1 on-ramp scenario.

Similar to the lane-drop scenarios, observe that AICC has no impact on the free-speed $V_0$ of the drivers, for neither of the lane-drop scenarios.

4.3 Impacts on bottleneck reliability

The results in Table 4-1 and Table 4-2 show how the variability of the bottleneck capacity increases, at increasing AICC penetration levels. This pertains mainly to the $z_I = 0.6$ s headway settings. As a consequence, it is expected that in case of on-ramps and small headway settings, the bottlenecks reliability is reduced due to AICC supported driving.

4.4 Time-to-Collision distribution

Similar to the lane-drop scenarios, we have also considered the distributions of the TTC values for different AICC penetration levels and headway settings.

4.4.1 TTC cumulative exposure times for headway setting A

Figure 4-5, Figure 4-6, and Figure 4-7 respectively show the exposure time distribution on the right, middle, and left motorway lane (i.e. the on-ramp).
Figure 4-5 Exposure time distribution for 2 + 1 on-ramp scenario at the 0% AICC penetration level for $z_1 = 0.8$ s.

Figure 4-6 Exposure time distribution for 2 + 1 on-ramp scenario at the 25% AICC penetration level for $z_1 = 0.8$ s.

Figure 4-7 Exposure time distribution for 2 + 1 on-ramp scenario at the 100% AICC penetration level for $z_1 = 0.8$ s.
Table 4-3 shows the impact of different levels of AICC penetration on the safety-critical and uncomfortable exposure times smaller than 1.5 and 3.0 seconds respectively, for $z_1 = 0.8 \text{s}$. 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 changes 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 4-3 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.

### Table 4-3 Impact of AICC ($z_1 = 0.8 \text{s}$) on TTC distribution for 2 + 1 on-ramp scenario. The right lane is the on-ramp.

<table>
<thead>
<tr>
<th>Penetration</th>
<th>0%</th>
<th>25%</th>
<th>100%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lane</td>
<td>left</td>
<td>middle</td>
<td>right</td>
</tr>
<tr>
<td>TTC &lt; 1.5</td>
<td>0.0</td>
<td>3.0</td>
<td>8.2</td>
</tr>
<tr>
<td></td>
<td>11.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TTC &lt; 3.0</td>
<td>0.5</td>
<td>9.8</td>
<td>11.2</td>
</tr>
<tr>
<td></td>
<td>21.4</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**4.4.2 TTC cumulative exposure times for headway setting B**

The same experiment was carried out for the headway setting $z_1 = 0.6 \text{s}$ (see Figure 4-8, Figure 4-9, and Table 4-4). Similar results are obtained in this case. That is, at the 25% AICC penetration level, increases in the number of safety-critical TTC’s are observed on the right motorway lane. However, compared to the case $z_1 = 0.8$, the increase is less profound.
For full AICC penetration, Table 4-4 shows that the frequency at which safety critical TTC's occur in the on-ramp case reduce substantially with respect to both 0% and 25% AICC penetration (compare to Table 4-3). Clearly, this does not hold for those TTC values that are considered uncomfortable, since there monotonically increase with increasing AICC penetration level.

Table 4-4 Impact of AICC ($z_1 = 0.6$ s) on TTC distribution for 2 + 1 on-ramp scenario.

<table>
<thead>
<tr>
<th>Penetration</th>
<th>0%</th>
<th>25%</th>
<th>100%</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>left</td>
<td>middle</td>
<td>right</td>
</tr>
<tr>
<td>TTC &lt; 1.5</td>
<td>0.0</td>
<td>3.0</td>
<td>8.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>11.3</td>
<td></td>
</tr>
<tr>
<td>TTC &lt; 3.0</td>
<td>0.5</td>
<td>9.8</td>
<td>11.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>21.4</td>
<td></td>
</tr>
</tbody>
</table>
4.5 Differences in lane-utilization for lane-drop and on-ramp scenarios

The differences in the capacities of the lane-drop and on-ramp scenario’s are partially caused by the differences in lane-utilization induced by the respective bottleneck geometries. The lane-drop causes oversaturation on the median lane, which in turn causes underutilization of the middle and shoulder lanes (see Figure 4-10). In the on-ramp case (see Figure 4-11), the utilization of the shoulder lane is better.

Figure 4-10 Lane use for 100% AICC penetration for lane drop from 4 to 3 lanes, collected at the downstream detector location 1.

Figure 4-11 Lane use for 100% AICC penetration for on-ramp 3+1 scenario, collected at the downstream detector location 1.

4.6 Capacity distribution and maximum on-ramp flows

To ensure the correct description of congestion propagation though the transportation network, it is important to know how the capacity is distributed over the main road and the on-ramp, and what the effect of AICC is on this distribution. To study this, we have considered the lane-flow upstream the on-ramps (detectors 2) for both the
2 + 1 and the 3 + 1 on-ramp scenarios in case congestion has set in (speeds at detector 2 below 70 km/h) for different AICC control settings.

Figure 4-12 shows the maximum lane flow-rates observed at the upstream detector 2, during congested conditions, for different AICC penetration levels, with $z_1 = 0.8$ s. Clearly, while the capacity of the bottleneck increases with increasing AICC penetration level, so does the maximum on-ramp flow rate (for this specific configuration). It turns out that the relative increase in the maximum on-ramp flow is constant, amounting to approximately 31% of the bottleneck capacity.

Figure 4-13 shows the same results for $z_1 = 0.6$ s. The same can be concluded as for the $z_1 = 0.8$ s case, namely that while the bottleneck capacity increases, so does the maximum on-ramp flow during congestion. Also in this case, the maximum on-ramp flow amounts to approximately 31% of the bottleneck capacity.

For the 3 + 1 bottleneck scenarios, the lane-specific maximum flow-rates show similar results (figures are not shown). For both $z_1 = 0.8$ s, and $z_1 = 0.6$ s, the maximum on-ramp flow rates during congestion amount to approximately 24% of the bottleneck capacity.

Figure 4-12 Maximum flow-rates during congestion collected at upstream detector 2 for 2 + 1 on-ramp scenario and $z_1 = 0.8$ s.
4.7 Summary

Summarising, for the on-ramp scenarios it can be concluded that AICC generally improves the bottleneck capacity. On the contrary to the lane-drop scenarios, capacity is a monotonically increasing function of the AICC penetration. The speed at capacity does not depend on the level of AICC penetration, irrespective of the considered AICC headway settings. For headway settings $z_1 = 0.6$ s, bottleneck reliability tends to deteriorate with increasing AICC penetration levels. This does not hold for headway setting $z_1 = 0.8$ s. As is expected, the free-speeds of traffic is not influenced by the introduction of AICC.

Based on studying the cumulative exposure times to both safety-critical and uncomfortable TTC values, the (subjective) safety of the traffic flow tends to decrease substantially, reaching its minimum at 50% AICC penetration. This high exposure values are observed mainly on the middle roadway lane, where traffic from the on-ramp merges with traffic on the main-road. For full AICC penetration, subjective traffic safety tends to recover.

The simulation experiments show that AICC has little or no influence on the merging behaviour of traffic merging from the on-ramp to the main road. It turns out that irrespective of the AICC penetration level, the fraction of the bottleneck capacity taken up by traffic from the on-ramp is constant for all penetration levels.
5 Results for lane-drop scenarios with ISA

In the preceding chapters 3 and 4, we have considered the impact of AICC on traffic flow operations, safety, and driving comfort. In chapters 5 and 6, both the lane-drop and on-ramp scenarios are considered for ISA supported driving. In this chapter, we will discuss both the impacts of ISA on traffic flow conditions and safety that can be observed from the simulation experiments for the lane-drop scenarios for different ISA speed limit regimes.

5.1 ISA impacts on capacity

Let us first consider the impact of ISA on the lane-drop capacities and the speeds at capacities for both regime A and B.

5.1.1 ISA capacity impact for 3 to 2 lane-drop

Figure 5-1 and Table 5-1 show the capacity estimates for different ISA penetration rates for both regimes A and B for the 3 to 2 lane drop scenarios. For the sake of comparison, the figure also shows the capacities for the AICC scenarios. Note that in case of ISA, the capacity is nearly unaffected. The small changes in the capacity value fall well within the range of statistical inaccuracies, as can be seen from the small values of $R^2$, respectively equal to 0.01 and 0.29. In other words, for neither regime A nor B, ISA has a significant influence on the bottleneck capacity, yielding average capacity estimates of 1924 veh/lane/h and 1919 veh/lane/h respectively.

![Figure 5-1 Capacity estimates for ISA in case of 3 to 2 lane drop scenario.](image)

Table 5-1 shows that in this case, ISA has no significant impact on the critical speed as well. For regime A and B the average critical speeds are equal to 85.0 and 87.0 respectively.
5.1.2 ISA capacity impact for 4 to 3 lane-drop

Figure 5-2 shows the results of the simulation experiments for the 4 to 3 lane-drop scenario with different levels of ISA penetration (see also Table 5-1 and Table 5-2).
For regime A, the influence of ISA on the capacity could not be established for a reasonable confidence level. For regime B however, ISA appears to have a small negative effect on the roadway capacity. This effect can be expressed by the following linear relation ($R^2 = 0.8$)

$$C(p) = 1774 - 11p \text{ where } 0 \leq p \leq 1$$  \hspace{1cm} (5-1)

The negligible effect of ISA on roadway capacity is not surprising. To understand this, recall that the capacity is by definition equal to the queue discharge rate. That is, the capacity is determined by measuring the rate at which vehicles flow out of the upstream queue. In the queue, speed are very small (below 70 km/h), and ISA has no effect. Downstream of the bottleneck, ISA is not active as well, since these locations lie beyond the controlled area.

For the lane-drop scenarios, ISA has no substantial negative effect either. Keeping in mind that ISA was not developed to increase roadway capacity, but rather to improve traffic safety, the fact that a capacity reduction is not observed is encouraging.

With respect to the critical speeds, it can again be shown that the impact of ISA is not significant. For the 4 to 3 lane-drop scenarios, the average critical speeds are equal to 91.1 km/h and 91.3 for regimes A and B respectively.

5.2 ISA and speed-flow relations

Figure 5-3 and Figure 5-4 respectively show the speed-flow relations for ISA-speed regimes A and B. The figure shows clearly how ISA effects the speeds at the free-flow branch of the speed-flow curve. Note that the congested branch of the speed-flow curve is not affected by ISA at all.

Figure 5-3 Speed-flow relation collected at detectors 1 and 2 for 0% and 50% ISA penetration for the 3 to 2 lane-drop scenario, for regime A.

Figure 5-4 shows the same relation for regime B. For this regime, the same conclusions can be drawn as for regime A: the free-flow branch of the speed-flow curve changes as expected, while the congested branch does not substantially change.
5.3 Bottleneck reliability

From the capacity standard deviations in Table 5-1 and Table 5-2, it is observed that in most cases, ISA has no considerable effect on the reliability of the bottleneck. Only for regime B in case of the 4 to 3 lane drop scenario, an increase in the bottleneck reliability is found.

5.4 Headway distribution

To analyze the impacts on traffic safety, among other things, the headway distribution can be studied. However, for neither regime A nor B, a significant change in the headway distribution could be observed. In illustration, Table 5-3 and Table 5-4 show the changes in the headway distribution for different ISA penetration levels for regimes A and B respectively.

Figure 5-4 Speed-flow relation collected at detectors 1 and 2 for 0% and 50% ISA penetration for the 3 to 2 lane-drop scenario, for regime B.

On the contrary to the AICC cases, ISA has a substantial effect of the average free-speed of the traffic flow. It turns out that the free-speed varies linearly between the free-speed of traffic without ISA (but nevertheless considering the impact of the speed-limits) and the prevailing speed limit in case of full ISA penetration.
Table 5-3 Impact of ISA (regime A) on headway distribution at detector 2.

<table>
<thead>
<tr>
<th>Penetration</th>
<th>Lane</th>
<th>0%</th>
<th>25%</th>
<th>100%</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>left</td>
<td>middle</td>
<td>right</td>
<td>left</td>
</tr>
<tr>
<td>headway &lt; 1.5</td>
<td>0.2</td>
<td>0.1</td>
<td>0.0</td>
<td>0.2</td>
</tr>
<tr>
<td></td>
<td>0.4</td>
<td></td>
<td></td>
<td>0.4</td>
</tr>
<tr>
<td>headway &lt; 3.0</td>
<td>0.9</td>
<td>0.8</td>
<td>0.7</td>
<td>2.5</td>
</tr>
</tbody>
</table>

Table 5-4 Impact of ISA (regime B) on headway distribution at detector 2.

<table>
<thead>
<tr>
<th>Penetration</th>
<th>Lane</th>
<th>0%</th>
<th>25%</th>
<th>100%</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>left</td>
<td>middle</td>
<td>right</td>
<td>left</td>
</tr>
<tr>
<td>headway &lt; 1.5</td>
<td>0.2</td>
<td>0.1</td>
<td>0.1</td>
<td>0.2</td>
</tr>
<tr>
<td></td>
<td>0.4</td>
<td></td>
<td></td>
<td>0.4</td>
</tr>
<tr>
<td>headway &lt; 3.0</td>
<td>0.9</td>
<td>0.8</td>
<td>0.7</td>
<td>2.5</td>
</tr>
</tbody>
</table>

The small influence of ISA on the headway distribution (at both detectors) is observed for all regimes and all scenarios. This is why for the remainder of this report, the headway distribution is not considered further for ISA controlled vehicles.

5.5 Time-to-Collision and subjective safety

To analyse the safety and driving comfort impacts, we can again consider the TTC-distribution for different penetration rates, for the different lane-drop scenarios, and ISA control regimes (A and B).

5.5.1 TTC exposure times for 3 to 2 lane drop scenario with ISA regime A

Table 5-5 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 adapt 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.

Finally, note that the non-equipped vehicle also adapt the speed choice behaviour to the prevailing speed-limits. Compared to the results in Table 3-3 (for 0% penetration), the fraction of safety-critical TTC values is not reduced.
Table 5-5 Impact of ISA (regime A) on TTC distribution.

<table>
<thead>
<tr>
<th>Penetration</th>
<th>0%</th>
<th>25%</th>
<th>100%</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>left</td>
<td>middle</td>
<td>right</td>
</tr>
<tr>
<td>TTC &lt; 1.5</td>
<td>0.3</td>
<td>2.6</td>
<td>11.3</td>
</tr>
<tr>
<td></td>
<td>14.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TTC &lt; 3.0</td>
<td>3.2</td>
<td>10.1</td>
<td>22.5</td>
</tr>
<tr>
<td></td>
<td>35.7</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

5.5.2 TTC exposure times for 3 to 2 lane drop scenario with ISA regime B

Table 5-6 depicts the results for regime B. In this case, 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.

Table 5-6 Impact of ISA (regime B) on TTC distribution.

<table>
<thead>
<tr>
<th>Penetration</th>
<th>0%</th>
<th>25%</th>
<th>100%</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>left</td>
<td>middle</td>
<td>right</td>
</tr>
<tr>
<td>TTC &lt; 1.5</td>
<td>0.2</td>
<td>2.0</td>
<td>13.1</td>
</tr>
<tr>
<td></td>
<td>15.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TTC &lt; 3.0</td>
<td>3.7</td>
<td>10.0</td>
<td>24.7</td>
</tr>
<tr>
<td></td>
<td>38.4</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

5.6 Summary

Summarising, for the lane-drop scenarios we can conclude that ISA generally has a negligible effect on the capacity of the bottleneck. This holds equally for the reliability of the bottleneck, and the speed at capacity. However, the free speeds are linearly dependent on the ISA penetration level. The range from the free speed of unequipped drivers (at zero penetration), to the prevailing speed-limit (for full ISA penetration).

Based on studying the cumulative exposure times to both safety-critical and uncomfortable TTC values, the (subjective) safety of the traffic flow tends to increase slightly for regime B. This holds equally for driver-comfort.
6 Results for on-ramp scenarios with ISA

In this chapter, let us consider the impacts of ISA supported driving for the on-ramp scenarios. Similar to the lane-drop cases, we will consider the impacts on roadway capacity, (critical) headways, and TTC’s.

6.1 Impact of ISA on on-ramp capacity

Let us first consider the capacity of the bottleneck caused by the on-ramp. Figure 6-1 shows the impact of ISA for different penetration rates, for both regimes A as well as B for the 2+1 on-ramp case. From the figure it appears that for regime A, no substation reduction in the capacity results from introducing ISA supported vehicles in the flow ($R^2 = 0.05$). However, for regime B a significant drop in the lane capacity results. It turns out that the capacity reduces with approximately 3 veh/h for each additional 10% ISA support, i.e. the capacity $C$ relates to the fraction of ISA controlled vehicles $p$ according to the following linear relation ($R^2 = 0.64$).

$$C(p) = 2109 + 251p \quad \text{where } 0 \leq p \leq 1$$  \hspace{1cm} (6-1)

For regime A, the critical speeds are also statistically independent of the ISA penetration level, and is approximately equal to 81 km/h. For regime B, the critical speed depends on the penetration rate $p$ according to the following expression ($R^2 = 0.62$):

$$V_{cen}(p) = 81.4 - 1.3p \quad \text{where } 0 \leq p \leq 1$$  \hspace{1cm} (6-2)
Table 6-1 Simulation results for lane drop scenario and different ISA speed regimes, for the 2 + 1 on-ramp scenarios (regime A and B).

Similar results are observed when we consider the 3+1 on-ramp scenario (Figure 6-2). No (significant) changes in the capacity are observed for speed regime A ($R^2 = 0.41$), while for speed regime B the capacity drops substantially (approximately with 2.5 veh/h for each 10% additional ISA support). The following second-order expression provides an adequate fit with the simulation results ($R^2 = 0.89$)

$$C(p) = 2000 - 68p + 43p^2$$

where $0 \leq p \leq 1$ (6-3)

Figure 6-2 Lane-capacities for the 3+1 on-ramp scenario for ISA regimes A and B.

Table 6-2 Simulation results for lane drop scenario and different ISA speed regimes, for the 3 + 1 on-ramp scenarios (regime A and B).
6.2 Impact on speed-density relations

Let us also consider the relation between speed and flow, and the changes that are incurred by ISA for the on-ramp situations.

Figure 6-3 Speed-flow relation collected at detectors 1 and 2 for 0% and 50% ISA penetration for the 2 + 1 on-ramp scenario, for regime A.

Figure 6-4 Speed-flow relation collected at detectors 1 and 2 for 0% and 50% ISA penetration for the 2 + 1 on-ramp scenario, for regime B.

Figure 6-5 and Figure 6-6 show the relations between speed and flow measured on detectors 1 and 2 respectively. The influence of ISA is clearly observable from these relations, especially for the upstream detector 2. Figure 6-5 (regime A) clearly shows how ISA reduces the speeds on the unconstrained branch of the fundamental diagram, to the prevailing speed limits of 90 km/h. Also the 0%-penetration rate yields reduced speeds. These reductions are caused by the model assumption that also unequipped drivers react to the prevailing speed limits, although not to the same extent as the equipped drivers.
Figure 6-6 (regime B) shows similar results. However, due to the low prevailing speed limits upstream of detector 1 and the finite acceleration capabilities of the vehicles, the speed at the downstream detector 1 is also influenced by the prevailing speed limits, and consequently by the level of ISA penetration.

Figure 6-5 Speed-flow relation collected at detectors 1 and 2 for 0% and 50% ISA penetration for the 3 + 1 on-ramp scenario, for regime A.

Figure 6-6 Speed-flow relation collected at detectors 1 and 2 for 0% and 50% ISA penetration for the 3 + 1 on-ramp scenario, for regime B.

Also for the on-ramp cases, ISA appears to have a substantial effect on the average free-speed of the traffic flow. It turns out that the free-speed varies linearly between the free-speed of traffic without ISA (but nevertheless considering the impact of the speed-limits) and the prevailing speed limit in case of full ISA penetration.
6.3 **Bottleneck reliability**

From the capacity standard deviations in Table 6-1 and Table 6-2, it is observed that in most cases, ISA has no considerable effect on the reliability of the bottleneck for neither of the on-ramp scenarios.

6.4 **Time-to-Collisions for ISA controlled on-ramp scenarios**

As with the lane-drop scenarios, we have also considered the distribution of the safety-critical TTC values (respectively smaller than 1.5 s and 3.0 s).

6.4.1 **Impacts of TTC distribution for 2+1 scenarios and ISA regime A**

Figure 6-7, Figure 6-8, and Figure 6-9 show the impacts of ISA on the TTC exposure time distribution for ISA (regime A), in case of the 2+1 on-ramp scenario for different penetration levels (0%, 25%, and 100% respectively). The figures show a clear shift in the distribution of small TTC values: while the frequency at which small TTC values on the right lane (i.e. the on-ramp) decrease, the frequency of small TTC values on the middle lane increase substantially. For the on-ramp, no changes in the small TTC's can be observed from the figures.

![TTC Exposure Time Distribution](image)

Figure 6-7 TTC exposure time distribution for 2+1 on-ramp scenario for ISA regime A at 0% penetration.
Considering the results depicted in Table 6-3, the same can be observed. The safety-critical TTC exposure times on the on-ramp increase, while on the middle lane they increase. 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.

<table>
<thead>
<tr>
<th>Penetration</th>
<th>0% Lane</th>
<th>0% shoulder on-ramp</th>
<th>0% median shoulder on-ramp</th>
<th>0% median shoulder on-ramp</th>
<th>0% median shoulder on-ramp</th>
<th>25% Lane</th>
<th>25% shoulder on-ramp</th>
<th>25% median shoulder on-ramp</th>
<th>25% median shoulder on-ramp</th>
<th>25% median shoulder on-ramp</th>
<th>100% Lane</th>
<th>100% shoulder on-ramp</th>
<th>100% median shoulder on-ramp</th>
<th>100% median shoulder on-ramp</th>
<th>100% median shoulder on-ramp</th>
</tr>
</thead>
<tbody>
<tr>
<td>TTC &lt; 1.5</td>
<td>0 0</td>
<td>3.8 8.6</td>
<td>12.4</td>
<td></td>
<td></td>
<td>0.0 12.9</td>
<td>6.7</td>
<td>19.5</td>
<td></td>
<td></td>
<td>0.0 15.8</td>
<td>6.7</td>
<td>22.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TTC &lt; 3.0</td>
<td>0.6</td>
<td>11.6 12.1</td>
<td>24.2</td>
<td>0.3</td>
<td>20.5 9.4</td>
<td>0.6</td>
<td>23.8 10.3</td>
<td>34.7</td>
<td></td>
<td></td>
<td>0.6 23.8</td>
<td>10.3</td>
<td>34.7</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 6-3 Cumulative exposure times of safety-critical Time-to-Collision values for 2 + 1 on-ramp scenarios and different fractions of ISA controlled vehicles for speed-regime A.
6.4.2 Impacts of TTC distribution for 2+1 scenarios and ISA regime B

Table 6-4 shows the simulation results for speed regime B, in case we consider the 2+1 on-ramp scenario. The same results apply that have been observed for regime A: a small improvement on the on-ramp with respect to both safety-critical as well as uncomfortable TTC exposure times, considerable deterioration of both on the shoulder-lane.

<table>
<thead>
<tr>
<th>Penetration</th>
<th>0%</th>
<th>25%</th>
<th>100%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lane</td>
<td>median</td>
<td>shoulder</td>
<td>on-ramp</td>
</tr>
<tr>
<td>TTC &lt; 1.5</td>
<td>0.0</td>
<td>5.3</td>
<td>8.7</td>
</tr>
<tr>
<td>TTC &lt; 3.0</td>
<td>0.2</td>
<td>13.5</td>
<td>12.3</td>
</tr>
</tbody>
</table>

Table 6-4 Cumulative exposure times of safety-critical Time-to-Collision values for 2 + 1 on-ramp scenarios and different fractions of ISA controlled vehicles for speed-regime B.

Assuming that TTC values provide some indication in shifts in (subjective) traffic safety, it would appear that ISA yields no improvement in traffic safety or comfort.

6.5 Capacity distribution and maximum on-ramp flows

To enable macroscopic analysis of the occurrence and propagation of congestion in a traffic network on which ISA equipped vehicles are present, we need to consider how the bottleneck capacity at the on-ramp is distributed with respect to the main road and the on-ramp. In section 4.6, we have considered this distribution for the AICC scenarios. In this section, we will consider the distribution of available capacity for the ISA scenarios.

6.5.1 Capacity distribution for 2 + 1 on-ramp

Figure 6-10 shows the maximum lane-flows that are observed during congested conditions, upstream of the bottleneck, i.e. inside the congestion. The figure shows that the simulation model predicts that during congestion, the highest flows are observed on the left (median) lane. For regime A, these flows are independent on the ISA penetration levels, while remaining at approximately 1600 veh/h. The on-ramp flows are also independent on the fraction of ISA supported vehicles and remain at approximately 1350 veh/h, which is almost 32% of the cross-section bottleneck capacity.
Figure 6-10 Maximum average lane flows observed upstream of bottleneck for different ISA penetration levels (regime A).

Figure 6-11 shows maximum average lane flows within congestion for ISA speed regime B. In section 5.1 we have observed that high levels of ISA equipped vehicles have a negative effect on the cross-section bottleneck capacity. Figure 6-11 shows that this also causes a small reduction in the maximum lane flow at the on-ramp. Nevertheless, the fraction of the cross-section capacity that is used by traffic on the on-ramp is nearly constant, and also pertains to 32%.

Figure 6-11 Maximum average lane flows observed upstream of bottleneck for different ISA penetration levels (regime B).

6.5.2 Capacity distribution for 3+1 on-ramp

Also for the 3+1 on-ramp scenario, the maximum lane flows during congested conditions have been determined. It turns out that for both regimes A and B, the
maximum on-ramp flows amount to approximately 24% of the cross-section bottleneck capacity, independent of the ISA penetration levels. However, for regime B, a small increase in the percentage of the bottleneck capacity used by the on-ramp can be observed, causing the small decrease in bottleneck capacity (see section 6.1) to reduce the maximum flow on the left roadway lane.

6.6 Summary

From these final experiments, we can conclude that for on-ramps, ISA either has no effect on the capacity of the bottleneck (regime A), or has a small negative effect on bottleneck capacity (regime B). With respect to the reliability of the bottleneck, no effect could be established. This holds equally for the speed at capacity. As for the lane-drop scenario, the free-speeds are linearly dependent on the ISA penetration rate.

More surprisingly, the improvements in traffic safety that are generally expected could not be established within the context of this experimental set-up. On the contrary, based on the safety-critical TTC exposure times, a decrease of (subjective) traffic safety is expected. This holds equally for driving comfort.

Finally, the simulation experiments show that ISA has no influence on the merging behaviour of traffic merging from the on-ramp to the main road. It turns out that irrespective of the ISA penetration level, the fraction of the bottleneck capacity taken up by traffic from the on-ramp is constant for all penetration levels.
7 Summary and conclusions

In this report, we have shown the effects of ADAS on traffic flow operations (capacity, speed-flow relations, headway distribution, and time-to-collisions) for different types of bottlenecks. To assess the impact of ADAS on motorway efficiency in general, and in particular with respect to bottleneck capacity, speed flow relations, (subjective) traffic safety, and comfort, for a number of representative bottleneck layouts, ADAS regimes, and penetration levels have been studied.

Both *Autonomous Intelligent Cruise Control* (AICC) and *Intelligent Speed Adaptation* (ISA) systems have been implemented in the microscopic simulation model SIMONE. For both AICC and ISA, four *bottleneck* lay-outs have been considered, namely the 3 to 2 lane-drop, the 4 to 3 lane-drop, the 2 + 1 on-ramp, and finally the 3 + 1 on-ramp. For each scenario, several levels of ADAS penetration (0%, 5%, 10%, 25%, 50%, and full penetration) are considered. Finally, different ADAS control settings are compared. For AICC, different headway settings are considered. For ISA, different speed-limit regimes are compared.

To assess the impact of ADAS on bottleneck efficiency, the bottleneck capacity (defined by the *queue discharge rate*) is considered. Bottleneck reliability is expressed in terms of capacity variability. Furthermore, relations between the flow and the speed, and changes due to ADAS are discussed as well. At this point, let us note that using estimates for the capacity, critical speed, and the jam-density, expressions describing the relation between speed and flow can also be determined. Indirect safety measures, such as time headways and Time-To-Collision (TTC) cumulative exposure times are considered and compared for the different cases, to assess the impacts on driving safety and comfort.

Table 9-1 provides a summary of the microscopic simulation results described in detail in the remainder of this report, depicting the expected impact of ADAS on bottleneck capacity, reliability, safety, and comfort.
### Table 9-1 Overview results ADAS on bottleneck capacity and reliability, safety, and comfort (I: expected impact, P: optimal penetration level).

<table>
<thead>
<tr>
<th>Support type</th>
<th>Scenario</th>
<th>Settings / regime</th>
<th>Capacity I</th>
<th>Reliability I</th>
<th>Safety I</th>
<th>Comfort I</th>
<th>Capacity P</th>
<th>Reliability P</th>
<th>Safety P</th>
<th>Comfort P</th>
</tr>
</thead>
<tbody>
<tr>
<td>AICC</td>
<td>3 to 2</td>
<td>( z_1 = 0.8 )</td>
<td>(+ 50%)</td>
<td>- 0%</td>
<td>+ 100%</td>
<td>- 0%</td>
<td>( z_1 = 0.6 )</td>
<td>(+ 50%)</td>
<td>- 0%</td>
<td>+ 100%</td>
</tr>
<tr>
<td></td>
<td>4 to 3</td>
<td>( z_1 = 0.8 )</td>
<td>(+ 50%)</td>
<td>- 0%</td>
<td>+ 100%</td>
<td>- 0%</td>
<td>( z_1 = 0.6 )</td>
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<td>- 0%</td>
<td>+ 100%</td>
</tr>
<tr>
<td></td>
<td>2 + 1</td>
<td>( z_1 = 0.8 )</td>
<td>(+ 100%)</td>
<td>- 0%</td>
<td>-- 0%</td>
<td>-- 0%</td>
<td>( z_1 = 0.6 )</td>
<td>(+ 100%)</td>
<td>- 0%</td>
<td>-- 0%</td>
</tr>
<tr>
<td></td>
<td>3 + 1</td>
<td>( z_1 = 0.8 )</td>
<td>(+ 100%)</td>
<td>- 0%</td>
<td>-- 0%</td>
<td>-- 0%</td>
<td>( z_1 = 0.6 )</td>
<td>(+ 100%)</td>
<td>- 0%</td>
<td>-- 0%</td>
</tr>
<tr>
<td>ISA</td>
<td>3 to 2</td>
<td>regime A</td>
<td>0 n/a</td>
<td>0 n/a</td>
<td>0 n/a</td>
<td>0 n/a</td>
<td>regime B</td>
<td>0 n/a</td>
<td>+ 50%</td>
<td>+ 100%</td>
</tr>
<tr>
<td></td>
<td>4 to 3</td>
<td>regime A</td>
<td>0 n/a</td>
<td>0 n/a</td>
<td>0 n/a</td>
<td>0 n/a</td>
<td>regime B</td>
<td>0 n/a</td>
<td>+ 50%</td>
<td>+ 100%</td>
</tr>
<tr>
<td></td>
<td>2 + 1</td>
<td>regime A</td>
<td>0 n/a</td>
<td>0 n/a</td>
<td>- 0%</td>
<td>- 0%</td>
<td>regime B</td>
<td>0 n/a</td>
<td>- 0%</td>
<td>- 0%</td>
</tr>
<tr>
<td></td>
<td>3 + 1</td>
<td>regime A</td>
<td>0 n/a</td>
<td>0 n/a</td>
<td>- 0%</td>
<td>- 0%</td>
<td>regime B</td>
<td>0 n/a</td>
<td>- 0%</td>
<td>- 0%</td>
</tr>
</tbody>
</table>

#### 7.1 Expected impacts of AICC

Table 9-1 clearly shows the positive impacts 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 (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.

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.
In general, the impact which AICC has on (subjective) 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.

7.2 Expected impacts of ISA

The impacts of ISA shown in Table S-1 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 Time-To-Collision 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.
References
