Supported Driving: Impacts on Motorway Traffic flow

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Supported Driving: Impacts on Motorway Traffic flow

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door

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civiel ingenieur
geboren te Bussum
Dit proefschrift is goedgekeurd door de promotor:
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_Samenstelling promotiecommissie:_

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This thesis is a result of a Ph. D. study performed from 1995 to 1999 at the Transportation Planning and Traffic Engineering Section of the Faculty of Civil Engineering and Geo Sciences of Delft University of Technology.
PREFACE

Growing car use is one of today’s major problems of economic centres all around the world. The users of the road transportation system in these regions suffer from daily congestion and long travel times, resulting in individual inconvenience and substantial economic losses. It is therefore a great challenge to both policy makers and researchers to seek for solutions which contribute to a more efficient transportation system.

This thesis investigates one of the possible solutions to enhance the traffic flow quality of the road transportation network in the near future. The thesis focusses on the effects that driver support systems may have on capacity and safety of motorway bottlenecks, which largely determine the road network performance. With this analysis, a better understanding of the impacts of driver support systems on traffic flows can be obtained, enabling conclusions about the design of support systems.

The work has been conducted at the Traffic Engineering section of the Civil Engineering Faculty of Delft University of Technology. It was part of the multidisciplinary research program “Automated Vehicle Guidance” initiated by and carried out under the auspices of the TRAIL Research School. This programme was funded by the Beek Commission and involved studies into a variety of aspects of driver task support and replacement. My colleague Marika Hoedemaeker studied the human factors aspects of driver support systems, Vincent Marchau investigated the policy and societal implications, while Kiliaan van Wees investigated the legal aspects of introducing driver support systems. I wish to thank them all for the constructive and stimulating discussions and cooperation I have experienced in the course of performing our challenging joint research.

I also wish to thank my colleagues at the Transportation Planning and Traffic Engineering Section, who provided me with many ideas, insights and stimulating discussions. Finally, I would like to express my thanks to Piet Bovy for his constructive ideas and comments during the different stages of the project and, at the end, on the preliminary drafts of this thesis.

Delft, May 8, 1999

Michiel Minderhoud

Acknowledgement

We thank the Dutch Ministry of Transport, Public Works and Water Management for kindly providing research data of the A2 motorway, enabling calibration of our simulation model.
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CHAPTER 1

INTRODUCTION

This chapter describes background, problem and objectives of the thesis. The subject of study is the question of what impacts introduction of advanced driver support systems may have on traffic flows, specifically on motorways. A short overview of the international context is presented in section 1.1. Section 1.2 continues with the problem description while section 1.3 addresses the objective and research-related questions of the study. Section 1.4 presents the intended scientific contributions of the study. Finally, section 1.5 provides the structure of the thesis.

1.1 Background

Fully automated driving has been an aim of engineers, planners and idealists for decades. During the 1950s, General Motors research engineers conceptualized and developed automobiles with steering and speed controlled by radio controls and mechanical systems (Shladover, 1995). In this period, it was envisioned that fully automated, hands-off, feet-off systems would greatly increase driver comfort.

By the 1960s, automation concepts were being explored not only as a means of enhancing driver comfort and convenience but also with more practical applications such as increasing traffic throughput in mind. At that time, congestion in urban areas fostered this idea in order to solve the growing traffic problems.

A new emphasis emerged in the late 1980s. Although work on fully automated systems continued through the decade, increased attention was being given by the public and private sectors to intelligent and partially automated products and services that supported the driving task. Advances in electronics, sensor and computing technologies generated increased interest in products that might enhance driver perception and driving capabilities. A comprehensive overview of the automated highway system activities that have occurred in the United States can be found in TRB SPECIAL REPORT 253 (1998) and Ioannou (1997).

The term ITS (Intelligent Transportation Systems) has been introduced for a variety of advanced surface transportation technologies that are intended to aid driving, enhance the road capacity and efficiency of motorway networks, and assist transportation agencies in managing transportation facilities (see for example NWAGBOSO, 1997).

In America, the federal funding of ITS research, development and implementation was
regulated by the Intermodal Surface Transportation Efficiency Act (ISTEA) in 1991. The act contained the following sentence: "develop an automated highway and vehicle prototype from which future fully automated intelligent vehicle-highways can be developed." This mandate represented a vision similar to that of the researchers in the 1950s and 1970s who studied an automated highway system application for implementation before the turn of the century. A so-called Automated Highway System (AHS) should accommodate platoon-driving (a traffic operation strategy that accommodates vehicles following each other at extreme small gaps), egress and access facilities to the dedicated lane and reversely, to the conventional motorway. The National Automated Highway System Consortium (NAHSC) was established and started the precursor studies aimed at identifying and understanding potential obstacles to the development and deployment of fully automated highway systems (SHLADOVER, 1996).

The program led to a prototype Automated Highway System with a test track which was in operation in 1997. Meanwhile, the US Department of Transportation changed its emphasis in automated driving research. Still, before the demonstration in San Diego in 1997, the department of transportation had indicated that the consortium’s mission was not well suited to more immediate program goals, so the funding of NAHSC was not prolonged. The department of transportation indicated to give greater attention to the development of nearer-term intelligent vehicle technologies with the potential to attain early safety benefits. Accordingly, the new Intelligent Vehicle Initiative (IVI) program will focus on these support systems warning drivers in unsafe situations or taking over vehicle control to avoid collisions (TRB SPECIAL REPORT 253, 1998).

In Europe, Intelligent Vehicle Highway System (IVHS) programs were performed from the mid-1960s onward. Automatic steering control experiments were conducted in Great Britain by the Road Research Laboratory in the late 1960s (NWAGBOSO, 1997). Longitudinal control system studies took place in Germany and France during the 1970s. The most significant activities in the field of ITS started in the mid 1980s with the DRIVE (Dedicated Road Infrastructure for Vehicle Safety in Europe) programme which was funded by the European Community. The DRIVE programme was followed by DRIVE II and III and is still ongoing. A main focus of the programmes has been infrastructure-oriented IVHS research including developing and carrying out pilot projects and demonstrations. Also, some effort on collision avoidance systems has been made.

Another program closer to fully automated driving was PROMETHEUS (Program for European Traffic and Highest Efficiency and Unprecedented Safety), a program initiated by the motor vehicle industry and funded by the European Commission within the framework of the EUREKA program. Despite the extensive and well-funded IVHS activities in Europe, the AHS activities are focussed on near-term implementations, such as intelligent cruise control and other driver assistance functions.

The magnitude of AHS research in Japan is comparable to that in Europe focussing also mainly on driver assistance systems, see e.g. NWAGBOSO (1997) and IOANNOU (1997). Automobile companies have been pursuing their own research on near-term applications, such as intelligent cruise control and collision warning systems.

In conclusion, fully automated driving has been a research topic for decades, but due to developments in the automotive industry the focus has changed to automated systems that partially replace the driver’s tasks. The gradual development and deployment of these driver support systems can be seen, at this moment, as the most realistic path towards fully
Chapter 1 - Introduction

automated driving. Expert opinions are in line with this view, see MARCHAU et al. (1998). Early safety and capacity benefits are hypothesised, although existing studies give little evidence of realizing these desired impacts.

1.2 Problem description

The main issue we intend to deal with in this thesis is that of supported driving, with its consequences on traffic flows. First, the framework from which this study originated is described (section 1.2.1) followed by the definition of the problem (section 1.2.2). We confine ourselves to traffic flows on motorways. To this end, some characteristics of motorway systems and developments in their use are described in section 1.2.3.

1.2.1 Framework of the study

Although in the past already much attention have been given to automated highway systems and driver support systems (see section 1.1), hypothesised advantages have still not been quantified and assessed satisfactorily. For example, it is still uncertain what the impacts on traffic flow throughput will be on a motorway network scale (this is shown in Chapter 5 with a review of the state of the art of research on traffic flow impacts), how support systems will affect road safety, how drivers will react to their changed driving task, and if driver convenience and comfort will increase. Furthermore, the legal aspects and role of the infrastructure supplier are unclear.

These uncertainties have led to the establishment of the multidisciplinary research program "Technology Assessment Automated Vehicle Guidance" by the Delft/Rotterdam Research School on Transport, Infrastructure and Logistics (TRAIL). The central research goal of the program is to increase the knowledge about future developments and impacts of AVG technologies, in order to reduce uncertainty for policy makers and support strategy development. The programme started in 1994 with funds received from the University Research Fund for a series of proposed PhD projects. A number of projects tackle the issue of AVG from different angles.

One project focusses on plausible future technological developments in the field of AVG as well as on the identification of necessary societal and political conditions for these developments (see e.g. MARCHAU et al., 1998). Another project deals with the man-machine interaction in the context of automation of driver tasks (see e.g. HOEDEMAEKER, 1997, 1999). A third project deals with the legal aspects of AVG technology implementation (see VAN WEES, 1997). The underlying thesis is a condensation of a fourth project of this programme which deals specifically with traffic flow impacts.

Related programs of the TRAIL Research School in the field of automated transportation systems include automated container transport in the harbor of Rotterdam (programme name SMAGIC, Smarter Automatic Guidance for Transport to Increase Capacity, see DE GRAAFF, 1997), on automated freight transport (programme name FTAM, Freight Transport Automation and Multimodality), and on underground automated transport of freight in the Schiphol area (project name OLS, see VERBRAECK et al., 1998). The next section outlines the problem definition and the research approach of the underlying thesis, which focusses specifically on motorway traffic flow impact analysis of advanced driver support systems.
1.2.2 Problem outline

It is generally expected that around the year 2000 most car manufacturers will launch advanced driver support systems on the public market that partially replace the driving task. Probably the first manufacturer in Europe who will include an AICC (Autonomous Intelligent Cruise Control) support system in its most expensive model is Mercedes-Benz (AUTOWeb, 1998). In Japan, longitudinal driver support systems have already being sold from 1995 on by several car manufacturers. The use of such longitudinal driver support systems may affect driver behaviour significantly since such systems actively support the longitudinal driving task, i.e., will automatically adapt driving speed and gap distance in order to follow a vehicle at a safe distance or approach a vehicle with an acceptable speed difference. It is claimed that such systems may increase road capacity, improve road safety, and contribute to enhanced travel convenience and travel comfort. These claims are not self-evident, even the reverse is conceivable. These potentially important consequences stimulated to investigate the hypotheses of an improved road capacity and safety with widespread availability of intelligent driver support systems. In studying these hypotheses, we will focus on the capacity impacts for motorways, since:

- the first generation systems are especially designed for motorway traffic conditions;
- motorway traffic flow processes are not too complex, so that motorways are a suitable road type to start investigating the impacts.

In addition, capacity improvements on motorways are relevant to society, since:

- there is much congestion on motorways (especially in large conurbations), as will be shown is section 1.2.3;
- physical capacity expansions are expensive and often not desirable;
- motorways carry a large proportion of all vehicle-kilometres driven (in the Netherlands about 40% of all veh-km).

Safety is not a great problem on motorways. Motorways are relatively the safest roads. Nonetheless, with the introduction of a driver support system we need to analyse the impacts on motorway safety. Although safety improvement is expected, driver support systems could lead to safety deterioration of motorways.

The capacity of a motorway network is determined by the weakest facilities in such a network. These weak points are discontinuities, or so-called bottlenecks such as on-ramps, off-ramps, and weaving sections. Our study will therefore focus on the capacity and safety impacts of motorway bottlenecks assuming the deployment of driver support systems in the traffic flow. Important research issues that will be dealt with in this study are:

- description and analysis of driver behaviour, driving tasks, and driving task execution;
- the impact of a driver support system on driver behaviour and driving task execution;
- definition of capacity and the impact of driver support systems on capacity;
- capacity and safety impact assessment methods;
- categorisation of driver support systems, and identification of system design variables;
- modelling driver behaviour and driver support system handling;
- formulation and carrying out simulation experiments;
- analyses of simulation outcomes and interpretation of the differences.

Because our study focusses especially on motorways, some general characteristics and statistics about motorway networks are described in the following subsection.
1.2.3 Characteristics and statistics of motorways

Motorway is a road type which is usually characterised by the following functional requirements:
- no level crossings;
- facilitating high travel speeds (mostly above 100 km/h);
- separated travel directions.

Motorway design therefore includes:
- traffic directions divided by a physical or natural barrier;
- multiple lanes per direction;
- hard shoulder along the far right lane, in each direction;
- uniformity in design of exit and entry facilities to and from the motorway;
- right of way for vehicles on main line.

The capacity of motorways is much higher than that of undivided roadways since high speeds can be achieved, vehicles can pass slower vehicles easily, and crossings are not present. The capacity of motorways can reach more than ten times the capacity of an ordinary two-lane road. The latter is often considered to be saturated at about 10,000 vehicles per day, whereas 2x2-lane motorways can carry about 50,000 vehicles per day. But there are differences between countries. For example, in the Netherlands the capacity of a two-lane motorway is about 4400 vehicles/hour, while in Germany 3500 vehicles/hour is a generally found value (see e.g. MINDERHOUD, 1996a). The unrestricted speed limit in Germany is probably the explanatory factor for this difference (HALL et al., 1994).

In Europe, motorways only cover a small proportion of the total road length. The total motorway length in Europe (which doubled over the period between 1975 and 1995) is about 51000 km. This is 1.3% of the total road network length (PETERSEN, 1998).

Table 1.1 provides some statistics on network availability and congestion for some developed countries in Europe, and also those for the USA and Japan (BOVY, 1996, 1997).

<table>
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<th></th>
<th>Road network (km/1000 inh)</th>
<th>Motorways (km/million inh)</th>
<th>Congestion² (% of links)</th>
<th>Performance³ (% of total veh-km)</th>
</tr>
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<tr>
<td>Belgium</td>
<td>12.9</td>
<td>169</td>
<td>5.9</td>
<td>31</td>
</tr>
<tr>
<td>Denmark</td>
<td>13.7</td>
<td>127</td>
<td>0</td>
<td>n.a.</td>
</tr>
<tr>
<td>France</td>
<td>15.8</td>
<td>129</td>
<td>4.5</td>
<td>26</td>
</tr>
<tr>
<td>Germany</td>
<td>7.6</td>
<td>136</td>
<td>7.9</td>
<td>31</td>
</tr>
<tr>
<td>Netherlands</td>
<td>6.1</td>
<td>141</td>
<td>14.8</td>
<td>37</td>
</tr>
<tr>
<td>United Kingdom</td>
<td>6.2</td>
<td>56</td>
<td>24.1</td>
<td>16</td>
</tr>
<tr>
<td>USA¹</td>
<td>14.5</td>
<td>331</td>
<td>n.a.</td>
<td>28</td>
</tr>
<tr>
<td>Japan</td>
<td>6.2</td>
<td>45 ¹</td>
<td>n.a.</td>
<td>n.a.</td>
</tr>
</tbody>
</table>

**TABLE 1.1** Road and traffic congestion parameters in different countries (n.a. = not available)

¹ Data of roadway network USA includes the interstate system plus the urban freeways from 1994
² The congestion indicator represents the percentage of motorway links with more than one hour congestion per day (Bukold, 1997).
³ The motorway performance indicator represents the proportion of total veh-km driven in 1995 (Brühning, 1997).
⁴ Data from 1996
The data in table 1.1 demonstrates that the availability of road infrastructure per capita differs by more than 100 percent. Of the countries shown, the motorway length per million inhabitants is lowest in the United Kingdom (third column). The level of congestion shown in the fourth column clearly appears to be related to the road network available. The last column in table 1.1 gives the performance of motorway networks for certain selected countries expressed as a percentage of the total road network performance.

Despite the large capacity of motorways, congestion problems are present predominant on (urban and suburban) motorways. Looking at the number and proportion of congested links, striking differences appear between European countries (Bovy et al., 1997). Exceptionally high proportions of congested links are found in Spain and the UK. The Netherlands and Italy also have comparatively high proportions of links with severe bottlenecks. The European road bottleneck problem is mainly an urban problem rather than a problem for long-distance connections or cross-border links.

The last finding has consequences for the application of driver support systems, or in a later phase, the application of fully automated vehicle guidance systems. Driver support systems aimed at improving capacity should increase capacity not only at uniform motorway sections in low density regions, but also at motorway discontinuities in high density conurbations. Since short-distance traffic is predominantly present on motorways in heavily populated areas, the number of lane-change manoeuvres to enter and exit the motorway is quite large. To what extent longitudinal driver support systems can improve the traffic processes near bottlenecks, and consequently the bottleneck capacity, is therefore an essential question to be investigated.

Fully automated vehicle guidance systems are also an option for improving motorway capacity, safety and driver convenience. Much research has been conducted on this subject, prototypes have been tested which have shown the technological feasibility of the concept. However, research has been concentrated predominantly on uniform segments without merging vehicles. Although large capacity benefits on such lanes are expected when vehicles drive in platoons, the negative impacts of merging processes on lane capacity appear considerable (Castillo et al., 1997). This especially holds for application of the AHS concept in conurbations with many on and off-ramps. The possibility to achieve large capacity gains on automated lanes by applying the AHS-concept (Shehadeh, 1997) in conurbations such as the Randstad area in the Netherlands, the Ruhr area in Germany, or the Flanders area in Belgium, is therefore debatable. Additionally, a transition lane to enter or leave the AHS may be necessary along almost the complete AHS-lane length in conurbations due to the high number of entry and exit points at relatively small distances. The AHS concept will not be investigated in this study, among other things, since AHS implementation will require large investments in physical infrastructure, as well as in communication infrastructure.

The motorway network in the Netherlands is quite special, compared to other European motorway networks. Since we will use some data from the Dutch motorway system to calibrate our simulation model, some attention is given to these special characteristics (see the text box).
Chapter 1 - Introduction

The Dutch motorway network covers 2% of the total road length - which is the highest percentage in Europe - while it is responsible for about 37% of all driven vehicle kilometres (see table 1.1). In addition, the Dutch motorway network is one of the safest systems in the world (BRÜNING, 1997). The motorway system connects the 40 most important economic centres of the country with detour factors of less than 1.4. The total length of the Dutch motorway network was 2223 km in 1997. Today, there are about 250 access points which imply an average distance between entry and exit points of about 8 km, which reduces to only 4 km in the Randstad region.

The congestion on the motorways is a daily returning problem in developed conurbations. In the Netherlands, about 15 locations show recurrent queue building, and about 50 queues are reported for an average workday (with about 200 km queue length). About 75% of all jams are of a recurrent structural nature (e.g., near a bridge, tunnel, on-ramp, off-ramp, weaving section), the remaining 25% being due to accidents and other incidental causes (see e.g., BOY, 1996). The direct costs of the delays in 1995 have been estimated at approximately 1.5 billion guilders.

Our study investigates the possibilities of relieving the recurrent congestion problems on motorways using driving task automation.

1.3 Objectives of research

The objective of the study is to quantify and assess the potential improvements (or deteriorations) of the traffic flow near bottleneck motorway sections given a number of conditions, such as the proportion of the vehicle fleet equipped with specific longitudinal driver assistance systems. One of the intended results of the investigation is a quantified overview of the potential capacity improvements with longitudinal driver support systems.

To this end a theory will be specified and transformed into an operational model that describes the behaviour of the individual driver with and without support systems in motorway traffic flow conditions. Simulation experiments will be conducted to assess the traffic flow impacts of driver support systems. The motivation using a longitudinal driver support system in the simulation experiments follows from a literature survey and assessment of possible driver support system functionalities.

In order to carry out the simulations properly, and to achieve the objective of the study, a number of related research topics are studied, namely:

- description of driver behaviour and driving task execution in general, and at motorway discontinuities in particular;
- identification of design variables of longitudinal driver support systems;
- analysis of longitudinal driver support system operation and driver interaction;
- selection of relevant system designs for simulation experiment.

With respect to the driver support system to be investigated, the so-called Adaptive or Autonomous Intelligent Cruise Control (referred to as AICC further on), many questions emerge regarding relationships between design choices, parameter settings and motorway capacity. Within the scope of the study, the focus is on the following relationships:

- impact of headway setting of AICC on motorway capacity, stability and safety;
- impact of other AICC design parameters such as minimum deceleration level, minimum speed, and manual/automatic reactivation of the system on motorway capacity, stability and safety;
- impact of proportion of the vehicle fleet equipped with AICC.
An experimental microscopic simulation approach has been followed to study the indicated relationships satisfactorily, with a view to drawing conclusions about the influence of these design aspects. To this end, a dedicated microscopic traffic simulation model will be developed, implemented, calibrated and applied. The SIMONE (Simulation model for Motorway traffic with Next generation vehicles) model will be capable of representing driver-vehicle behaviour on motorway sections, possibly with on and off-ramps, with a mixture of conventional (manually driven) vehicles and semi-automated vehicles.

1.4 Scientific and practical contributions

Given general objectives of the dissertation research, the following specific outcomes of the research are envisaged. The dissertation aims at making improved and new contributions to theoretical assumptions with regard to

- driver behaviour and traffic flow operation with longitudinal driver support systems;
- methodological approach for assessing capacity and traffic safety impacts;
- modelling motorway traffic behaviour.

A new purposeful driving task classification is being developed to classify driving tasks which can be replaced or supported by on-board support systems. A theory about driver behaviour and support system operation is described using a control model. Optimization of an individual objective function is the basic assumption here. The model description followed enables a comparison between human driver and support system, and stresses the functional aspects of a support system.

Based on the proposed driving task classification, functional groups of potential driver support systems are identified, leading to a preliminary qualitative assessment of potential effects on traffic flows. This assessment shows, among other things, the promising features of longitudinal driver support systems. Specifically, we focus on the design aspects of longitudinal driver support systems. Our study identifies the design variables of these systems which has not been done in earlier research. We consider the reactivation functionality and speed range supported of an AICC in the experimental setup.

An extensive elaboration is given of how longitudinal driver support systems might affect traffic flow quality on motorways. To this end, dedicated improved notions of macroscopic capacity, stability and safety are developed. It is concluded that capacity estimation must be performed in motorway bottlenecks, using the queue discharge flow as an estimator. Also, new aggregate safety indicators are developed using the time-to-collision notion.

A state-of-the-art review is established showing the current knowledge on expected capacity and safety impacts of longitudinal driver support systems. The literature study shows the potentials of AICC and the unclear benefits of the Automated Highway Systems. In contrast to past research, we find that a traffic flow quality assessment must be conducted focussing on discontinuities in the motorway network. In addition, an unambiguous capacity estimation approach is needed, distinguishing the pre-queue and queue discharge capacity.

Our experiments include the selection of several distinct AICC concepts and representative motorway bottleneck test cases. With our enhanced experimental setup reliable estimates of motorway bottleneck capacity can be obtained and transformed into network impacts.

The developed dedicated microscopic simulation model SIMONE is able to represent
**Chapter 1 - Introduction**

*manual and assisted driving, in free flow, capacity, as well as congested traffic conditions. The model can represent traffic processes at discontinuities in the motorway network. New and improved elements of this simulation model as compared to other microscopic models are the ability to simulate driver assistance system functionalities on a proportion of the vehicle fleet, to simulate the interactions between driver and system, and an improved method for gap selection. The lateral lane change decisions include a new gap acceptance procedure and anticipatory traffic behaviour aspects. Several elements in the model are stochastic, such as the user class dependent car-following sensitivity parameters, speed desired, and minimum gap distance desired.*

The results from the simulations are relevant to policy makers, traffic engineers and others since they indicate increased motorway capacity with next generation vehicles. We show that the increasing application of electronics in road vehicles, supporting the driver with part of the longitudinal driving task, may improve the motorway capacity significantly. Equipment penetration rate, time headway setting, and other design parameters of Autonomous Intelligent Cruise Control systems are responsible for the eventual impact on motorway traffic flows. We will also show that the capacity gains greatly depend on the type of motorway bottlenecks. Capacity gains on three-lane motorways will be approximately twice the capacity gains encountered on two-lane motorways. The capacity gains at a 2x2-symmetric weaving section are comparable with the gains at a three-lane motorway with an on-ramp bottleneck. Safety impacts are investigated using a new safety indicator, which shows the safety hazards of full penetration of the Extended AICC at 0.8 s headway setting.

1.5 **Outline of Thesis**

After this introductory Chapter, Chapter 2 starts with the examination of the central research topics. A driver behaviour theory and a control model are presented on which the impact assessment will be based. A functional categorisation of groups of driver support systems will be derived in Chapter 3. Subsequently, Chapter 4 deals with traffic flow quality assessment. Its focus is on the (macroscopic) capacity estimation, stability notion, and the safety assessment issue. Chapter 5 describes the findings of a literature survey conducted on the state-of-the-art knowledge of capacity impacts of longitudinal driver support systems, the outcome of which will guide the experimental work to be done.

Thereupon, Chapter 6 deals with a more detailed description of the research questions to be tackled and the experimental setup applied. A microscopic simulation tool has been developed to assess the impacts on traffic flow. The (microscopic) model description, assumptions, and driver behaviour theory are described in Chapter 7. Chapter 8 continues with the presentation and analyses of the experimental results achieved with the microscopic simulations. Chapter 9 concludes this study with a summary of the results and implications of the study, along with recommendations for further research and application of the SIMONE model.

Figure 1.1 shows the structure of the thesis. The thesis can be read according to the routes indicated. The first route (Chapters 2, 3, 5, 8 and 9) concentrates on substantial issues: the system and driver behaviour description, state of the art on capacity impact research, and simulation results. The second route (Chapters 4, 6, 7, 8 and 9) starts with the traffic flow quality assessment approach and gives specific information about the methodology applied
and the simulation model used. Of course, the chapters can be read in sequence as well from Chapter 1 to Chapter 9 to cover the full research.

FIGURE 1.1 Structure of dissertation
CHAPTER 2

DRIVING TASKS ON MOTORWAYS: DESCRIPTION, ANALYSIS, AND CONTROL MODEL

The execution of the driving task by the driver population on motorways determines to a large extent the macroscopic flow indicators such as road capacity. In case part of the driver population is going to use advanced driver support systems in the future, the execution of the driving task by these drivers will probably change. Since behavioural adaptations may affect traffic flow characteristics, this chapter is dedicated to the general subject of the driving task execution by drivers. The specific subject of driving task execution with the aid of driver support systems will be analysed in the next chapter. First, basic notions with respect to the driving task execution are given in section 2.1. A new purposeful categorisation of driver tasks is specified in section 2.2. Section 2.3 examines the driver’s objectives on which in section 2.4 the establishment of the continual control model is based. Its use is exemplified by a car-following model. The chapter closes with a summary of our model of the driving task which will be used in sequel to the dissertation.

2.1 Introduction

Many new possibilities for supporting today’s car drivers will emerge with the introduction of advanced technologies, incorporating electronics, microprocessors together with cameras, radars, lasers or other types of sensors. Market introduction and deployment of driver support systems will probably start with systems that only partially replace or support the human driving task. The consumers will be able to afford these first generation support systems, which require only a limited number of advanced technologies within the vehicle.

As a result of the expected changes in the vehicle fleet composition, we hypothesise changes in traffic flow characteristics. In order to attain more knowledge about the impacts of advanced driver support systems, information is needed about the system properties and differences with non-supported human driving task handling. We considered it therefore necessary to dedicate a chapter to the subject of human driving tasks to be performed on motorways. On this basis, a description of supportable driving subtasks can be given, followed by a comparison of support systems with the human driver (Chapter 3).
Let us start with some definitions and basic assumptions. STANTON (1995) discusses the psychology of driver behaviour distinguishing the following main principles for describing driver behaviour:

*Driving as skilled behaviour*
Driving requires the driver to possess a large set of perceptual and cognitive skills (for steering, changing gears, operating the pedals and decision making, prediction and fault diagnosis). Controlling a vehicle is a highly skilled task by an experienced driver, but still requires an attentive driver. For example, the control of the vehicle will occupy much of the novice driver’s conscious attention, leaving little reserves for attending other tasks, such as perceiving hazards. With extended practice, as more driving tasks are executed more or less automatically, the driver has more additional resources available for hazard perception. Driving as skill-based activity is in the domain in which humans are generally considered to perform quite well and errors are minimal. Accidents resulting from driver errors stem mainly from risk taking behaviour, influence of alcohol, and violations of traffic rules.

*Driving as sharing attentional resources*
The driver has frequently to deal with several sources of information concurrently. For example, the manoeuvres of other traffic participants, traffic signals, and the local traffic conditions in combination with information from inside the vehicle. The concept of limited pools of attentional resources states that drivers share the attentional resources among the tasks actually needed. The premise of this argument is that the allocation of attentional resources to one task will result in fewer resources available for another. Under certain conditions, the driver may find the demands of performing multiple concurrent tasks overwhelming. Automation potentially has much to offer in relieving the driver of an excessive workload (which occurs when the driver performs beyond the limits of his resources).

*Driving as utility optimization*
A good example of the application of the utility optimization principle in the driving task execution is the Risk Homeostasis Theory as proposed by Wilde. The theory makes the assertion that people seek to maintain a target level of risk despite changes in environmental risk. If the environment becomes safer, drivers will engage in riskier behaviour and conversely, if the environment becomes more dangerous drivers will engage in more cautious behaviours. The utility optimization concept applied on the risk compensation hypothesis states that drivers optimize their control actions taking into account their individually estimated risk, comfort, and preferred safety levels. The theory predicts that drivers using comfort increasing support systems would engage in more risky behaviours to restore target risk levels.

The latter theory is an example where the utility optimization theory can be applied. The *utility optimization* principle is, among other things, also appropriate to describe the performance of the driving task, as will be shown in section 2.4. First, the frequently used term ‘driving task’ is defined more precisely in the following.

The *driving task* is a comprehensive term that comprises all tasks which must be executed by the driver to reach his destination safely, comfortably and timely. A driver must keep a safe distance to the vehicle in front, follow the desired route, conform to the prevailing traffic rules, use turn indicators timely, keep the vehicle on the roadway, etc.
Chapter 2 - Driving Tasks on Motorways: Description, Analysis and Control model

The driving task is performed by the execution of vehicle control actions. For an accurate performance of the driving task, it can be assumed that the traffic state is continuously monitored and estimated, expectations about future states are continually being made, and control actions are initiated according to driver’s objectives and preferences. The control actions affecting the vehicle’s state and consequently the traffic state can be the following:

- braking;
- accelerating or decelerating by adjusting the throttle position;
- change gear;
- change foot from one pedal to another (e.g. from accelerator pedal to brake pedal);
- change course by adjusting steering wheel;
- apply turn indicator;
- turning on (or off) a driver support system.

Obviously, vehicle control actions are required continuously during the trip, and mainly consist of speed adaptation and course adaption. Even when no change in speed or course is made, this can be regarded as a control action. Driving objectives, e.g., safe driving, efficient driving, fast driving or environmental friendly driving, define the individual’s execution of the driving task.

A functional classification of the human driving task is desirable in order to create a suitable division of (potential) support system functionalities. The categorisation of support systems is presented in the subsequent chapter. In the following sections the human driving task is analysed in more detail, starting with a new classification of the driving tasks.

2.2 Proposed driving task model

Various models for driving task categorisation exist. An overview of some important models is presented in Hoedemaeker (1995, 1999). We summarize some of the important models.

Existing driving task models

A well-known model of the driving task is described by Michon (1993). The hierarchical structure in Michon’s model of driving tasks distinguishes a strategic level, a manoeuvre (tactical) level, and a control (operational) level of sub-tasks.

The strategic level includes the choice of modality, route planning, and navigation tasks during the trip, thus decisions needed to reach the destination properly. The manoeuvre level deals with reactions to events in the traffic environment. These reactions concern interactions with other traffic participants, such as overtaking and distance keeping during braking. The control level concerns elementary vehicle handling during a trip, such as following and keeping the vehicle on the road. Tasks at this level usually cause little mental workload: they are performed quite unconsciously and automatically.

This classification can be extended by the three levels of task performance in Rasmussen’s model (Rasmussen, 1983), namely the knowledge-based, rule-based, and skill-based level of performance of the driving task. Switching gears is for example a driving task which is unconsciously performed, thus skill-based. Skill-based driving has been elaborated in the introductory section as one of the main principles of driver behaviour psychology. It was concluded that skill-based driving is generally performed accurately by experienced drivers.
Development of a new driving task categorisation

A driver support system will replace or support part of the driving task (preferably without introducing complex new tasks). The supportable parts of the driving task should be identified in advance to study selling possibilities, initiate new developments, and analyse the impacts of market introduction on traffic flow characteristics. Unfortunately, the division made by Michon - and extended with Rasmussen's model - is insufficient for identifying subtasks which can be taken over by an in-vehicle driver support system. It is necessary to explicitly distinguish subtasks dealing with vehicle control in relation with the roadway or in relation with other traffic participants, since electronic systems (especially their sensor equipment) cannot make this distinction by themselves, in contrast to the human driver.

![Diagram of driving tasks](image)

**FIGURE 2.1 Classification of driving tasks. The route navigation is separated from the more operational tasks shown in the right-hand-side of the figure.**

Based on these considerations, a purposeful model of the driving task is developed and shown in figure 2.1. The figure shows all essential subtasks of the driving task. Five subtasks are distinguished, which are mostly performed simultaneously. We distinguish a longitudinal and a lateral control direction of a subject vehicle. In addition, we consider the roadway guidance and vehicle interaction levels as two distinct control levels in the driving task of a human driver or support system. The subtasks are explained in the following.

- The strategic **route navigation** is a subtask in which drivers choose their destination, travel direction, route, and roads. The choice for a destination or route depends on specific goals and preferences of the driver, and on traffic conditions. We will not discuss these types of driving task decisions, nor the driver support systems focussing on these tasks. The topic is out of the scope of the thesis. Example tasks are: select route, take correct exit, etc.

- The **lateral roadway subtask** is defined as the collection of decisions of the driver which are needed to guide the vehicle properly and comfortably over the available infrastructure and its elements such as driving lanes, curves and on- or off-ramps, while dealing with the lateral direction. Example tasks are: maintaining an adequate lateral position on the
lanes or on the roadway to avoid a run-off.

- The *longitudinal roadway subtask* is defined as the collection of decisions of the driver which are needed to guide the vehicle properly and comfortably over the available infrastructure and its elements such as driving lanes, curves and on- or off-ramps, while dealing with the longitudinal direction. Example tasks are: maintaining an adequate speed to avoid hazardous situations, e.g. in curves, with bad road surface conditions, etc.

- The *lateral vehicle interaction subtask* is defined as the collection of decisions of the driver which are needed to guide the driver-vehicle combination properly and comfortably around obstacles, vehicles, and possibly other traffic participants actually present on the roadway, while focussing on the lateral direction. Example tasks are: lane-change decisions and gap acceptance behaviour.

- The *longitudinal vehicle interaction subtask* is defined as the collection of decisions of the driver which are needed to guide the driver-vehicle combination properly and comfortably around obstacles, vehicles and possibly other traffic participants actually present on the roadway, while focussing on the longitudinal direction. Example tasks are: speed and distance keeping towards vehicles in front.

We elaborate the classification with the following example.

| A person decides to drive with his car from his home to the city center. Therefore, a pre-trip decision about the route will be taken, the so-called strategic route navigation subtask. If necessary, the driver changes his route during the trip due to new information about traffic conditions. The driver tries to keep his vehicle on the roadway, on the appropriate lane, thereby taking into account longitudinal roadway restrictions (such as speed limits) and the lateral margins to the side of the roadway or lane. Course adaptations and speed adaptations may be necessary for a comfortable, safe ride along the roadway. In addition, the driver has to deal with other vehicles on the road. The longitudinal vehicle interaction subtask requires distance keeping and speed adaptations in order to maintain a safe gap distance to other vehicles and to prevent collisions. The lateral vehicle interaction subtask deals with desired lane-changes and sufficient space keeping to other vehicles in the environment, e.g., on adjacent lanes. Lane changes might be necessary to reach the destination accordingly to the route navigation task performed by the driver. |

The driver task classification will be employed in the next Chapter 3 for identifying functional groups of driver support systems. The following section deals with the differences in performance of the driving task between drivers, which is mainly caused by the differences in the individual driving objectives.

### 2.3 Objectives of the driver

As can be concluded from several studies (FANCHER et al., 1996, HOGEMA, 1995 and HOEDEMAEKER, 1999), drivers differ in driving style. For example, different drivers have different preferences for the desired driving speed, desired comfortable deceleration level, and desired minimum gap distance. Some drivers give priority to safe driving, although their
behaviour may increase their travel time. Others prefer high speeds and accept small
headways or take more risks, for example in order to minimise their travel time.

The differences in driving style can be explained by the different preferences (such as
desired speed, desired minimum gap distance) and driving control objectives (e.g., safe,
comfortable or efficient driving) drivers have, within the possibilities of the vehicle (e.g.,
maximum speed, deceleration) under similar conditions. The distribution of preferences over
the driver population and car types also explains the stochastic nature of maximum traffic
flow rates and other macroscopic flow characteristics (see Chapter 4).

Driving objectives of human drivers in driving a car on motorways can be a subset of the
following options:
- maximise safety and minimise risks;
- minimise lane-change manoeuvres;
- maximise travel efficiency (restricting speed deviations with the desired driving speed);
- maximise smoothness and comfort;
- minimise stress, inconvenience, fuel consumption, accelerations, decelerations, etc.

The importance of each of the objectives will also vary among individuals. Experience,
travel motives, age, driver’s condition, time of day, etc., are factors affecting the subjective
importance of the driving objectives. Vehicle characteristics such as length, flexibility,
maximum speed, acceleration and deceleration capabilities of the vehicle also determine the
driver’s objectives. The prevailing weather and environmental conditions affect the average
preferences and objectives over the whole driver population.

In conclusion, the execution of the driving task is largely dependent on the preferences,
objectives, and vehicle capabilities. A formalized description of the execution of the driving
process is elaborated in the following section.

2.4  Execution of the driving task: a conceptual model

This section describes a conceptual model for the execution of the driving task. This model
is used in the description and comparison of human driving behaviour with driver support
systems in Chapter 3, and is the basis for the simulation model developed in Chapter 7.

2.4.1  Driving as a feedback oriented control system

A driver is constantly monitoring his position and speed relative to other vehicles, and to the
road boundaries. Such monitoring allows the driver to take corrective actions, or in other
words, the driving process is feedback oriented. Once the driver begins to drive, his actions
are not predetermined but are adaptive to current driving conditions. Driver and vehicle are
therefore part of a closed loop or feedback control system (EISENBERG, 1971, BARWELL,
1973). A continual feedback control system consists of a comparison between the input
vector (positions, speeds, accelerations of observed vehicles) and the controlled output
variables (accelerations and course adaptations). The driver tries to minimise the difference
between the input signal and the desired output signal. We assume in the sequel that the
driver-vehicle-combination operates as one control system, see figure 2.2.
The figure shows the vector of the variable $\mathbf{x}$, representing the influences from the environment on the driver-vehicle combination (referred to as 'subject', see right hand-side of figure 2.2). This vector includes, among other things, speeds of and distances to neighbour vehicles. The vector $\mathbf{z}$ is the influence from the subject on the environment. The vector $\mathbf{u}$ are the actions of the driver, possibly supported by a driver support system, changing the vehicle position and speed.

2.4.2 Control model

A fruitful approach to describe the execution of the driving task is using the utility optimisation model as conceptual tool, as indicated by, among others STANTON (1995) and VAN TOORENBURG (1983). The utility optimisation process, its parameters, and its resulting control decisions differ between drivers - assuming similar conditions - due to different objectives, preferences and vehicle types. This section attempts to describe the execution of the driving task in a generic way using this approach.

Figure 2.3 shows the continual process of the driving task handling, together with the involved variables. This process evolves in continuous time. The depicted system is a vehicle-driver combination in relation to its direct environment. The figure shows that the driving task process can be described as a continuously repeated sequence of state observations and state estimations (or state monitoring), followed by predictions of the expected future states (the evaluation of impacts of possible control decisions), and a control decision after which the control actions are carried out and the state may be changed. This process is depicted in figure 2.3 and will be described in more detail in the following, together with an explanation of the symbols applied.

The following vectors and functions are introduced to describe a single driver-vehicle combination as a system:

- $\mathbf{x}(t)$: vector of the actual state attributes at instant $t$
- $\mathbf{y}(t)$: vector of state observations (e.g., speeds, relative speeds, distances);
- $\hat{\mathbf{x}}(t)$: vector of estimated state attributes
- $\mathbf{u}(t)$: vector of feasible control actions
- $\mathbf{u}^*(t)$: vector of selected control actions
- $\overline{\mathbf{u}}^*(t)$: performed control actions
- $\mathbf{e}_{\text{obs}}$: vector of perception/estimation errors
- $\mathbf{e}_{\text{dec}}$: vector of prediction/decision errors
State observation and estimation
The actual traffic state at instant 𝑡 is denoted with state attribute vector $\mathbf{x}(t)$. A human driver continuously makes state observations (of densities, speeds, etc.) with his senses. By looking, hearing, feeling (such as temperatures, pedal pressures, steering forces) and smelling, information is collected and parts of the state are monitored. The state is estimated with this information. The observed and estimated state attributes by a driver-vehicle combination, which will be a subset of the actual true state $\mathbf{x}(t)$, is denoted with vector $\mathbf{y}(t + \tau_{\text{obs}})$. Here, $\tau_{\text{obs}}$ denotes the time delay involved with the perception and estimation task. The state observation will, among others, include the following information:
- own speed and acceleration;
- distance to other vehicles;
- relative speed to other vehicles;
• lane-change status (turn indicator) of other vehicles;
• traffic signs, road geometry, etc.

Observation and estimation errors $e_{ob}$ can be expected from a human driver with respect to the true state. Distances and speed differentials cannot be estimated with 100% reliability according to psycho-physical models. Research into perceptual psychology has shown that drivers are subject to certain limits on the stimuli to which they respond. The basis of such models is that at large spacings the driver of a following vehicle is not influenced by the size of the speed difference and that at small spacings driver response is not expected if the relative motion is too small (Wiedemann, 1974, Barwell, 1973 and Leutzbach, 1988).

The following dependency holds for the state observation at instant $t$:

$$y(t) = g(x(t - \tau_{ob}), e_{ob})$$

(2.1)

For the state estimation holds:

$$\dot{x}(t) = k(y(t), \dot{x}(t - 1))$$

(2.2)

**State prediction and control decision**

An important aspect in driver behaviour is the control decision. How does a driver decide for what kind of control action? We assume that there exist a set of control actions $U$ possible in a given situation. A driver following a vehicle with a lower speed can, for example, decide to enlarge the distance gap by decelerating or initiate a lane-change manoeuvre to the left or right. Even trying to impress the vehicle in front by accelerating to an uncomfortable headway distance (so-called tailgating) is a possible control action. Based on his observed and estimated state, a driver may predict the expected impact of possible control actions on the future state. The driver's control decision is based on his experience and knowledge. The existence of a prediction or expectation element in human driving task execution has been observed by, among others, Koff et al. (1997). Under most traffic conditions and for the majority of drivers, this is a skill-based task which is more or less performed automatically and unconsciously.

We assume that each driver continually tries to maximise its own individual utility (or minimise disutility). Examples of this approach with an objective function $J$ can be found in, e.g., Burnham et al. (1974), Peppard (1972) and Wilkie (1970).

In the decision making process, we assume that drivers consider a limited time horizon $H$ for determining the optimal decision to be taken at an instant $t$ (the rolling horizon approach). This decision refers to a trajectory of control actions to be taken over period $H$. Expected changes of the traffic situation, lane configuration, vehicle positions and speeds, anticipation on oncoming lane-changes are, among others, examples of information incorporated in the state prediction. Therefore, a future state trajectory over time period $H$ starting at instant $t$, symbolized by $\tilde{x}_{[t, t+H]} (t)$ is predicted at instant $t$ by evaluating the expected impacts of possible control action trajectory $u_{[t, t+H]} (t)$ which is one of the conceivable control actions of set $U$ (i.e. $u \in U$). As depicted in figure 2.3, the feedback process involves an objective function and time delays. The premise of the utility optimisation theory is that a driver selects a control action trajectory $u^*$ that minimises his
objective function $J$ for the time horizon considered. In order to achieve this, the driver needs a certain decision time $\tau_{dec}$ to evaluate the possible control actions and to determine the optimal control decision $u^*$. The objective function, referred to as by symbol $J$, is a weighted function consisting of a number of relevant aspects for an individual driver, such as travel time, comfort, energy consumption, risks, convenience, stress, etc. The weighting factors describing the relative importance of the objectives are also driver and trip dependent (e.g., driver experience, travel motive). For example, a driver $i$ who tries to optimize his following distance and energy at instant $t$ over a certain time horizon $H$ might try to minimize an objective function of the following format:

$$J_{[Lt,t+H]}(t) = \int_{t}^{t+H} \left( q_{i}(t)\hat{x}_{i-1}(t) - \hat{x}_{i}(t) - s_{i,min}(t) \right) + \ldots + q_{k,j} u_{*}^{*2} \right) dt \quad (2.3)$$

where $\hat{x}_{i}(t)$ is the estimated position of the driver, $\hat{x}_{i-1}(t)$ the estimated position of his leader, $s_{i,min}(t)$ the desired gap distance for safe and comfortable driving at instant $t$, and $q_{i}$ the weighting factor of the distance error for individual $i$. Equation (2.3) can easily be extended by all kinds of objectives taken into account by a driver. A fixed running cost term can also be added to represent the fixed disutility of (a certain) control decision.

A state trajectory prediction over a time horizon $H$ at an instant $t$ can be formalized as follows:

$$\hat{x}_{[Lt, t+H]}(t) = f(\hat{x}(t), u_{[Lt, t+H]}(t), \varepsilon_{dec}) \quad (2.4)$$

with $u_{[Lt, t+H]}$ representing a possible control action trajectory.

Each potential control action yields a perceived utility for a driver, and a driver will choose a control action trajectory $u^*$ with maximum perceived utility (or equivalently, a response with minimum perceived disutility) according to the following equation:

$$u^*_{[Lt, t+H]}(t) = \arg \min u J(\hat{x}, u, t - \tau_{dec}) \quad (2.5)$$

Focussing on motorway traffic, a control decision will typically be twofold, dealing with the longitudinal and lateral driving task. We assume that a speed change decision and lane change decision are continuously needed. In addition, we presume that the longitudinal control actions (speed changes) and the lateral driving tasks (course adaptations and lane changes) are simultaneously performed. Thus:

$$u_{i}(t) = \begin{bmatrix} \text{speed change} \\ \text{course change} \end{bmatrix} \quad (2.6)$$

**Control action**

A control action $u^*$ is performed by applying the brake, throttle or steering actuator (e.g., accelerating, decelerating or starting a lane change). Maintaining the same position of the brake pedal, throttle and steering wheel is also a control action that may change the vehicle’s
state (e.g., the position of the vehicle).

A new state results after performance of the control action of the driver and the control actions of other traffic participants in the neighbourhood, and possibly by changed road and weather conditions. The time needed to apply the brakes, and the time needed to reach the desired control level (e.g., time needed to change the deceleration level from zero to \(-0.2g\) taking into account the maximum allowable jerk and vehicle dynamics) is denoted by \(\tau_{\text{act}}\). In addition, the human driver attempts to control the actuators according to the desired control action, but human behaviour is imperfect and will likely result in some actuator control errors \(\varepsilon_{\text{act}}\). Equation 2.7 gives the relationship between control decision \(\bar{u}^*\) and control action \(\bar{u}^*\).

\[
\bar{u}^*_{[\tau_{\text{t+e}}]}(t) = u^* (t - \tau_{\text{act}}) + \varepsilon_{\text{act}}
\]

(2.7)

The overall time delay - the minimum time needed for a state change after starting a state observation - of a particular driver can be specified with (LEUTZBACH, 1988):

\[
\tau = \tau_{\text{obs}} + \tau_{\text{dec}} + \tau_{\text{act}}
\]

(2.8)

In summary, at instant \(t\) a new state results from driver observations taken place a specific time delay \(\tau\) before instant \(t\), namely at instant \(t-\tau_{\text{obs}} - \tau_{\text{dec}} - \tau_{\text{act}}\) applying a utility optimization process. The presented control model will be applied in the analysis of human driving behaviour as well as in the analysis of the driver support system as will be shown in Ch. 3. The next sub section proceeds with an example of the control model.

2.4.3 Example of control model

We illustrate the use of the control model with Helly’s stimulus-response car-following model (PAPAGEORGIOS, 1991), which has been applied in several traffic simulation models, see e.g., BROQUA et al. (1991) and VAN AREM et al. (1995b). An adapted version of the original model - introducing several parameter sets for distinct car-following conditions - has been developed and applied in the simulation of the experimental scenario’s (see Ch. 7).

State observation and estimation

Assume that state observations have been made by driver \(i\) (a follower) at instant \(t-\tau\). The observed attribute vector \(y(t-\tau)\) consists of, among others, speed observations of the vehicle in front and the driver’s own vehicle, and position observations of the vehicle in front \(i-l\) and the subject vehicle \(i\). Symbol \(\tau\) denotes the overall time delay between observation and performed control action.

Helly’s car-following model requires these observations as input variables to determine a control decision. Possibly, other stimuli are observed by the driver, but the model assumes that this information does not improve the control decision determination. More practically, the model does not take into account the state of one or more drivers in front of the lead vehicle and does not react to accelerations and decelerations of the lead vehicle. In addition, the state observations are envisaged to contain disturbances \(\varepsilon\) in the perception of the
relevant stimuli since the human driver is imperfect in estimation of distances and speed differences (Barwell, 1973, Wiedemann, 1974). As a consequence, a driver is assumed to use stimuli which are generally not the true values, but values from a distribution around the true values (see equations 2.1 and 2.2).

**State prediction and control decision**

The driver is assumed to use an internal model for determining an appropriate control decision, either an acceleration or deceleration. Generally, experience and knowledge have skilled the driver in performing this task. Appropriate parameter sets for car-following under distinct conditions are selected automatically. By using these skill-based parameters, nearly all situations will be safely and efficiently handled, and a control decision and action \( u^* \) will be determined unconsciously. A model to represent this behaviour quite understandably and realistically is Helly's model. The model supposes that a driver continuously attempts to minimise both the speed difference and the difference between his actual headway and desired minimum headway with respect to the leading vehicle.

The applied objective function \( J \) of a driver \( i \) can therefore be seen as a utility optimisation based on two observed stimuli: the relative speed difference and the distance error to the lead vehicle. The weighting factors in the objective function determine the importance of both aspects and will probably differ under different conditions.

Helly's model formulation of the 'optimal' control decision \( u^* \) - neglecting driver perception thresholds, and ignoring the expected variety of parameter values under distinct car-following conditions - is shown in eq. (2.9):

\[
\begin{align*}
\dot{u}_i^*(t) &= c_1 [\dot{X}_{i-1}(t - \tau) - \dot{X}_i(t - \tau)] + \\
&\quad c_2 [X_{i-1}(t - \tau) - X_i(t - \tau) - S_{i,\text{min}}(t - \tau)]
\end{align*}
\]

where \( c_1 \) is the speed error sensitivity parameter, \( c_2 \) the headway error sensitivity parameter, and \( S_{i,\text{min}} \) the desired minimum gap distance. The subscript \( i \) denotes the subject driver-vehicle combination, subscript \( i-1 \) denotes the leading vehicle. Theoretically, the sensitivity parameters can be driver specific, which has been adopted in our developed simulation model (see Ch. 7). The control decision and action, which is a positive or negative acceleration, is indicated with \( u^* \).

The desired minimum gap distance to a leader (for a driver \( i \)) can be represented by, for example, the following linear relationship:

\[
S_{i,\text{min}}(t) = l_i + m_i + z_i \cdot \dot{x}_i(t)
\]

where \( l_i \) is the length of the vehicle and \( m_i \) represents the desired gap margin at zero speed. Parameter \( z_i \) is sometimes referred to as the time headway parameter. The parameter values depend on the driver’s preferences with respect to a safe distance gap. Consequently, different drivers may have different objective functions and may therefore have deviating control actions under identical circumstances. This aspect is also incorporated in the simulation model which is described in Chapter 7.

Parameters in equations (2.9) and (2.10) may thus differ between drivers and conditions. For example, a driver with a high priority on safety will judge the speed difference stimulus as more important than someone with a preference for quick driving. Other drivers prefer
smooth driving and try to reduce the fuel consumption: these drivers will limit both the weighting factors $c_1$ and $c_2$.

Each driver has a specific, individually defined car-following task execution which can be described with a unique parameter value combination. However, since some parameters are correlated, the number of combinations is restricted. For example, a driver with a preference for quick driving will typically be more alert (has a small value of $\tau$), accepting relatively small gap distances $s_{\text{min}}$ and reacting less sensitive on speed differences than other drivers (thus a small parameter value of $c\tau$). Safe drivers will generally maintain larger headways in combination with an emphasis on reducing speed differences.

The car-following task, which can be modelled by eq. (2.9), is not always the most critical longitudinal driving task. In practice, a driver will optimize his response by taking into account several other aspects of the longitudinal driving task, such as speed adaptation to vehicle speeds on adjacent lanes, and anticipation on oncoming lane-changes. These aspects are elaborated in Chapter 7 where the longitudinal and lateral driving tasks are identified, analysed and described, focussing on model implementation.

### 2.5 Conclusions

In this chapter, a purposeful classification of the driving task has been presented. Five essential subtasks are distinguished and described. We assume that the subtasks are executed simultaneously and cover our definition of the ‘driving task’. This new classification will be used for identifying driver support system functionalities in the following chapter. Furthermore, the driving task execution has been described as a continual feedback control system. The conceptual model assumes that drivers make observations, estimations, predictions, decisions, and control the actuators continuously. Time delays are expected for the perception, estimation, decision and control action. State perception, state estimation, state prediction, control decision and actuator control also involve corresponding perception, estimation, prediction, decision and actuator errors.

Each driver is unique and will therefore execute his driving task in his own unique way. This aspect is incorporated in the theory by subjective driving objectives and preferences, transformed into individual parameter values. The developed control model is not only suitable for describing the process of human driver behaviour but is equally well suited to describe the driver support system operation (see Chapter 3). Also the simulation model developed to analyse the impacts of supported driving (see Chapter 7) has been founded on the same line of thought.

The next chapter deals with the description and categorisation of driver support systems in general, and longitudinal driver assistance systems in particular.
CHAPTER 3

DRIVER SUPPORT SYSTEMS: DESCRIPTION AND CATEGORISATION

Driver support systems assist the driver in executing the driving task. These systems may therefore change driving behaviours and affect traffic flow characteristics. To enable a thorough analysis of the potential changes in traffic flow characteristics, driver support systems must be analysed, described, and categorised. The chapter starts with an overview of past developments of motorization and early driver support systems (section 3.1). The deployment issue is addressed, and assumptions about the introduction of advanced driver support systems are made. Section 3.2 focusses on driver support system objectives and gives a driver support system classification based on the assistance level. The driving subtasks identified in Chapter 2 are used to categorise driver support systems. Section 3.3 focusses on the driving task execution with support systems, followed by a comparison of supported driving with human driving (section 3.4). Section 3.5 deals with the longitudinal driver assistance systems, a distinct group of support systems which will be the subject of study in the sequel of the report. Its purposes, functioning, and benefits are concisely described. The chapter closes with a summary of the key issues with respect to longitudinal driver support systems (section 3.6).

3.1 Introduction

Driver support systems are automotive applications supporting the driver in performing one or more elements of the driving task, such as car-following, lane-keeping, etc. The exact functionality of a system depends on the system definition. To structure the wide range of applications, a categorisation of support systems is established in section 3.2 and discussed in section 3.3 using the control model. For the promising longitudinal driver assistance systems an overview of possible system designs is outlined in section 3.5.

In this section, the discussion starts with a concise history of the road vehicle and early driver support systems. The deployment issue is presented next. Then, a review of the terminology used in this field is given.
3.1.1 Concise history of the motorised road vehicle

The first experimental motorized road vehicle was developed by Nicolas J. Cugnot in the period 1765 to 1770. The French engineer used steam power for traction. Maximum speed of the car was about 6 km/h, while it had to stop every fifteen minutes for building up sufficient steam power. Financial circumstances stopped Cugnot's work on these motor vehicles. It was until 1803 before another engineer, Richard Trevithick, experimented with a (steam driven) road vehicle. Its maximum speed reached 18 km/h. However, further development of the road vehicle retarded since railway projects were financially more attractive at that time. After a pause of decennia, more than fifty motorized vehicles were constructed on British territory in a time period of twenty years.

A new development in the road vehicle was the street locomotive, which was applied in agriculture in the 1860s. For thirty years, they were the only useful application of steam traction in vehicles.

Karl Benz' three-wheel-based vehicle from 1885 can be seen as the precursor of the current motor car. The one cylinder engine used a gasoline/air mixture as fuel and could reach a speed of about 12 km/h. Further development and perseverance eventually resulted in a four-wheel car with a doubled maximum speed. In 1889 he sold his first cars, in 1896 already 181 vehicles left the factory. In 1900, there were about a hundred manufacturers all around the world busy developing and selling cars. Reliability and simplicity of handling the vehicle appeared to be the decisive factors for success. The consumer of the year 1904 had a wide choice of powerful vehicles with maximum speeds above 100 km/h, although they were affordable for only few individuals.

Steam, fuel, and electricity were in competition as traction power at the beginning of the 20th century. However, the mass production of the vehicle with a combustion motor - which was initiated in 1908 by Henry Ford - led to affordable prices and a great public demand. Although steam power and electrical traction had some advantages compared to the combustion motor, the winner of the competition appeared to be the fuel-powered vehicle. In the period until 1927 fifteen-million four-cylinder T-Fords were sold. Other manufacturers took over the concept of mass production. Speed was no longer the decisive factor for selling vehicles, instead reliability, comfort and simplicity were getting more important. Obviously, this selling point has not changed much the last decennia. For an extensive overview of the history of the road vehicle we refer to LAY (1991) and GEORGANO (1972).

3.1.2 Short history of driver support systems

The current road vehicle is equipped with many additional, under certain circumstances indispensable features which are developed and implemented to lighten the driver task and thus enhancing driver comfort. Some of these developments are described in this section. Although these applications can be denoted as driver support systems, it is common to use this term only for relatively new automotive applications based on electronics and micro processors (the definition issue is described in section 3.1.4).

Categorisation of driver support system by its purposes
Progress in lightening the driving task has been made in several fields related to driving a car from origin to destination. Figure 3.1 presents a schematic overview of in-vehicle
applications and their impacts (subdivided into user, network and environmental impacts).

We can distinguish two types of in-vehicle support systems. The *vehicle enhancement* systems are especially developed and designed for optimisation of the vehicle performance, e.g., to reduce fuel consumption and increase the efficiency of the engine. The (advanced) driver support systems are deployed in order to increase *driver comfort* and possibly *driving performance*.

![Diagram of in-vehicle systems purposes and impacts](image)

**Figure 3.1** Purposes and impacts of in-vehicle systems

The notions of driver performance and comfort are explained in the following:

The notion of *driver performance* expresses the valuation of the driving task execution (state observation, state prediction, decision making, control action). The driver performance indicator is affected by driver preferences and objectives which depend on driver (age, gender, experience, travel motive, etc.) and vehicle characteristics (maximum acceleration, maximum speed, flexibility, etc.). Large reaction times in perception, decision and actuator control will decrease the driver performance, as will perception, decision and actuator control errors. The driver performance affects traffic flow quality indicators, such as capacity and safety. Driver performance of individuals can hardly be measured, however, the performance of a driver population is measurable. Macroscopic flow data represent aspects of the population’s driving performance.

*Driver comfort* is a qualitative term describing the available resources while executing the driving task. Little demand or workload corresponds to high driver comfort levels. Driver comfort depends on the task complexity and is affected by technologies, such as navigation aids and information provision. In-car systems can reduce the complexity of the driving subtasks, but in some cases may increase the workload. A poor comfort level may affect the driving task execution negatively. Workload can be measured at individuals under experimental conditions.

There exist several relationships between driver comfort systems, vehicle enhancement
systems and impacts on driver performance. For example, an increase in drivers' satisfaction may contribute to an improved driving performance, as has been indicated in figure 3.1 by the dotted relationship. An improvement of the vehicle performance (e.g., braking capabilities) can also lead to an improved flow quality. A short overview of driver comfort and performance measures is given in the following.

**Driver support systems aimed at increasing driver comfort**

Lightening of the navigation task started already in an early stage with introducing street maps and traffic signs. Until some decades ago, no - technological - progress was obvious to reduce the navigation task further. The availability of micro computers and route navigation software with route planning features did introduce a new development with respect to the drivers' navigation task. Not only the route planning process could be simplified at home, but also new advanced techniques made it possible to give a driver individual route information in the vehicle during the trip. Even incorporating real-time traffic conditions is now a possibility.

Apart from navigation aids, there has been made progress in other areas of vehicle technology aimed to increase driver comfort and perception of safety. Tires, suspension, spring action and ventilation mechanisms have been adapted and improved. Lately, new safety constructions and facilities (such as air bags) have been developed and implemented.

**Driver support systems aimed at increasing driver performance**

Also during the 20th century, there have been large improvements in the vehicle control mechanism, aimed to improve the driving performance by better braking and indirectly offering more comfort and travel convenience. New techniques for braking have been developed, such as drum brakes, disc brakes and the brake assister.

In 1978 the Anti-lock Braking System (or shortly ABS) was presented and is currently being implemented in many models of various manufacturers. Latest developments are Automatic Stability Control and Traction control to prevent sliding in curves (see, e.g., PAUWELIUSSEN, 1995). The invention of the automatic transmission replacing the needed gear-and-clutch actions for gasoline powered vehicles, was directed to decrease the complexity of the driving task. In America, this development led to a high penetration of automatic transmission in the vehicle fleet. However, in Europe the automatic transmission is still in the minority.

Another innovation widely implemented in vehicles in the USA is the cruise control (CC), which is a device for automatically maintaining a constant speed specified by the driver. The development of the CC started in the late 1950s with mechanical systems, but in the 1980s improved electronic types were introduced (SHAOUT et al., 1997). At the moment, cruise control is installed in 70% of the new vehicles in the United States.

The impact of vehicle and road illumination on the driving task should be noted. A vehicle or infrastructure equipped with illumination makes it possible to drive safely in dark or bad weather conditions. In addition, the driving performance under these conditions appears to be positively affected. Capacity improvements on roads with illumination have been observed, BOTMA et al (1998).

Mirrors are a well known equipment of the present car which can help the driver to sense the environment around the vehicle and make decisions according to his observations. Also, turn indicators were introduced to make direction changes visible for other traffic participants who could anticipate on the foreseen manoeuvre.

Most of the technological innovations are launched by car manufacturers wanting to satisfy their consumers. From a historical point of view, it is clear that consumers are willing to pay for more comfort and safety features. We expect that drivers (the potential buyers of support systems) and car manufacturers will maintain this attitude as long as this situation is beneficial for the actors involved.

**Expected impacts of early driver support systems on traffic flow**

One of the hypothesised impacts of the early driving task support systems introduced so far
is an increase of road capacity. But there are other factors that may have contributed to an increased capacity over the past period as well. We recall the following factors for growing capacity:

- improved *vehicle technology*, including deployment of early support systems;
- improved *road geometry design* and traffic regulation;
- improved *driving performance* due to better driving education, improved driving experience due to increased exposition in dense traffic, and changed attitude with respect to safety.

In literature, evidence can be found for the hypothesised growing capacity trend. AGYEMANG-DUAH & HALL (1991) describe the capacity change that follows from traffic flow research. Whereas the Highway Capacity Manuals from 1950, 1965 and 1985 adopt 2,000 passenger cars per hour per lane as the numerical value of the design capacity of a basic section of a motorway, the last edition of the manual (HCM, 1994) adopts a design capacity value of 2,200 veh/h/lane. COHEN (1995) studied the evolution of realised motorway capacity by comparing time series of maximum flows measured in the period 1980 - 1983 and measured in the period 1990 - 1993. He concludes that the motorway capacity increases almost 9% in a decade for a typical three-lane motorway section. For uniform four-lane sections, the observed increase has been even larger. According to these findings, the capacity growth is approximately 0.5% to 1% per year due to improvements in vehicle performance and changes in driving behaviour.

In the Netherlands, maximum flow rates on the left lane can easily exceed 3,000 vehicles/hour (see e.g. Appendix A), whereas the maximum flow observed in the 1930s was about half of this value. This can partly be explained by the increased average speed in the period 1930 to 1990, as has been shown by LEUTZBACH et al. (1993). From the reported findings, we hypothesise an annual average capacity growth rate between 0.5 and 1% for a given road geometry.

![FIGURE 3.2 The growth of motorway lane capacity](image)

Figure 3.2 gives an indication of the capacity growth in Europe in the period 1930 to 2000, based on highest measured intensities.
New possibilities for supporting today's drivers will emerge with the introduction of advanced technologies, incorporating electronics, microprocessors together with cameras, radars, lasers or other types of sensors. The hypothesised advantages of electronic driver support systems - compared to human drivers - are discussed in section 3.4. The question then is whether these new devices may be expected to contribute to a further growth in road capacity in the future. This is a key question of this dissertation, to be dealt with in Chapter 8. The deployment speed of driver support systems in the vehicle fleet is also an important factor, among others for the use of the systems and its impacts on traffic flow characteristics. This issue is described in the next section 3.1.3.

3.1.3 Deployment of driver support systems

A human factor that is strongly decisive for sensible changes in traffic flow characteristics and the transportation system as a whole, is the deployment speed of innovations such as a driver support system.

Generally, once innovations are introduced that demonstrate potential technical and economic viability, they are put forward for societal testing (GRÜBLER, 1990). The innovation is either refused or accepted, and in case of acceptance it starts to diffuse into the economic and societal environment. If solutions prove to be better adapted to the actual technical, economic and social requirements than the existing techniques and practices, the innovations will start to replace old ones.

Figure 3.3 illustrates the diffusion process of different technological innovations (automatic transmission, power steering, air conditioning, disc brakes, radial tires, and electronic ignition) in the United States car industry. A logistic function - a S-shaped curve - can be recognized in all of the shown applications. Such a diffusion process can also be assumed to occur with the introduction of driver support systems in the car industry. At this moment, the diffusion process of assisting systems is currently in its first phase of

![Figure 3.3 Diffusion of automotive applications in US car industry (in percent of car output) (Source: Grubler, 1990)]
prototyping, testing, and careful market introduction. Despite the uncertainties of public acceptance and willingness of consumers to buy these systems, for research purposes we assume that the longitudinal driver support systems examined here will be adopted by the public.

The liability issue is not discussed in this thesis, although it is one of the issues that might probably delay the development and deployment of (autonomous) longitudinal driver assistance systems. For example, a person driving with a driver support system may in some critical situation react too late and cause a rear-end collision (see e.g., Hoogena et al., 1996). We can argue who is responsible in this case. Is this a design failure of the manufacturer (by neglecting a possibly predictable decreased driver alertness)? Is the system constructor or car retailer responsible for the crash? Or is it expected that the driver should be as alert as without an assistance system (as stated in the system's user manual)?

In addition, what happens if the system incidentally malfunctions without an adequate warning? And if this is the cause of an accident, can a temporarily - but fatal - system malfunctioning being proved? These questions and their consequences for system design are still under investigation, see e.g., Van Wees (1997, 1999).

For convenience, the next subsection describes the variety of terms and definitions used and applied in this field.

3.1.4 Terminology and definitions

Electronic, computerized in-vehicle systems that partially or fully replace drivers’ driving tasks, are interchangeably referred to as Automated Vehicle Guidance, driver support systems, driver assistance systems or Advanced Vehicle Control Systems (AVCS). The use of different terms for a broad range of systems works confusing, so, firstly the definitions used in this thesis are given. Figure 3.4 positions the terminology according to our definitions.

**Advanced Vehicle Control Systems**

The comprehensive term Advanced Vehicle Control System (AVCS) represents the subclass of Intelligent Transportation Systems dealing with vehicle control automation and driver support functions (see, e.g., Shladover, 1995). Applications referred to as AVCS can support or replace driving tasks, however, other in-vehicle applications such as ABS or traction control are sometimes also called AVCS, whereas it is ambiguous if these type of vehicle control systems can be addressed as driver support systems. The words ‘advanced vehicle control systems’ are in fact a somewhat misleading description of the technologies and services that comprise AVCS.

**Automated Vehicle Guidance**

The term ‘Automated Vehicle Guidance’ (AVG) is used by many authors to referred to as systems which can fully or partially replace the driver’s driving task on dedicated or existing road infrastructure. Its definition does include systems that control the vehicle autonomously - vehicle control regulated by the in-vehicle system and its sensors - and systems that controls the vehicle relatively non-autonomously, e.g., communication needed with other vehicles, with infrastructural facilities or with road side based traffic control centres. Platoon-driving, or the Automated Highway System, is a concept that is sometimes as referred to as Automatic Vehicle Guidance. In addition, all driver support systems can be described with this comprehensive term since partial driver support is also covered by the definition.
Driver support and assistance systems

Driver support systems are a subgroup of the described AVG systems. The term includes only electronic systems that partially replace the driver with some of its driving tasks. The system functionality can be either informing, warning or actively supporting. In addition, for the latter functionality, the term 'driver assistance systems' is also applied. Assistance refers here to actively supporting the driver with some parts of the driving task, thus automatization of some tasks, e.g. steering or speed control. For example, AICC belongs to this definition.

Other classifications of driving task automation focus on the type of supported vehicles. Public transport, individual transport and cargo transport are possible categories for automated road transport. This classification will not be used here: the focus is on individual car driving.

3.2 Objectives of driver support systems

Human driver behaviour is characterised by drivers' individual preferences and driving objectives, as has been pointed out in section 2.3. In contrast to human driver behaviour, the objectives of a specific support system will generally be the same over the population using this system. Identical, and more predictable driver behaviour follows from this characteristic.

The driving performance of a supported driver is largely dependent on the objectives of the system, and consequently, on the implemented algorithm found suitable for this task. It is assumed that the algorithm has been tested, specified and that appropriate parameters have been selected by the system manufacturer. In other words, we assume that the objectives of the system are set by the designer, making a trade-off between safety, efficiency, liability and comfort aspects.

Nonetheless, it is foreseen (see, e.g., KOPP et al., 1997 and AUTOWEB, 1998) that the driver can adjust some of the system parameters - within boundaries specified by the system designer - and so can personalize the system's performance with his driving preferences and own objectives. An example of this possibility is the Adaptive Cruise Control described and tested by REICHART et al. (1996) which includes an adjustable headway between 1.1 and 1.8 s, and an adjustable gain factor for deceleration moment. This aspect is important, since too much freedom in setting the support system characteristics may result in an equipped vehicle fleet with varying driver behaviour. Hypothesised advantages of such systems on traffic flow can then probably not be realised.

In the following sections, the extent of driving task replacement is identified, described and analysed (section 3.2.1). Based on this classification and on the driving subtasks distinguished in section 2.2, a categorisation of functional driver support system groups is presented and analysed in section 3.2.2.
3.2.1 *Extent of the driving task replacement*

Driver support systems may to a certain extent replace specific driving tasks. The extent of this replacement depends on the functional design of the support system. Roughly, the following basic designs can be distinguished, with increasing level of complexity (Broqua et al., 1991):

- information systems;
- warning systems;
- overr Throwable assistance systems;
- overr Throwable assistance systems.

An assistance system that replaces specific driving tasks while the driver can not stop the system actions, is denoted by the term assisting non-Throwable. For example, a system controlling the vehicle on a dedicated lane where the driver can not intervene.

If the driver is still in the 'loop', and can intervene in the system's vehicle control, such as for example with Autonomous Intelligent Cruise Control, the system is called assisting Throwable. Unfortunately, the differences between assisting Throwable and assisting non-Throwable systems can become a little bit vague since assisting non-Throwable systems should also be turned off in cases of emergencies or whenever the vehicle must stop or leave a dedicated lane. Informing and warning systems can always be overruled by the driver.

Based on the literature it is expected that the level of automation of systems will increase over time from informing systems to driver assistance systems, possibly leading to fully automated vehicles (Reichart et al., 1996 and Hall, 1997, Stevens, 1995, 1997). Nonetheless, the deployment step from assisting Throwable to non-Throwable is doubted, and non-Throwable types can possibly be introduced on dedicated lanes only.

By using a driver support system, some part of the driving task is assisted. On the other hand additional new tasks for the driver may be introduced, such as the decision to switch a support system off or on (Stanton, 1995). These new tasks depend on the precise system functionality. The effect of the new task on driving performance depends on the complexity of the introduced task. The human factors - aspects dealing with interaction between driver and support system - are not discussed here further but should be studied extensively. In some cases, the added tasks may cause safety hazards and do therefore not obey the goals of the system. In the sequence, assumptions about human factors will be made according to literature findings and based on expert opinions.

In the following, functional definitions of the assistance levels are presented. Control schemes of the considered systems are shown in section 3.3.

A. Informing driver support systems inform the driver about the actual and/or possible future position of the vehicle on the roadway and/or its position in relation to the other vehicles observed. Possibly, an advise for control actions will be displayed. As a consequence, a driver is not forced to adapt his position relative to other vehicles or roadway, however, he may judge the situation and react according to his own and renewed interpretation of the situation.

B. A *warning* system will support the driver in dangerous situations by making the driver alert timely. However, the driver must interpret the situation and must still make the appropriate decisions by himself. The system layout of a warning system requires an electronic interpretation unit which determines if the conditions are met for supplying a warning signal, and is therefore more sophisticated than an information system.
Supported Driving: Impacts on Motorway Traffic Flow

C. Overrulable assisting driver support systems will take over part of a driving task automatically. A driver can always take over vehicle control while an assisting overrulable system is activated. The design of an assisting system can easily be re-arranged in a manner that it can be downgraded towards an informing support system. A collision avoidance system (CAS) and autonomous intelligent cruise control systems (AICCC) are examples of this type of driver support systems. The difference between these systems is eminent. A CAS only supports the driver if the situation requires intervention to prevent a collision, and is therefore more complicated and expected to appear in a later phase on the market.

D. A non-overrulable assisting system aims to replace a driving task completely without driver cooperation, most likely on dedicated lanes. The system decides whether the driver should take over (a part of) the driving task again.

The four distinct assistance levels presented above enable us to draw up a variety of support system groups with distinct functional characteristics, as will be presented in the ensuing subsection.

<table>
<thead>
<tr>
<th>Support</th>
<th>Purpose and impact assessment</th>
<th>Example of system</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>Applications of these support systems provide information or warnings on longitudinal interactions between vehicles.</td>
<td>Provision of time-headway information, time-to-collision information, obstacle warning. Systems of this type are currently not available.</td>
</tr>
<tr>
<td>B1</td>
<td><strong>Impacts:</strong> These systems will have some impact on driver comfort and performance (see Jahake, 1982). The driver is better informed about its current traffic state and may use this to anticipate on future conditions.</td>
<td></td>
</tr>
<tr>
<td>A2</td>
<td>Informing systems for longitudinal control dealing with the road have in common that they are informing (can be ignored by the driver) and don’t deal with other vehicles in traffic. Main task of such a support system is to inform the driver about the state of the vehicle with regard to the longitudinal motion.</td>
<td>Although these types don’t exist yet, we can think of several functional systems. For example a Speed Limit Indicator (giving the actual speed limit on the road section), Speed Adviser (giving a speed advice for a comfortable ride through curves e.g.) and Bad Road Surface warning (giving a warning about the state of the road).</td>
</tr>
<tr>
<td>B2</td>
<td><strong>Impacts:</strong> These systems are only informing, and will not replace the driver. The information can be valuable to the driver and enhance its comfort during driving.</td>
<td></td>
</tr>
<tr>
<td>A3</td>
<td>These systems inform the driver about the lateral state with regard to the interaction of vehicles (to its left or right).</td>
<td>Dead Angle Alert (warning about vehicle in dead spot of vehicle), Passing State Information (information about presence of neighbour vehicles), Lateral Collision Warning (warning when too close to other vehicles).</td>
</tr>
<tr>
<td>B3</td>
<td><strong>Impacts:</strong> Traffic flow safety will probably increase.</td>
<td></td>
</tr>
<tr>
<td>A4</td>
<td>Systems of this type inform the driver about the state of the vehicle with regard to the lateral position on the road.</td>
<td>Yet non-existing examples of this group of systems are among others: Dangerous Curve Warning , Speed Advice (to prevent lateral position failures), Lane Use Advice (giving advice about what lane the driver should chose), Passing Prohibition Information, Lateral Position Warning.</td>
</tr>
<tr>
<td>B4</td>
<td><strong>Impacts:</strong> The functions supported are of relatively minor importance in the driving process. The driver will be supported and possibly experience a higher comfort level. The impact on traffic flow safety and efficiency is expected to be minimal.</td>
<td></td>
</tr>
</tbody>
</table>

TABLE 3.1  Functional groups of informing and warning driver support systems

3.2.2  Functional categorisation of driver support system

A number of distinct groups of support systems can be determined using the driving subtask classification (derived in section 2.2) and the support mode classification (described in
section 3.2.1). The groups are described and elaborated in tables 3.1 to 3.3. In table 3.1 the informing support system groups (A.) and warning systems (B.) are presented, table 3.2 deals with the assisting-overrullable systems (referring to C.) and table 3.3 describes the assisting non-overrullable support system functional groups (D.). For convenience, the driving subtasks are numbered from 1 to 4:
1. Longitudinal support with respect to vehicles;
2. Longitudinal support with respect to the roadway;
3. Lateral support with respect to vehicles;
4. Lateral support with respect to the roadway;

The categorisation gives a better relationship between the subdivision of driving tasks and the functional characteristics of driver support systems than other classifications.

<table>
<thead>
<tr>
<th>Support</th>
<th>Purpose and impact assessment</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1</td>
<td>The support of these systems deals with the relationship to other vehicles on the roadway. This task is of major importance for driving in normal traffic conditions.</td>
<td>Headway and Speed Adaptation (system names in practice: Adaptive Cruise Control, Autonomous Intelligent Cruise Control, Collision Avoidance System)</td>
</tr>
<tr>
<td></td>
<td><strong>Impacts:</strong> The application of Headway and Speed Adaptation systems are seen as promising first generation support systems. It can easily be understood that these systems can affect the efficiency of traffic substantially by their capabilities to control the headway and driving speed of individual vehicles. Although the system's vehicle control can be overruled, a positive impact can be expected when control algorithms are well-designed.</td>
<td></td>
</tr>
<tr>
<td>C2</td>
<td>The assisting but overrullable systems for longitudinal control can replace a part of the longitudinal driving task. The system only deals with the roadway.</td>
<td>Adaptation Speed to (Actual) Speed Limit, Adaptation Speed to Prevailing weather and road conditions.</td>
</tr>
<tr>
<td></td>
<td><strong>Impacts:</strong> These systems support the driver in some elementary driving tasks. It can lead to more driver comfort, traffic safety and efficiency. However, the assisting system can be overruled.</td>
<td></td>
</tr>
<tr>
<td>C3</td>
<td>These lateral systems support the lateral driving task with regard to the neighbour vehicles in other lanes. The adaptations can be overruled by the driver.</td>
<td>Lateral Collision Prevention</td>
</tr>
<tr>
<td></td>
<td><strong>Impacts:</strong> No major impacts on traffic flow quality are expected. Traffic safety will probably increase due to less side-collisions.</td>
<td></td>
</tr>
<tr>
<td>C4</td>
<td>The system will support the driver in maintaining an appropriate lateral position on the roadway or driving lane. The driver can take over the task any moment, for example when passing a vehicle.</td>
<td>Lateral Position Adaptation (see, e.g., Chira-Chowala, 1993)</td>
</tr>
<tr>
<td></td>
<td><strong>Impacts:</strong> These type of systems can be installed without the need of integration with other support systems. No major impacts on traffic flow safety or efficiency is expected.</td>
<td></td>
</tr>
</tbody>
</table>

TABLE 3.2 Functional groups of assisting-overrullable driver support systems
The functional categorisation provides a comprehensive overview of the possible systems. Most of the systems are yet not investigated with respect to their impacts. Exception is the longitudinal driver assistance system concentrating on the interaction with other traffic participants (C1). Several studies have examined this system concept with respect to traffic flow impacts, starting with e.g. BROQUA et al. (1991) and BENZ (1993). It is understandable why this system concept gets much attention by researchers. The system concept has several elements that make a more extensive study worthwhile, because, such a longitudinal driver assistance system:

- can quite easily be implemented compared to other (lateral) support systems (e.g., only sensor measuring distance to a single lead vehicle is needed);
- can be used in mixed traffic conditions (infrastructural adaptations or dedicated lanes are not required);
- can offer comfort and safety gains for drivers (important selling point for automotive industry);
- can potentially improve the traffic flow quality (road capacity, travel times) and reduce congestion.

Consequently, this system type is chosen as subject of further study. Section 3.5 will focus on this type of systems and give a more detailed discussion of the possible system definitions of this concept. Next section 3.3 gives a general overview of the driving task.
execution with the aid of support systems, using control schemes similar to the control scheme presented in Chapter 2.

3.3 Execution of the supported driving task

The execution of the driving task by human drivers has been analysed and described in section 2.4. In the following, a similar description based on the same control model is given for the case of supported driving with in-car electronics equipment.

State observation and estimation

A driver support system makes observations with sensors, such as acoustic devices, laser, radar, infrared devices or video imaging systems, see for example HALL (1995) or NWAGBOSO (1997). Depending on the exact system definition and sensor characteristics, the observation can include the following variables:

- distances to and speed differences with vehicles in front, and at the rear, and with vehicles on adjacent lanes;
- distances to the edge of the road and position on the lane.

The state observation can also include information received from other vehicles or the roadway by means of communication. This however requires infrastructural adaptations and communication facilities which will therefore be more expensive. Advantage is the availability of more precise data from the roadside and vehicles in the environment, information that cannot be obtained with on-board sensors only. The platoon-driving concept requires such a flow of information between vehicles and roadside to control the vehicles safely while driving at small gap distances. Section 5.3 describes this automated vehicle guidance concept in more detail. On the basis of the sensor observations computer algorithms estimate the actual distances, speeds, speed differences, and speed changes. Time delays $\tau_{obs}$ are needed to perform the observation and state estimation.

State prediction and control decision

Based on the observations, an estimation of the future state can be made. Firstly, the collected state information is filtered and will include only relevant material for the state prediction and control decision. The state prediction can be applied in order to determine the next control action. This control decision will depend on the system’s objectives.

Actually, the objectives of the system are predefined by the system designer and translated into parameter values and control algorithms. The variety of objectives of distinct support systems is partly explainable by the different support levels (warning, informing or assistance) and overrulability of the support system. The difference has been pointed out in section 3.2 and applied further on in this section, using control schemes.

The control decision is carried out by an electronic, computerized device, using predefined algorithms, parameters, and possibly stored historical and user dependent data. The processing time of the information depends on the amount of information collected in the observation process. For example, a video imaging system will receive much more (and different) information than a distance sensor mounted on the front bumper. The processing time is correlated with this amount of information. In general, the time $\tau_{dec}$ for making a control decision will be accomplished within a tenth of a second.
Control action
Finally, the control action is performed by adequately applying the brakes, steering wheel or accelerator pedal. These actuators are instructed by the electronic computer unit. Communication between sensors, computer unit and actuators is accomplished by electronic circuits. A time delay $\tau_{ac}$ is needed to control the actuators.

The overall time lag $\tau$ of a support system depends on the time needed for state monitoring, control decision, future state prediction, and actuator control. In general, the total time delay between observation and changed state is substantially smaller than that of human drivers. A value ranging from 0.1 to 0.2 s is often mentioned (RAO et al., 1993a).

In order to show the differences between support system types A to D, the informing, warning, assisting overrulable and non-overrulable support systems are each structured according to the control scheme presented for the human driver (figure 2.3).

![Diagram](image)

**FIGURE 3.5** Informing driver support system

Informing driver support system
Figure 3.5 shows the general control structure of a driver with an activated informing support system. The system provides information or advise about the supported task, using an appropriate user interface (display), which the driver can use in his control decision.

It is expected that informing systems will have no significant impact on microscopic traffic flow characteristics. With an informing system, the driver is still the essential part in controlling the vehicle and will only re-evaluate his decisions based on informative messages received from the support system. For example, studies by JANKE (1982) and REITER (1993) show little impact on road capacity. Under normal driving conditions there will be
a limited benefit of having an informing support system. Nonetheless, an intelligent in-vehicle application such as route guidance may have certain impacts on a more macroscopic scale (by distributing traffic over routes, increasing the utilisation of available capacity).

![Diagram of Driver Support Systems](image)

**Warning support system**

A system giving warning signals in dangerous situations can be structured as depicted in figure 3.6. A warning signal is essentially a kind of information provision to the driver, which can be applied in the control decision and state prediction. A warning support system is more complex than an informing system since the system must decide when a warning must be given, see, e.g. Hirst et al. (1997) and Landau (1995) for examples of a warning moment criterion and algorithm. Impacts on capacity are expected to be limited since the system is activated only sudden and brief, until the hazardous situation disappeared.

Positive effects on safety - a reduction of rear-end collisions - are expected by some researchers (e.g., Scott, 1997) and found by means of simulation, e.g., by Asher et al. (1997). A main problem in a simulation assessment is the estimation of the driver reliance on the system, thus the question to what extent drivers will react on the warning signal.
Overrulable driver assistance system

Figure 3.7 shows a schematic model of the functioning of an overrulable assistance system. This is the control model representing vehicle control with the so-called Adaptive or Autonomous Intelligent Cruise Control, see e.g., NILSSON (1995), WATANABE et al. (1995), and REICHART et al. (1996), a system design with the objective to assist the driver in his longitudinal driving task execution. The figure shows the additional driving subtask needed when such system is used: the decision to take over control, the so-called overrule action, and the decision to reactivate the system. To facilitate the overrule action, several designs options are possible. The system can be de-activated, for example, when a driver applies the brake or accelerator. The system reactivation can be accomplished by pressing a special button. The driver remains always responsible for performing the driving task, even with an overrulable support system.

A collision avoidance system, actively supporting the driver only during dangerous situations (see, e.g., TIERINA, 1995), also belongs to this category. The overrule decision is however less important for performing the driving task, since the driver controls the vehicle almost constantly without any support of the collision avoidance system.

Non-overrulable driver assistance system

Figure 3.8 shows the control model of a non-overrulable assistance system. The system is fully responsible for performing the driving task safely and efficiently, and the system should decide when to give the vehicle control back to the driver. An emergency stop functionality
will probably be available. Examples of these systems can be found in RAO et al. (1993), SWAROOP et al. (1994), from which it is concluded that large lane capacity improvements are attainable with such a platoon-driving design. It appears that the impact depends strongly on the applied algorithms for car-following and system performance parameters (e.g., sensor delay time, sensor range, and actuator control capabilities). The disadvantages of such an assistance system are the communication requirements and the need for dedicated lanes.

![Diagram of human driver and support system](image)

**FIGURE 3.8 Non-overrulable assisting driver support system**

A comparison of the control schemes for the distinct driver support systems shows that the assisting systems will have the largest impact on the driving task execution. Both driver and system make observations, predictions and control decisions when the vehicle is equipped with an overrulable assisting system.

The control scheme of the overrulable AICC described here (see figure 3.7), thus with the additional driver subtask for overruling system’s vehicle control, will also be applied in the simulation model (Chapter 7) to assess the traffic flow impacts.

### 3.4 Control benefits of driver support systems

We speculate that, with the current state of the art of automotive applications, a driver support system is able to perform part of the driving task more accurate, with less errors and faster, compared to human drivers. Using the notions from the control theory described in section 2.4, advantages can be expected in:

- state observations and estimation;
state predictions and control decisions;
control actions.

It is expected that both the various time delays \( \tau \) as well as error components \( \varepsilon \) will be affected positively by driver support systems. Considering that the actual values for both the time delays and error components at the individual level follow from probability distributions it is assumed that driver support systems will have as result smaller average values for these delays and errors, as well as smaller variances of the respective probability distributions. The latter implies among others an increasing homogenization of behaviour in the traffic flow, with possibly a higher predictability of this behaviour for the drivers.

A qualitative description of the theoretically expected benefits is given in the case that well designed, well functioning driver support systems partly replace the tasks of the human driver.

**State observation and estimation**

It is assumed that a well-designed, well-functioning support system is able to make observations \( y(t) \) more frequent, faster and more accurate than a driver could do. For an AICC system, observation time intervals of 0.1 s are reported by Shaout et al. (1997) and Fancher et al. (1996). The control decision delay and actuator delay for an AICC is estimated at 0.2 s (see e.g., RAO et al., 1993). According to experiments after reaction times of human drivers, a reaction time of 0.7 s is a low value (see e.g., Tijerina, 1995). Drivers have thus reaction times that are at least a factor two larger than the overall reaction time of an AICC system. However, a driver support system will normally focus on a limited number of stimuli (e.g., the distance and speed difference to the lead vehicle), while a human driver also can and likely will monitor other stimuli as well (e.g., distances and speed differences to vehicles on adjacent lanes, in front of the lead vehicle, and on the rear). A driver support system may improve only that part of the driving task execution it is designed for.

A comparison between driver’s and system’s task execution may be made with the comment that the observed benefits only hold for the supported task, and not for the complete driving task. Let us compare a driver assistance system and a human driver with respect to the execution of the longitudinal car-following driving task.

The estimation of the distance (and speed difference) towards a vehicle in front can be done very precisely and fast with a laser or radar, while the human eye and mind can only make a rough estimation. Thus, for the observation time delay \( \tau_{\text{obs}} \) will generally hold:

\[
\tau_{s,\text{obs}} < \tau_{h,\text{obs}}
\]

where the subscripts \( s \) and \( h \) refer to a support system and a human driver respectively.

The accuracy improvement of the state observation and state estimation by support systems can be described with the expected reduction of perception errors (smaller distribution and less bias) with respect to the observation of relative speeds and gap distances:

\[
E(\varepsilon_{s,\text{abs}}) < E(\varepsilon_{h,\text{abs}})
\]

\[
\sigma(\varepsilon_{s,\text{abs}}) < \sigma(\varepsilon_{h,\text{abs}})
\]

where

\[
E(\varepsilon_{s,\text{abs}}) < E(\varepsilon_{h,\text{abs}})
\]

\[
\sigma(\varepsilon_{s,\text{abs}}) < \sigma(\varepsilon_{h,\text{abs}})
\]
where $E(\varepsilon_{\text{obs}})$ denotes the expectation vector of measurement errors of the observed stimuli for the supported task, and $s(\varepsilon_{\text{obs}})$ denotes the variance vector of the errors.

Current state-of-the-art sensors have a limited sensor range of about 150 metres under good weather conditions (see e.g. SHAO et al., 1997 and RAO et al., 1993a) which is smaller than the observation range of human drivers under normal weather conditions. The mentioned benefits of a support system can therefore only be attained if the object is within the sensor range.

Another important characteristic of a support system is the small observation update frequency. The sensor of the support system can make observations at small constant and regular intervals of about 0.1 s, under all conditions (see e.g., RAO et al., 1993a). A driver is not able to carry out the observation task that regularly and intensively for a long period. This aspect will contribute to an overall improvement of the driving task performance. Again, it should be emphasised that we assume well-functioning sensors.

**State prediction and control decision**

The control decision based on state observation and estimation is assumed to be made quicker and more predictable when it is conducted by a driver support system. The decision can mostly be made within a few hundreds of seconds in contrast to normal drivers needing some tenths of seconds (Tjernina, 1995). Thus, the decision time delay $\tau_{\text{dec}}$ of support systems is expected to be substantially smaller than that of drivers:

$$\tau_{s,\text{dec}} < \tau_{n,\text{dec}}$$

(3.3)

We assume that the control algorithm is tested and implemented by the system manufacturer after a trade-off between objectives (comfort, safety, efficiency, energy, etc.) and will not change in time. Consequently, the system response under identical circumstances will demonstrate identical control actions, such as accelerations. Human drivers however, will mostly show different behaviour in same situations. We expect therefore:

$$E(\varepsilon_{s,\text{dec}}) < E(\varepsilon_{n,\text{dec}})$$

$$s(\varepsilon_{s,\text{dec}}) < s(\varepsilon_{n,\text{dec}})$$

(3.4)

where $E(\varepsilon_{\text{dec}})$ denotes the expectation vector of decision errors while $s(\varepsilon_{\text{dec}})$ denotes the variance vector of these errors.

**Control action**

Eventually, we expect that the control action can be executed more quickly and accurately by a support system. The actuators, such as the brake or steering wheel, can be controlled directly to a desired state as has been calculated by the support system’s computer algorithms. A driver also controls the actuators in order to achieve the desired state, however, this action is skill-based executed and based on knowledge and expectations for the sensitivity of the actuators. We expect that the manually controlled brake, throttle or steering actuator is less precisely controlled compared to automated actuator control.
systems.

For example, the electronically controlled ABS braking system facilitates optimal braking with a precision which cannot be achieved by a normally skilled driver.

Besides the mentioned benefits, the time delay for the actuator control $\tau_{act}$ is expected to be smaller with a support system. Pedal control and movement delays are estimated at 0.2 s for human drivers (TRB SPECIAL REPORT 165, 1998).

$$\tau_{a,act} < \tau_{h,act}$$  \hspace{1cm} (3.5)

Also, both the expectation of the errors as well as the variance vector in errors in applying the actuators correctly will most probably be smaller with a support system:

$$E(\varepsilon_{a,act}) < E(\varepsilon_{h,act})$$

$$S(\varepsilon_{a,act}) < S(\varepsilon_{h,act})$$  \hspace{1cm} (3.6)

The control actions of support systems are likely to be more precise due to the high frequency of state observation and interpretation of the situation, enabling a high frequency of actuator control. This also positively contributes to higher accuracy of the system.

In summary, it can be expected that driver support systems are able to execute the driving subtask - for which the support system has been developed - more frequently and more regularly, with less delays, and with less estimation and execution errors than human drivers can do (assuming operation of a well-functioning system and driver). This will probably lead to more alert and responsive driving, more homogeneous responses, less fluctuations, etc.

Still, the human driver should execute the non-supported driving subtasks (and possibly the additional tasks with respect to the interaction with the system) himself. Nonetheless, it can be hypothesised that the overall driving performance of the driver will improve. And as a consequence, the traffic flow quality might increase. This hypothesis is our subject of investigation. In order to conduct this investigation, promising driver support systems are selected for a detailed quantitative analysis. The next section describes the longitudinal driver assistance system selected for further study.

3.5 Longitudinal driver assistance systems

From the preliminary assessment in sections 3.2 and 3.3 it can be concluded that there are only a few groups of support systems with promising properties with respect to impacts on capacity, safety and comfort. These are the overrulable assisting systems for vehicle interaction and road control. The systems in this group correspond with the definition for longitudinal driver assistance systems, so for convenience they are denoted with this name further on. An AICC is an example of a system in this category.

The expected potential benefits on motorway capacity and safety of these headway-keeping systems are partly confirmed by the opinion of experts in this field. Marchau conducted a Delphi study in which experts were asked to give their opinion on questions related with the development of driver support systems (MARCHAU et al., 1998). The author
reports that 82% of the experts expect that the market introduction of longitudinal driver assistance systems will start before the year 2005. The experts also indicated that the accuracy of the systems is the main barrier for a rapid introduction.

The objectives, which include design issues, functions and limitations of this system type are discussed in the following subsections.

3.5.1 Objectives of a longitudinal driver assistance system

The design of a longitudinal driver assistance system depends largely on the objectives adopted by the system manufacturer, and possibly by the system settings of the car driver and car distributor. Although the main objective of such an assistance system can be described with 'increasing the comfort level of driver and improving the performance of the longitudinal driving task by assisting the longitudinal vehicle interaction driving task', subtle differences in the objectives are foreseen by the variety of design choices which can be made by the support system developers.

![Diagram of design issues of a longitudinal driver assistance system]

FIGURE 3.9 Design issues of a longitudinal driver assistance system

The design of a driver support system is thus related with the chosen objective by the manufacturer. Figure 3.9 illustrates important design issues which play a role in designing a longitudinal driver assistance system. We identify six main design variables of such assistance systems and give a short description for each of these in the following.

Longitudinal control

With respect to the longitudinal controller (the kernel of an assistance system), there are many considerations that affect algorithm and parameter selection. The selection also depends on the other design issues as will be brought up further on. Roughly, a longitudinal controller embodies the following elements (see the example in section 2.4.3):

- a desired speed-dependent minimum car-following gap distance setting;
- a stimulus-response mechanism determining braking, deceleration and acceleration
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characteristics.
In addition to the control algorithm, a car or system manufacturer may give a driver some freedom in determining his own comfortable parameter setting. The target speed will generally be set by the driver. Other adjustable parameters affecting the longitudinal control might be the following (see e.g. BENZ, 1996, and REICHART et al., 1996):
- headway setting;
- maximum and minimum accelerations;
- car-approaching, car-following and car-discharging behaviour (deceleration and acceleration sensitivity, the moment of starting deceleration);
- type and length of warning signals when reaching system boundaries (e.g., sound, buzz, display), see e.g. HIRST et al, 1997.

Autonomous / non-autonomous
A longitudinal driver assistance system is called autonomous in case no information from other vehicles or roadside traffic control centre is needed to control the vehicle. The non-autonomous driver assistance system is a feasible concept, but it requires communication with other vehicles and/or roadside facilities. Advantage of autonomous systems is the possibility to act in conventional manually controlled traffic, if designed well.

Overruable / non-overrutable
Due to operational limitations of the (early) assistance systems and traffic engineering considerations the driver assistance systems to be deployed shortly will be overruable. The non-overruable versions require a dedicated environment (e.g., dedicated lanes) and possibly communication with other vehicles in the flow or with a roadside-based traffic centre.

Driving with an overruable driver assistance system requires the motorist still to execute his other driving tasks and to replace the system control if necessary. In addition, the support system introduces an additional driving subtask (overrule the system or not). It can be questioned if the driver is capable of performing this new task accurately in borderline situations (see e.g. HOHEMA et al., 1996). The overrule aspect is described in more detail in section 3.5.3.

Manual reactivation / automatic reactivation
In case a longitudinal driver support system is overruable, a driver may intervene in the system's vehicle control, for example by braking or pressing the accelerator pedal. From that point, the assistance system is overruled. Two seriously different reactivation concepts can be distinguished.
- First option is that the driver must manually resume the driver assistance system - e.g. by pushing a resume button - when he thinks the situation allows the assisted mode.
- Second option is an automatic reactivation of the system if the driver stops his - braking - intervention.

An on/off functionality is always present in overruable driver assistance systems. The reactivation methods are outlined in section 3.5.3.

Full / partial acceleration range
The minimum and maximum supported acceleration level can theoretically be equal to the vehicle acceleration and deceleration capabilities. However, due to the combination of legal
considerations (responsibility driver/manufacturer in case of accidents), safety factors (alertness driver in case of full supported acceleration range) and technological limitations (sensor range, sensor observation limitations, state estimation problems) the first generation of assistance systems will only have partially supported acceleration and deceleration functionalities. A warning signal will be given when the system reaches its operational limits.

Full / partial speed range

Technological limitations with respect to the sensor range and performance dictates a maximum allowable speed at which the system supports the driver. The detection capabilities also determine a lower speed boundary (see e.g., NWAGBOSO, 1997). Standing objects and non-moving vehicles cannot be distinguished with the relatively simple and therefore affordable sensors as they will be expected to be implemented in the first generation longitudinal driver assistance systems (see e.g., NILSSON, 1995).

It is concluded that system design has an important impact on how, and to what extent, the driving subtask is assisted. The system design may therefore have a substantial impact on driver behaviour and consequently on the traffic flow impacts. Our study after traffic flow impacts is restricted to the design issues of autonomous and overrulable systems. Different acceleration and speed ranges are considered, and both reactivation options are taken into account in the experimental setup (Chapter 6).

3.5.2 Execution of the longitudinal driving task by a driver support system

The execution of the driving task by a driver supported with an AICC system follows the scheme of figure 3.7. We discuss the components of the figure in the following in order to explain the functioning of an AICC.

State observation and estimation

The longitudinal driving task by an activated assistance system (such as AICC) is performed by making state observations with sensors measuring the distance and relative speed towards the next vehicle on the same lane. During driving in curves, the system will try to identify the direct vehicles in front on the same lane by using the actual steering angle to adapt the sensor observation angle or by considering the steering angle in the information filtering and state estimation process.

The relative speed can be calculated after two consecutive distance measurements and with the aid of the following vehicle’s speed sensor. Some sensors are able to directly - that is after one scan - assess the speed of a lead vehicle. Irrelevant information is filtered before the control decision is made. An extensive technical description of Intelligent Cruise Control is given by (SHAOUT et al., 1997).

State prediction and control decision

A control decision is determined based on the implemented car-following algorithm in the on-board computer unit. An example of such an algorithm has been described in section 2.4.3. Other approaches are possible, for example, using fuzzy logic or self-learning systems (SHAOUT et al., 1997). After the calculation of the needed acceleration, an appropriate actuator control signal is determined and sent to the actuator for the control action.

The working principle of an AICC is schematically depicted in figure 3.10 and described
in the following.
As long as the equipped vehicle does not detect another vehicle within its sensor range, the vehicle will accelerate to the pre-set desired speed or maintains the desired speed when this is already the current driving speed (fig. 3.10a).
When at a certain moment the sensor of the equipped vehicle observes a slower driving vehicle within its range, the longitudinal controller calculates the needed deceleration to approach the vehicle smoothly and in a way that, eventually, both vehicles will drive nearly with the same speed at the system's pre-set desired car-following distance (fig 3.10b). Eventually, after a period of slowing down, the equipped vehicle follows the vehicle in front at the desired minimum distance with almost equal speed. Overtaking might be initiated by the driver. The assistance system follows the car as long as the vehicle in front is observed, the assistance system is activated and the operational boundaries are not exceeded (fig 3.10c).

FIGURE 3.10 Principle of functioning of an activated longitudinal driver assistance system (Autonomous Intelligent Cruise Control)

The first assistance systems to be introduced on the market (referred to as AICC) will have a limited assistance functionality. It is foreseen (see REICHTHT et al., 1996, KOPF, 1997, SHAOUT et al., 1997 and AUTOWEB, 1998) that the first generation of longitudinal driver assistance systems will be equipped by:
• limited deceleration and acceleration capabilities (about -2.5 to +1.5 m/s²);
• a restricted operational speed range (about 30 to 150 km/h);
• a manual reactivation design (resume button);
• a longitudinal controller imitating conservative driver behaviour with respect to safe distance keeping and approach behaviour;
• a possibility for the driver to adjust the safe distance setting within predefined boundaries (probably between 1.0 and 2.0 s headway).
Overrule decision

As a consequence of the system limitations of the first generation Autonomous Intelligent Cruise Control - deceleration and acceleration boundaries, as well as a minimum and maximum operational speeds - a driver is still responsible for the longitudinal driving task when the system warns the driver of having reached the operational boundaries.

A field operational test of a longitudinal driver assistance system indicated that drivers apply the brakes heavily, with a deceleration level higher than 0.25g, about 1.3 times for every 1000 miles of driving (BURGETT et al., 1998). These braking actions were mostly executed if the lead vehicle decelerated. Based on these findings, they concluded that an AICC system with a deceleration authority of 0.25g can manage almost all of the situations observable in practice, except situations in which the lead vehicle strongly decelerates.

Apart from the system limitations, a driver might intervene if (MINDERHOUD et al., 1998):
- the driver approaches a standing queue or objects (which follows from the sensor limitations);
- another vehicle wants to merge in the front gap;
- a lane change must be executed and speed must be adapted to merge in a gap smoothly;
- the right lane speed is higher than at the left adjacent lane, while according to the European legislation passing on the right side has been prohibited;
- the driver perceives an uncomfortable acceleration or deceleration (too small or too high level).

Thus, a driver can intervene - or overrule - the assistance system vehicle control if he perceives an uncomfortable situation or undesired action carried out by the assistance system. By pressing the brake or accelerator pedal, the driver overrules the system and the control is given to the driver. The assistance system is then idle and can be resumed by the driver himself or automatically by the system. These two solutions for system reactivation are outlined in section 3.5.3.

In some cases, the intervention is difficult to accomplish with an automatic reactivation functionality, for example if the system accelerates with a higher level than wanted by the driver. By pressing the brake, the system will be overruled with a deceleration. However, with the automatic reactivation, the braking pedal should not directly apply the brakes and decelerate, but first reduce the acceleration level. These problems can be solved with vehicle technology which will not be discussed here in detail. One possibility to overcome this problem is to introduce a single 'acceleration' control, a kind of joystick with which both positive and negative accelerations can be actuated. The braking pedal and accelerator pedal are then integrated in a single device - mounted on the steering wheel - which are controlled with the hands. With this approach, the brake and throttle actuators are continually applied depending on the desired acceleration.

3.5.3 Longitudinal driver assistance system reactivation design

An active longitudinal driver assistance system (AICC) can be overruled by the driver as explained in the previous subsections. This is also shown in figure 3.7 in the control model of the driving task execution with the 'manual control' block. Apart from the overrule decision, there is the possibility to switch the system on and off. These are important new driving tasks for the driver which require his attention and skilful performance. In order to
assess the potential impact of these new subtasks on driving performance and traffic flow, a description of this task is necessary.

![Diagram showing driver-system interactions](image)

FIGURE 3.11 Sequence of driver-system interactions during a trip. Two reactivation functionalities are shown.

In figure 3.11, the process of overruling, turning on and turning off the system is illustrated. The left side scheme (a.) assumes a manual reactivation AICC. The system must firstly be switched on before it can be applied. Thereafter, the desired speed, e.g. 100 km/h, must be set during driving (possibly, other system settings can be set, such as the desired headway, braking force, etc.). When the assistance system is activated, it will accelerate the vehicle towards the desired speed as far as possible. The system replaces the manual longitudinal driving task until the driver overrules the system. Then, the assistance system is still activated but idle. The system is reactivated after the driver applies a resume button. The assistance system can be switched off completely at every moment.

Another system design approach is also considered, since it was found that - for the latter described design - in some situations the driver thinks the system is active while it is actually idle, thus not active (see e.g., SCOTT, 1997). The improved design is illustrated in the right side scheme (fig. 3.11 b). Here, the driver must also switch on and set the desired speed to activate the assistance system. However, after an overrule action has been occurred - initiated by the driver - the system will automatically resume the assistance mode directly. This design prevents driver’s mistakes as they can occur with the ‘manual reactivation’ design due to reliance on an activated assistance system when the system is actually idle.

It is clear that the way of handling this equipment by the driver will affect its impacts.

In the experiments conducted in the underlying study (described in Chapter 6), we assume that both reactivation design types will be deployed in future Autonomous Intelligent Cruise Control systems. The modelling approach of the AICC handling by the driver is discussed further in Chapter 7.
3.5.4 **Benefits of a supported longitudinal driving task**

The functions and characteristics of a longitudinal driver assistance system as described in sections 3.4 and 3.5 will probably result in an improvement of the longitudinal driving task performance compared to current manual longitudinal driver behaviour. The general benefits for driver support systems described in section 3.4 are still claimed, but a more specific and practical description of the expected benefits of the *longitudinal* driver assistance systems can be given. This is done in Chapter 4 using microscopic traffic flow notions.

Generally, drivers can hardly maintain a constant speed for long periods, are inconsistent in their approaching behaviour, and drive at alternating car-following distances (HoeFS, 1972, Leutzbach, 1988 and Hogema et al., 1996). The expected decrease of the overall time delays in the driving task execution with AICC-systems enables a smaller car-following distance or headway to be adopted, and increases the responsiveness on stimuli. In addition, the system operation of a particular AICC design will be similar over the equipped driver population, so individual differences between these drivers will diminish to a large extent. The variation in individual car-following headways during a trip will be limited to a minimum as well.

Nevertheless, with several different AICC types present in the traffic flow, the hypothesised advantages will probably smaller or even negligible compared to the situation with non-supported driving. Such a traffic flow composition will probably not contribute to a more homogeneous driver behaviour. The number and extent of adjustable parameters of the deployed AICC systems should be restricted in order to gain maximum benefit from these assistance systems, otherwise differences between drivers' behaviour will remain.

The reduction of variability in gap sizes, speeds and speed shocks may result in higher capacities. These hypothesised benefits will be studied in detail in Chapter 4.

3.6 **Conclusions**

Based on a categorisation and assessment of potential driver support systems, it appears that autonomous longitudinal driver assistance systems are most promising to contribute to an increased capacity and other traffic flow quality aspects, without the need for infrastructural adaptations and without the need for communication with a traffic control centre.

It can be assumed that driver support systems can contribute to an improved driver performance by reduced average time delays, smaller errors, and less variance in the errors than with manual driving. This holds for all elements of the supported driving subtask, such as the state observation and estimation, future state prediction and control decision, as well as the control action performance.

Although the principle of a longitudinal driver assistance system is quite simple (supporting the driver with his longitudinal driving task in order to improve the driving performance, safety and comfort level) there exist a number of design issues which makes a wide range of system designs and system objectives possible. Each combination of design choices may affect the impacts on traffic flow differently. We speculate that, in the worst conceivable case, with several AICC types equipped with many freely adjustable parameters present in the traffic flow, the mentioned advantages of AICC use will be not be attainable. Such a traffic flow composition will probably not contribute to a more homogeneous driver behaviour compared to the situation with non-supported drivers only.
The first generation of longitudinal driver assistance systems - referred to as AICC - will exhibit some restrictions with respect to the assistance given to the driver. An AICC is an in-vehicle application consisting of one or more sensors, such as laser or radar, an electronic unit interpreting distance and speed data, and actuator equipment for direct control of brake and throttle actuators. The AICC-equipped vehicles can drive easily in today’s traffic: the infrastructure is simply shared with non-equipped vehicles. The ‘shared infrastructure’ possibility is one of the major advantages of autonomous driver support systems compared to other, more advanced automation concepts requiring infrastructural adaptations.

Important in the analysis of AICC is that a driver - driving in an AICC-equipped vehicle remains responsible for his driving task, including the supported longitudinal driving task, since not all situations can be handled properly by the assistance system. An additional driving subtask is introduced, namely the decision to deactivate the assistance system (and if the system is idle, to reactivate the system).

In the following chapters, the consequences of AICC introduction in the traffic fleet are investigated. Focus is on changes in traffic flow quality on motorways, to be elaborated in the next chapter.
CHAPTER 4

Traffic Flow Quality Assessment

This chapter deals with traffic flow quality assessment. Such an assessment is used in the sequel to the thesis in a comparative analysis of AICC-system layouts. Traffic flow quality is a comprehensive term for indicators describing microscopic and macroscopic traffic flow characteristics. Changes in the indicators can be used to judge driver support systems on their impacts. First, some definitions of traffic flow notions are presented (section 4.1). The possible microscopic changes in motorway traffic flow characteristics assuming a AICC deployment are outlined in section 4.2. The capacity notion is pointed out in section 4.3. Capacity calculation and estimation methods are assessed. Expectations about possible effects of AICC introduction are addressed. Stability of traffic flow at a motorway lane is discussed in section 4.4. The section provides definitions, results from past investigations and presents expectations of the impacts of AICC on traffic flow stability. The safety aspect is described in section 4.5. Safety indicators are described and a new approach to assess motorway safety is introduced. Section 4.6 closes the chapter with conclusions.

4.1 Introduction

Chapter 3 suggests that the introduction of driver support systems, especially AICC systems, may affect traffic flow characteristics because of a more effective and efficient performance of the driving task. This chapter discusses the quality aspects which should be taken into account in the evaluation of AICC concepts, and presents expectations about changes in the traffic flow quality as a result of AICC introduction. We use the term traffic flow quality as a comprehensive concept that comprises relevant indicators expressing the characteristics of a traffic flow. Traffic flow quality has many aspects, but we will concentrate on the traffic flow quality of individual drivers on motorways, and on traffic flow quality of motorway links and networks. These partly related quality levels are also referred to as microscopic and macroscopic, respectively. The traffic flow qualities of motorway links and networks, the macroscopic level, are important to the road authorities. Microscopic traffic flow quality is important to the individual drivers.

The microscopic and macroscopic levels have different quality aspects which can be used to evaluate the traffic flow quality. At the microscopic level, we can distinguish travel time (or travel speed), predictability, and comfort over a road section as quality aspects. At the
macroscopic level, the capacity is of major importance (together with the speed and density at capacity). Other macroscopic quality aspects are the stability of the traffic flow, and the safety. An overview of traffic flow quality aspects is given in table 4.1. It should be noticed that the microscopic traffic flow characteristics determine the macroscopic traffic flow quality aspects to a large extent.

<table>
<thead>
<tr>
<th>Microscopic</th>
<th>Macroscopic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Travel speed (travel time)</td>
<td>Capacity</td>
</tr>
<tr>
<td>Predictability</td>
<td>Stability (sensitivity to shock waves)</td>
</tr>
<tr>
<td>Smoothness and comfort</td>
<td>Safety</td>
</tr>
</tbody>
</table>

TABLE 4.1 Aspects of traffic flow quality

**Microscopic traffic flow quality aspects**

Microscopic traffic flow quality aspects express the drivers’ individual evaluation of traffic flow characteristics. The traffic flow quality for drivers on motorways is closely related to the experienced travel time (or travel speed) over a road section, the predictability of future traffic conditions (e.g., travel speed, waiting times, etc.), and experienced comfort of the trip (number of stops, needed accelerations and decelerations, possibilities to drive at the desired speed, etc.).

The importance rating of these aspects depends on the driver objectives, as indicated in section 2.3. Driver objectives and preferences differ between different drivers, so will the traffic flow quality judgements. The travel time for drivers over a stretch from A to B depends on their desired speed (which is the speed a driver wants to maintain in free flow traffic conditions) and road, traffic, and weather conditions. Drivers try to minimise the travel time within the constraints (the prevailing conditions and desired speed), based on their driving objectives.

With respect to AICCC introduction, the following microscopic changes may occur:

- supported drivers prefer other desired speeds;
- supported drivers will approach their desired speed better;
- improved travel conditions for all drivers as a consequence from macroscopic flow improvement with AICCC introduction.

The impacts that these changes may have on the microscopic traffic flow quality are analysed as part of the macroscopic changes in the following sections.

**Macroscopic traffic flow quality aspects**

The macroscopic traffic flow quality aspects refer to network or motorway related measures of performance, expressing the quality of that network or motorway. The macroscopic traffic flow quality is an important notion for the operator of a motorway network.

The optimal use, performance, or quality of any facility, in whatever kind of industry, can be expressed in one or more variables which are suited for this task. One of the important variables describing the quality and performance of a transportation facility is its capacity. Capacity expresses the maximum number of units (e.g. containers, vehicles) the facility (e.g. terminal, motorway) can handle at a given level of flow quality. The performance of a facility depends on the processes that occur during the presence of the units in this facility. At motorways microscopic driver behaviour determines the capacity.

For capacity analysis it is thus needed to have knowledge about the traffic processes and
microscopic driver behaviour at motorways. For our study, we are interested in the changes in microscopic driver behaviour that can be expected when the traffic fleet composition changes due to AICC deployment. Section 4.2 will therefore provide an outline of the expected changes that may occur when AICC systems are integrated in the vehicle fleet. The section is relevant for understanding the mechanisms that affect the capacity values of motorways. The capacity notion is described in detail in section 4.3. It presents among others capacity estimation methods and outlines the expected macroscopic traffic flow changes as a result of AICC deployment.

Another macroscopic traffic flow quality aspect is the stability of the traffic flow. This aspect is elaborated in section 4.4 together with thoughts about impacts of AICC on stability. Traffic safety is the last traffic flow quality aspect considered in this chapter (section 4.5). Indicators for assessing traffic safety are identified. The theoretical impact of AICC on traffic safety is described, and new purposeful safety indicators are developed.

4.2 Expectations on microscopic traffic flow impacts with AICC

The introduction of AICC will probably change the traffic flow quality both at the microscopic level for individual drivers, at the mesoscopic level for groups of drivers, and at the macroscopic level for the total flow. This section attempts to identify the possible microscopic changes qualitatively. We will use the scheme shown in figure 4.1 to explain the possible impacts of AICC deployment on changes in the traffic flow quality.

![Causal diagram of factors affecting flow levels and flow distribution on motorways](image)

In Chapter 2, a control model for the driving task execution has been described. This control model can also be applied for the supported driving subtask, as shown in Chapter 3. We expect that the use of AICC systems will reduce the time delays and errors involved in the driving task execution. It is expected that state observations and estimations, control decisions, and control actions needed for driving the car are more efficiently and accurately
performed with such a dedicated electronic device, which will likely affect driver behaviour of the driver-vehicle combination. This is investigated here qualitatively. Fig. 4.1 shows the causal relation between output (densities, speeds, flows) and input (driver behaviour, AICC penetration, traffic demand) of traffic processes on motorways. These factors will be elaborated in the following, as well as the intermediate factors (such as average gap distance, user class distribution, speeds per lane).

Factors affecting traffic flow quality changes
The driver behaviour block in figure 4.1 comprises the elements needed for execution of the driving task, see the control model in figure 2.3. The resulting control actions are (longitudinal) speed adaptations and (lateral) course and lane change decisions. We will concentrate on expected changes in drivers’ longitudinal speed adaptation behaviour, since this subtask is supported by AICC.

Several individual driver characteristics and preferences determine the execution of the longitudinal driving task. Drivers have different desired speeds, and drivers differ in preferred responses on stimuli. Another important element of the longitudinal subtask is the selection of a specific desired gap distance. Several researchers report that the desired gap distance is a function of speed (e.g., Wiedemann, 1974, Vermeij, 1992 and Hoxema, 1996). We refer to figure 4.10 for three example functions. But with the introduction of AICC, the (speed-dependent) desired gap distance is defined by the manufacturer or adjustable by the driver, possibly within boundaries. A constant time headway variable is often used to express the AICC gap distance setting. Besides what functional characteristics AICC-systems have, the impacts on traffic flow will largely depend on how these systems are used by the drivers.

The actual use of an AICC system in motorway traffic depend on how an individual driver experiences the traffic situation. Drivers’ characteristics, objectives and preferences, the encountered traffic situation and the AICC characteristics (supported speed range, supported acceleration range, etc) will influence the moments and time a driver will overrule and eventually reactivate the system (see e.g., Hoxema et al., 1996, Koff, 1997).

An important microscopic traffic flow parameter is the average gap distance between vehicles. As indicated in figure 4.1, it affects the average speeds and densities on a motorway lane. In addition, the minimum desired gap distance drivers want to maintain determines the maximum flow or capacity. Changes in the average gap distance (per vehicle) per lane depend on many factors which we will discuss in the following.

- traffic demand and user class distribution
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. For example, if the inflow of a lane is 900 vehicles/hour the average headway is 4 s. Assuming an average speed of the vehicles on this lane of 108 km/h, then the average gap distance is 120 m including the vehicle length. If the traffic demand is doubled to 1800 veh/h, the average gap distance is halved (60 m).

The distribution of the flows over the lanes depends also on the traffic demand, see for example figure 4.12. This can be explained by the differences in the desired speed preferences of drivers within a user class, and differences in the average desired speed
among user classes (such as passenger cars and trucks). At low flows, all vehicles can
drive unconstrained at their desired speed. As the flow rate increases, the use of the left
lane is intensified and the desired speed may not always be achieved. The speed at
capacity flow levels depends to a large extent on the user class with the lowest desired
speed (heavy trucks). The user class distribution (proportion of passenger cars, trucks,
etc. in the traffic flow) thus affects the average gap distance per lane by influencing the
lane change opportunities and decisions.
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 (HogeMa et al., 1996).
For further discussions, we assume a bottleneck motorway section with sufficient inflow
from the upstream section to arrive at the bottleneck capacity. We assume that both
trucks and passenger cars are present in the flow, and that these user classes have
different desired speed distributions.

- **AICC design and use**

  The AICC system design and drivers’ 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 are
  also important for changes in the traffic flow quality. We describe the impacts of these
design issues on expected changes in the gap distance in the following.

  - 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. Thus, 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. If speeds above 60 km/m are
    not supported, the system is not useful in free flow and capacity conditions of the
    motorway.

  - 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 (see e.g., Benz, 1996). 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 system will drive for a longer time at
    the defined headway setting, and approaches the desired speed closer. This affects
    the average distance gap positively (smaller gaps).

  - The reactivation method determines also the time a driver drives without the
    support functions of the system. In section 3.5.3 two reactivation design options
    are described. 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 maximise the time the system is activated. It follows that this design, compared to the manual reactivation type, will enlarge the time the system can accelerate towards the preset desired speed and can maintain the preset gap distance.

An important design variable of an AICC, directly affecting the average gap distance per lane, is the headway setting (the gap distance expressed in a time unit). Section 4.3.2 will demonstrate the impact of the desired gap distance of drivers and speed on the lane capacity. 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, which is illustrated in figure 4.2.

![Reduction of variation in gap distances with supported driving](image)

This gap homogenization is expected to be observed at large AICC penetration rates at capacity flow levels and especially at the left lanes. A reduction in the headway variation has been reported by, among others, FANCIER et al. (1997), HOGEMA (1995) and HOGEMA et al. (1996). HEIDEMANN (1998) derived theoretically an increased lane capacity when the variance in gap distances is reduced.

Vehicles driving at the right lane exhibit other behaviour, e.g., they will take into account the left adjacent lane speed to prevent passing on the right. This aspect is outlined in Chapter 7. In addition, the desired speed of vehicles driving on the right-hand-side lane might affect the headway distribution by means of influencing the lane distribution.

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. This car-following model (or algorithm) is important for possible changes in the driving task performance of AICC-equipped vehicles. Section 2.4.3 gives an example of a car-following algorithm.

By selecting appropriate values for the parameters, the behaviour of an equipped
vehicle can be improved compared to an average driver. Another aspect that contributes to an improved driving performance is the short observation time interval of an AICC. An AICC sensor makes measurements at short regular intervals, and can also make the control decision and perform the control action in a considerable shorter time than a human driver. The resulting reduction of the overall time delay $\tau$, and 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. We will illustrate this with an example.

Drivers have sometimes a very slow response on accelerations of a vehicle in front. This is illustrated in figure 4.3 with trajectories. It is shown that 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. Consequently, higher speeds are possible at same densities.

![Diagram showing trajectories](image)

**FIGURE 4.3** Adequate and alert control actions with supported driving as leader's state changes

Furthermore, since the longitudinal behaviour of AICC systems is universal (given a specific type) differences in car-following behaviour between drivers will diminish, while inconstant car-following behaviour of drivers when following a vehicle in front will also decrease, 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. These characteristics of a well-designed AICC-longitudinal controller, compared to varying human car-following behaviour, will probably lead to a reduced average gap distance per lane, and higher speeds on average. At the end, a higher capacity may be hypothesised, even with unchanged average minimum gap settings.

- **the 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.

We will summarize the expectations on changes with figure 4.4. The left chart in figure 4.4 shows the expected change in the headway probability density function at capacity flow levels in case the vehicle fleet is replaced with AICC-equipped vehicles. To facilitate a comparison, we assume that the AICC-headway setting is equal to the desired headway drivers normally try to maintain in the non-supported situation. Thus the average preferred headway is the same for the hypothetical 100% AICC and 0% AICC case.

We expect that the headway distribution is shifted to the left and tighter due to the adequate and quick actions performed by the AICC system. The average observed headway will likely decrease (vehicles will follow each other closer) since extreme high headways from laggards will be abandoned. Extreme low headways are also assumed to be eliminated.

The speed distribution is expected to exhibit the same properties (right side figure 4.4). With full penetration of AICC the speed variance is expected to decrease due to the reduction of drivers with extreme large headways, restricting the attainable speed. We refer to the trajectories in figure 4.3 which show the impact of accurate, and responsive performed control actions. Due to the elimination of extreme low speeds, the average lane speed will probably increase. As a consequence, the distribution of flows over the lanes might change.

![Graph showing qualitative differences between probability density functions of headway and speed at capacity conditions of the motorway in cases with and without AICC-equipped vehicles.](image)

FIGURE 4.4 Expected qualitative differences between probability density functions of headway and speed at capacity conditions of the motorway in cases with and without AICC-equipped vehicles

The analysis in this section shows the expected improved driving performance of drivers using an AICC. The impact on the macroscopic level follows from these microscopic changes. Since our study focuses mainly on capacity impacts, the macroscopic capacity notion is described in more detail in next section 4.3.
4.3 Motorway capacity

In the introductory chapter we showed that motorways comprise only a small percentage (less than 2%) of the total road network. Nevertheless, motorways are responsible for a large proportion of the total vehicle-kilometres. In the Netherlands almost 40% of all vehicle-kilometres are driven on motorways. These figures indicate the importance of motorways in developed countries. Our study is restricted to motorways. Not only because motorways carry a large proportion of all vehicle-kilometres, but also since traffic processes on motorways are relatively uncomplicated compared to other road types. The performance (or capacity) of motorway networks is not defined yet clearly, but it is obvious that the network capacity depends on the bottlenecks in the network. These bottlenecks are e.g. on-ramps, off-ramps or other sites in a motorway network where many lane-change manoeuvres are needed by the drivers to continue their trip on another link. Capacity restrictions are normally not encountered on uniform motorway segments, due to the absence of bottlenecks, although a change of weather conditions may decrease the capacity of such motorway link suddenly.

Based on these considerations, we decided to focus on the capacity of motorway segments that include a bottleneck. A thorough description of the capacity notion is provided since it is an essential element in our study.

First section 4.3.1 describes and analyses the capacity notion and its characteristics. Then section 4.3.2 presents a car-following model for calculating a capacity value with assumptions about drivers’ preferred minimum desired gap distance. The model is useful to determine a theoretical upper limit of the motorway lane capacity, among others for preliminary impact assessment of AICC-system design on motorway lane capacity. Section 4.3.3 outlines capacity estimation methods and describes the requirements for application of the selected ‘queue discharge flow distribution’ method. Finally, section 4.3.4 gives the expectations on motorway capacity impacts as result of AICC use in the vehicle fleet.

4.3.1 Capacity notion

Various capacity definitions can be found in literature, see e.g. BOEKHOLT et al. (1996), CIA (1999), and HCM (1994). The HCM gives the following definition for the capacity of a roadway facility:

- The maximum sustained 15-minute rate of flow that can be accommodated by a uniform segment under prevailing traffic and roadway conditions in a specified direction.

We adopt this definition but adapt the time interval in which flow rates are aggregated into capacity values. This is elaborated in section 4.3.3. In addition, our ‘maximum flow’ is concisely described in the following, by considering capacity as a stochastic variable, and applying an unambiguous capacity estimation approach.

Still, several aspects make a practical single definition of capacity complicated, among others, the two-capacity phenomenon and the difference between motorway lane, motorway bottleneck, and motorway network capacity. We discuss these issues in the following.

Motorway network, link, and bottleneck capacity

The motorway network capacity notion expresses the optimal use of the motorway network.
Although no unambiguous definitions of network capacity have been found in literature, the importance of the motorway network capacity notion can easily be illustrated with an example. If, for example, the lane capacity of motorways increases by 10% with full penetration of a specific longitudinal driver assistance system, this does not automatically imply that the network capacity will increase accordingly. When we assume that AICC will hardly increase the capacity of the underlying road network (due to complex traffic situations that require manual driving for an efficient and safe driver performance), it is questionable if the motorway capacity increase is relevant. The egress and entry points of the motorway network might become the new bottlenecks, limiting the overall benefits of a substantial lane capacity improvement (see e.g. RAn e.a., 1997 and MINDERHOUD, 1999b).

Motorway link capacity represents the maximum attainable flow on a motorway link, with or without a bottleneck. This capacity notion is relevant and measurable, mostly expressed in vehicles/hour or passenger car equivalents to take into account the different vehicle characteristics in the vehicle fleet. The capacity notion can hold for the complete roadway (two travel directions), for a main line (one travel direction) or for a single lane.

We restrict our capacity analyses to bottleneck locations, the weakest points in the motorway network (such as on-ramps, weaving sections and lane-drops). If significant changes in capacity can be demonstrated for these bottlenecks we may safely assume that the whole motorway network capacity is affected accordingly.

**Stochastic nature of motorway capacity**

The maximum flow is not a constant value. Maximum flows observed at a cross-section of a motorway facility vary as a result of several factors. The stochastic nature of maximum flows results from the many time-dependent trip, vehicle, and driver variables present in the traffic process (see, among others, MINDERHOUD et al., 1997). Important varying aspects are the following:

- vehicle fleet composition;
- traffic composition according to trip purpose;
- weather, road and environmental conditions;
- time of day, day of week, month of year;
- applied measurement method (time, location, observation period).

Observed maximum flows appear to follow a distribution, the form of which depends on the chosen definition and measurement method. In most cases a normal distribution applies. For the remainder of our study maximum flows are considered to be realisations from a probability distribution and we define capacity as a location parameter of this distribution, e.g. mean or median value.

Figure 4.5 depicts an example of a maximum flow probability density function. The mean of the density distribution is a
possible location parameter for the capacity. However, another value of the density distribution may be selected for this purpose, e.g. the 90th percentile.

The two-capacity phenomenon at a motorway bottleneck

The capacity of a motorway can be illustrated and elaborated with the aid of the fundamental diagram, describing the relation between speed, flow and density of traffic in a cross section (see May, 1990). Figure 4.6 presents two speed-flow diagrams of a three-lane motorway, one applying to upstream section of a bottleneck, the other describing the flow at the downstream section of the bottleneck. The upstream section shows smaller maximum flow rates than the downstream section. Theoretically, the free flow branches of the two sections are similar in case the on-ramp is closed. In practice however, the on-ramp traffic flow restricts the maximum attainable flow rates in the pre-queue traffic state (point a. in fig. 4.6). This holds for the cross section of one travel direction as well as for a single lane. We refer to Appendix A for empirical data of a three-lane motorway that exhibits this characteristic. Section 6.6.1 gives a similar example for a simulated two-lane motorway.

A second important difference between the upstream and downstream section is the lack of a congested branch (point c. in fig. 4.6) in the speed-flow relationship of the downstream section. At the downstream section, at a sufficient distance from the bottleneck, the drivers have accelerated their vehicles towards higher speeds. The traffic state is not congested, but is denoted with the 'queue discharge' state. It appears that the queue discharge flow rates are also higher at the downstream section (point b. in fig. 4.6) than at the upstream section. The on-ramp flow is responsible for the lower flow rates, as well as for the low speeds at the upstream section.

![Diagram showing speed-flow relationships upstream and downstream an on-ramp bottleneck](image-url)

**FIGURE 4.6** Speed-flow relationships upstream and downstream an on-ramp bottleneck
In conclusion, we established that capacity flows should be measured downstream the bottleneck, at a sufficient distance from the on-ramp influence area (about 1 km). The flow rates at the downstream location must not be disturbed by other bottlenecks (and their queue spill-back) located further downstream.

According to the literature (see, among others, Cassidy et al., 1999) and based on many observations we presume that there exist two different maximum flow states, namely pre-queue and queue discharge respectively, each having its own maximum flow distribution:

**Pre-queue maximum flow**
We define the pre-queue maximum flow as the maximum flow rate observed at the downstream location just before the onset of congestion (a queue) upstream.
These maximum flows are characterised by the absence of queues or congestion upstream the bottleneck, high speeds, instability leading to congestion onset within a short period, maximum flows show a large variance.

**Queue discharge maximum flow**
The queue discharge flow is the maximum flow rate observed at the downstream location as long as congestion (a queue) exists.
These maximum flow rates are characterised by the presence of a queue upstream the bottleneck, lower speeds and densities, a constant outflow with a small variance which can sustain for a long period, however with lower flow rates than in the pre-queue flow state.

Figure 4.6 illustrates that the pre-queue capacity and queue discharge capacity can only be measured downstream the bottleneck location. It is also indicated that the queue-discharge capacity is lower than the pre-queue capacity. This is often called capacity drop. It can be observed that the corresponding speed at capacity is lower after the congestion onset. In literature (see e.g. Banks, 1991, Persaud et al., 1988, 1998), the phenomenon of the capacity drop has been noticed and analysed. Average capacity drop percentages of -1% to -15% for all lanes have been found. The capacity drop of the median lane often is even much higher, e.g., -10% to -26%. In a recent study by Cassidy et al. (1999), a capacity drop of about 10% was found. Based on these studies we state that the long-run queue discharge flow should be viewed as the capacity of the bottleneck, since this state can be sustained for long periods while its flow rates show only small variability, in contrast to the higher but unstable maximum flows that can be observed before congestion onset.

One explanation for the capacity drop phenomenon is the assumed preference for larger headways if drivers experience congested conditions (Dijk et al., 1997a). Differences between acceleration and deceleration behaviour may also contribute to this phenomenon. In compliance with the utility maximisation theory described in Chapter 2, it can be claim that drivers try to optimize their comfort and safety perception level. Typically, the individual travel speed in congestion hardly depends on the individual driving style but mainly on the prevailing conditions: individual optimization of travel speed in congestion is restricted.

Figure 4.7 shows example maximum flow distributions for the pre-queue and queue discharge state respectively. We select the stable queue discharge state as basis of our capacity estimation procedure. The mean of the queue discharge flows $C_{eq}$ will be applied as a capacity estimate. Although this capacity estimate underestimates the total capacity of a cross-section, for comparison of AICC concepts this approach is preferable to the unstable
and highly varying pre-queue flow rates. The nonstationary traffic conditions in the transition from pre-queue to queue discharge flows should not be included in the capacity analyses.

Next section 4.3.2 discusses the factors affecting lane capacity, and presents a theoretical model for calculation of the lane capacity. Available capacity estimation methods are briefly described in section 4.3.3 in which the choice for the queue discharge distribution method to be used in our study will be motivated. The expected impacts of AICC use on capacity of bottlenecks will be dealt with in section 4.3.4.

4.3.2 Safe gap distance models in car-following behaviour

It is important to understand the mechanisms how AICC can change capacity. When we want to formulate expectations about changes, knowledge about the influencing variables is needed. We assume that the capacity of a single lane will depend on, among others things,

- vehicle speeds and speed differences among vehicles;
- desired gap distance of a driver and its variation among drivers;
- desired gap distance of a driver as function of time;
- desired gap distance of a driver as function of speed;
- car-following behaviour (approaching and following behaviour of drivers).

This section describes the impacts of these variables on lane capacity, assuming all vehicles driving at a constant speed, all driving at the same desired gap distance, while the vehicles progress under stationary conditions (without accelerations or decelerations). We neglect the impact of lane changes or left lane speed adaptations since we focus on a single lane. The approach followed here is appropriate to determine a theoretical maximum flow, which is useful for comparison of AICC systems without conducting simulation experiments. More advanced approaches take into account the desired speed and variation in gap distances, see e.g. HEIDEMANN (1998).

The theoretical bottleneck lane capacity can be estimated with assumptions about safe distance behaviour of drivers in capacity conditions. When we assume that all drivers on a lane drive at their desired gap distance determined with an adopted safe distance model, the relationship between speed and lane capacity can be defined. Purpose of such an analysis is the calculation of the upper boundary of the lane capacity given a safe distance strategy. Such safe distance models are, for example, applied in a car-following algorithm of an AICC system and used in microscopic simulation models for representing drivers' gap distance keeping behaviour.

Traffic flow theory

Firstly, some basic relationships between spacing, headway, density and speed are described (see e.g. MAY, 1990). Let us define:
i : index for vehicle
\( d \) : net gap distance [m]
\( l \) : vehicle length [m]
\( x \) : driving speed vehicle [m/s]
\( s \) : gross gap distance [m]
\( h \) : gross time headway [s]
\( q \) : flow rate [vehicles/hour]
\( c \) : index capacity state
\( n \) : sample size
\( m \) : safety margin [m]
\( \tau \) : reaction time [s]

**FIGURE 4.8 Distance notions of two consecutive vehicles at instant t**

At a specific cross-section of a motorway, measurements of passing times of vehicles can be performed. The gross time headway, which is the time headway that includes the vehicle length passing time, of vehicle-driver combination \( i \) at cross-section \( x_i \) is defined as the time between the passage of the rear of vehicle \( i-1 \) and the rear of vehicle \( i \) at cross-section \( x_i \). However, when we take a picture of the motorway lane from sufficient altitude at a time instant \( t \), the passage times are not known although the intervehicle distances can be determined easily. The time headway of a subject vehicle \( i \) can be approximated by dividing the intervehicle distance by subject’s speed, see figure 4.8. This results in expression (4.1):

\[
h_i(t) = \frac{d_i(t) + l_i}{x(t)} \quad [s] \quad (4.1)
\]

where the sum \( d_i(t) + l_i \) is equal to the distance gap \( s_i(t) \). If \( n \) vehicle-driver combinations pass the cross-section during a given period, then the mean time headway over the sample is:

\[
\bar{h} = \frac{\sum h_i}{n} \quad [s] \quad (4.2)
\]

Under the assumption that all time headway measurements (direct or indirect according to expression 4.1) of vehicle-driver combinations are made at the capacity state of the bottleneck, the lane capacity \( q_c \) can be determined using the formula:

\[
q_c = \frac{3600}{\bar{h}^*} \quad [\text{veh/h}] \quad (4.3)
\]

in which \( \bar{h}^* \) is the mean gross time headway of drivers during the capacity state of the bottleneck.

By using a model for the relationship between driving speed and desired minimum gap distance capacity values can be calculated. Essential in this approach is the selection and justification of a safe distance model determining the desired minimum gap distance \( s_{\text{min}} \). Stochastic safe distance models - assuming differences in gap preferences among drivers - will not be discussed here: a simulation approach is envisioned to assess the impacts of the stochastic elements in driver behaviour. In the continuation of the section a less complicated
deterministic approach is described to illustrate the capacity estimation with, and limitations of this approach.

**Safe distance models**

Various models for safe distance keeping exist and are implemented in traffic simulation programs (see e.g., VAN WINSUM, 1991, VERMIJS, 1992 and WIEDEMANN, 1974). In the following, we describe a model specification which is applicable to a wide range of driving styles. The actual driving objective depends on the parameter values chosen (LEUTZBACH, 1988 and BROQUA et al., 1991 give some examples). The general kinematic safe distance model is presented in equation (4.4):

\[
s_{i, min}(t) = l_i + m_i + \dot{x}_i(t) \cdot \tau_i + \ddot{x}_i(t) \cdot \dot{T}_{i, brake} + 0.5 \cdot a_i \cdot (T_{i, brake})^2
- \dot{x}_{i-1}(t) \cdot T_{i-1, brake} - 0.5 \cdot a_{i-1} \cdot (T_{i-1, brake})^2 \quad [\text{m}] \quad (4.4)
\]

in which \(l_i, m_i, \tau_i, a_i\), and \(T_{i, brake}\) are constants. The values depend on vehicle type and driver \(i\). The vehicle speed is denoted by \(\dot{x}_i\), which is a function of time. It is important for a correct interpretation of \(a_{i}\) and \(a_{i-1}\). Constant \(a_i\) is the subjective expectation by driver \(i\) of the deceleration performance of its own vehicle \(i\). Constant \(a_{i-1}\) is the subjective expectation by driver \(i\) of the deceleration performance of vehicle \(i-1\) direct in front.

A simplified, identical formulation of the kinematic model is the following:

\[
s_{i, min}(t) = l_i + m_i + z_1 \cdot \dot{x}_i(t) + z_2 \cdot \ddot{x}_i(t) ^2 \quad [\text{m}] \quad (4.5)
\]

where \(z_1\) and \(z_2\) are constants. These constants, or model parameters, are correlated with behavioural parameters referring to the expected deceleration performance of subject's own vehicle and subject's leader, as well as the reaction time. This will be shown in the derivation of equation 4.4.

Different parameter settings in either eq. (4.4) or eq. (4.5) will lead to different safe distance strategies. The following safe distance keeping behaviours can be distinguished by applying different model parameters:

**Brick-wall distance keeping**

The brick-wall distance keeping strategy is based on the assumption that the direct vehicle in front is a non-moving object - even if this not true - and that the subject vehicle-driver combination wants to avoid a collision. Adopting this strategy results in conservative, unrealistic driving behaviour.

**Reaction time distance keeping**

This safe distance keeping strategy takes into account the actual speed of vehicles ahead in the determination of a control action. Within this class, three different parameter combinations and behavioural assumptions can be considered:

- **Prudent behaviour**: The driver-vehicle combination judges its own deceleration capabilities compared to the expected deceleration performance of the vehicle in front as insufficient for a safe distance keeping \((a_i > a_{i-1})\).
- **Progressive behaviour**: The driver-vehicle combination assumes its own deceleration capabilities equal to the expected deceleration of the vehicle in front \((a_i = a_{i-1})\).
- **Rash behaviour**: The driver-vehicle combination judges its own deceleration capabilities
compared to the expected deceleration performance of the vehicle in front as sufficient and even better ($a_i < a_{i-1}$), so the chosen following headway will be less than the safe headway determined with the progressive or prudent strategy.

**Derivation of a generic safe distance model with behavioural parameters**

Some assumptions about human behaviour are needed to derive a generic mathematical safe distance model with the characteristic behavioural constants, see eq (4.4). First assumption is that of a constant deceleration during applying the brakes. This simplifies the calculation procedure while it approximates braking behaviour in practice quite well. Secondly, we assume that the deceleration level is independent of the driving speed. This is appropriate as long as drivers brake at a comfortable level.

The components of the minimal required gap distance $s_{i,\text{min}}$ in case the brick wall distance strategy is adopted, are shown in figure 4.9.

![Diagram of braking distance components](image)

**FIGURE 4.9** Components of the braking distance $s_i$ for vehicle $i$ approaching standing vehicle $i-1$ (Source: Leutzbach, 1988)

The components are defined as follows (Leutzbach, 1988):

- $r$: reaction time distance (resulting from observation, decision, and control action time delays) [m]
- $b$: minimum braking distance with subjective expected deceleration level [m]
- $a$: acceleration level (negative value is deceleration) [m/s$^2$]

The minimum distance gap $s_{i,\text{min}}$ of vehicle $i$, in case the driver approaches a vehicle $i-1$ in front with safe distance keeping based on the brick wall strategy, is a summation of the components shown in figure 4.9. A minimum braking distance $b_{i,\text{min}}$ is required to determine the minimum safe distance:

$$s_{i,\text{min}}(t) = l_i + m_i + r_i(t) + b_{i,\text{min}}(t) > s_{i,\text{min}}(t) \quad [m] \quad (4.6)$$

In case the prudent, progressive, or rash strategy is applied, the speeds and assumptions about the potential deceleration level of the vehicle in front must be incorporated. In practice, this means that the needed gap distance can be much shorter than derived with the
brick wall strategy, eq. (4.6). The assumed braking distance $b_{i,t}$ of the vehicle in front enables the following vehicle $i$ to maintain a shorter minimum gap distance. Equation (4.7) describes the minimum gap distance required with these more realistic safe distance strategies. The equation is identical to eq. (4.4).

\[
s_{i,min}(t) = l_i + m + r_i(t) + b_{i,min}(t) - b_{i,t} \quad [m] \quad (4.7)
\]

in which $b_{i,min}$ is the subjective expected minimum braking distance of subject $i$, its value depends on the constant $a_i$ as well as on the driving speed. It holds $b_{i,min} = \dot{x}_i \cdot T_{i,brake} + 0.5 \cdot 0.5 \cdot a_i \cdot T^2_{i,brake}$. Variable $b_{i,t}$ is the braking distance of the lead vehicle $i-1$ at instant $t$ as expected by subject $i$. It holds $b_{i,t} = \dot{x}_{i,t} \cdot T_{i,brake} + 0.5 \cdot a_i \cdot T^2_{i,brake}$. Variable $r_i$ is the distance subject $i$ drives during his reaction time, thus without adjusting his speed. It holds $r_i = \dot{x}_i \cdot T_r$.

Now the generic mathematical description for the required minimum gap distance $s_{i,min}$ can be specified by replacing the reaction distance and braking distance components in equation (4.7) with the appropriate kinematic relationships. Additionally, the subjective expected braking time $T_{brake}$ for vehicles $i-1$ and $i$ can be calculated by $T_{brake} = -\dot{x}_i / a_i$ (in which a negative acceleration $a$ must be applied). Furthermore, capacity estimation based on safe distance models assumes the cars driving at an equal constant speed, at any time instant $t$. Thus it holds $\dot{x}_i = \dot{x}_{i,t}$, or shortly $\dot{x}$ at capacity conditions. Formula (4.4) has only practical meaning when equal speeds between vehicles hold (see e.g., Leutzbach, 1988).

An expression for the maximum lane flow as a function of driving speed and driver parameters can be obtained by eq. (4.3) using eqs. (4.1) and (4.4). This results in the following generic relationship for the maximum flow as function of bottleneck speed (in metres per second), with $q_e$ in vehicles per hour:

\[
q_e(\dot{x}) = \frac{\dot{x} \cdot 3600}{l_i + m + \bar{r} \cdot \dot{x} - 0.5 \cdot \left(\frac{1}{a_i} - \frac{1}{a_{i-1}}\right) \cdot \dot{x}^2} \quad [\text{veh/h}] \quad (4.8)
\]

From equation (4.8), the parameters $z1$ and $z2$ applied in equation (4.5) can easily be obtained. For $z1$ it holds:

\[
z1 = \bar{r} \quad [s] \quad (4.9)
\]

Thus $z1$ equals the average time delay assumed for the drivers. For parameter $z2$ we find a relationship that includes the assumptions about the expected deceleration performance of subject vehicle $i$ and subject's leading vehicle $i-1$:

\[
z2 = -0.5 \cdot \left(\frac{1}{a_i} - \frac{1}{a_{i-1}}\right) \quad [\text{m/s}^2] \quad (4.10)
\]

The maximum flow versus speed function has an optimum value if there exists a first derivative of the maximum flow with respect to speed. The optimum bottleneck speed $x_e$, at which capacity is reached, can be formulated as follows, with $x_e$ in kilometres/hour:

\[
\dot{x}_e = 3.6 \cdot \sqrt{\frac{T + \bar{m}}{0.5 \left(\frac{1}{a_{i-1}} - \frac{1}{a_i}\right)}} \quad [\text{km/h}] \quad (4.11)
\]
For equation (4.11), there exist only solutions if $a_{i,t} < a$, (using negative signs for negative accelerations), thus if drivers adopt the relatively safe prudent distance keeping strategy. It appears that the speed at capacity is independent of the reaction time parameter.

**Example of safe distance model application to calculate lane capacity**

Safe distance models can be applied in preliminary capacity impact estimation studies of AICC-system deployment when the safe distance model of the assistance system is known. This approach has some limitations for a broader use. Safe distance models focus on single lane driver behaviour and do not consider vehicle interactions between adjacent lanes. No differences between user classes are taken into account. Nonetheless, many microscopic traffic flow models use such a model in order to determine the desired minimum gap distance of driver-vehicle combinations. The desired minimum gap distance specification is an important element in a model since it affects the attainable road capacity directly, see eq. (4.8).

As an example, the microscopic simulation model FOSIM employs a safe distance function of the simplified general form (equation 4.5), see VERMIJS (1992), with the vehicle length $l$, set at 4 m in case of passenger cars, an average margin of 2.5 m, while $z_1 = 0.8 \, s$ and $z_2 = 0.01 \, m^2/s^2$. The parameters vary among user classes.

We will show further on that equation (4.5) with these assigned parameter values is equivalent to the prudent distance strategy. Another well-known safe distance model specification is the one applied by e.g. WIEDEMANN (1974) and REITER (1994). They adopt the following function in their simulation models to determine the average minimum desired gap distance of drivers on motorways:

$$ s_{i, \text{min}} (t) = l + m_i + \alpha \cdot (\dot{X}_{i,t} (t) )^{0.5} \quad [m] \quad (4.12) $$

with $\alpha$ estimated at 4.5 m s$^{-0.5}$. Distance variables are expressed in metres and speed expressed in metres/second.

To illustrate the use of safe distance strategies, three models are compared. First model is the FOSIM model which corresponds with the 'prudent' safe distance strategy. The second model represents the 'progressive' strategy, implying that drivers assume equal deceleration levels if a leader suddenly brakes. The third model is based on Wiedemann's approach.

Figure 4.10 shows a comparison of the desired minimum gap distance functions discussed. For all functions, a vehicle length of 4 m and safety margin of 2.5 m has been assumed. All functions show an increasing gap distance with increasing speed. However, with Wiedemann's model the rate of change diminishes with increasing speed. The progressive strategy represents behaviour in which only the reaction time (set at 0.8 s) is taken into account for the safe distance selection. This strategy shows the smallest gap distances over the speed range zero up to 120 km/h. In our study, we adopt the prudent approach which has been employed in FOSIM.
Figure 4.11 shows the resulting lane capacity estimates for the three tested models over the speed range of zero to 120 km/h, calculated with eq. (4.8). The three models show quite different characteristics. An optimum capacity flow rate (and corresponding speed at capacity flow rate) can only mathematically be determined for the prudent model, which is similar to the distance function implemented in FOSIM. The Wiedeman and progressive safe distance models deliver high capacity values at high speeds. This is quite unrealistic. We conclude that the prudent safe distance strategy matches best with actual human behaviour with respect to the estimated capacity and speed at capacity.
The prudent strategy will be applied in our simulation model. The characteristic points of the prudent strategy (FOSIM curve in fig. 4.11) are comparable to empirical data. Today's lane capacity is in the range of 2,500 to 3,000 vehicles/hour at speeds of 90 km/h. For empirical maximum flow values see also Appendix A.

Capacity estimation based on assumptions of safe distance behaviour is useful in preliminary assessments of theoretical maximum flows attainable with driver assistance systems (AICC), if the headway setting is known. A first impression of positive or negative impacts of assistance systems - compared with the achievable maximum flow by human drivers - can be obtained. However, in order to have more realistic capacity estimations empirical estimation methods must be used, applied on real-life motorway traffic flow data or simulation generated traffic flow data. The next section summarizes the available empirical estimation methods and summarizes the selected approach.

4.3.3 **Empirical capacity estimation methods**

A capacity estimation approach is required for determining a correct capacity value appropriate for comparative purposes, see e.g. MINDERHOUD et al. (1996c, 1997). A capacity estimation method with unambiguous qualities is necessary to assess the capacity value reliably. An overview of available capacity estimation methods, the selected method, and experimental set up choices are summarized in the following.

---

**Methods which do not require capacity observations**

Methods based on free flow traffic and constrained traffic measurements are generally less reliable than methods using capacity measurements. If the capacity state has not been reached and a capacity estimation must be performed the following methods are applicable:

- **Headway Distribution method.**
  The observed headway distribution and assumptions about the functional form of minimum headway distribution are used to estimate a single capacity value. The major disadvantage of the method is the need for specification and estimation of a functional form (see e.g. HOOGENDOORN, 1998).

- **Fundamental Diagram method.**
  This approach uses the relationship between speed, density, and flow rate to estimate a capacity value. A functional form needs to be selected and assumptions about the critical density (where capacity is reached) must be made (see e.g. BOTMA et al., 1998a).

**Methods which do require capacity observations**

Methods using explicit capacity flows sometimes use additional flow measurements in order to get a better capacity estimate. Some methods do not distinguish between queue and pre-queue maximum flow rates.

- **Selected Maxima method.**
  Measured flow rate maxima are used to estimate a capacity value or distribution. The capacity state must be reached during each maxima selection period. This estimation method should be applied over a long period.

- **Bimodal Distribution method.**
  This method may be applied if the observed frequency distributions of flow rates exhibits a clear bimodal form. The higher flow distribution is assumed to represent capacity flows.

- **Extreme value methods.**
  These methods use capacity flow rate observations to estimate possible extreme values which have not yet been observed. The methods are not very useful for empirical capacity estimation.

- **Queue discharge distribution method.**
  Straightforward method which uses queue discharge flow observations to construct a capacity distribution or capacity value. This method requires additional observations to determine the congestion state.

- **Product-Limit Method.**
  This method uses below-capacity flows together with capacity flows to determine a capacity value distribution, without the need to specify a functional form. Speed and/or density data is needed to distinguish the type of flow measurement at a road section upstream the bottleneck (MINDERHOUD et al., 1996c).
Overview of existing models
The text box in this section gives a brief overview of the available empirical capacity estimation methods. A more detailed overview can be found in MINDERHOUD et al. (1996c, 1997).

Selected capacity estimation method
The assessment of capacity impacts of AICC deployment will be performed using the queue discharge distribution method. Among others, CASSIDY et al. (1999) adopt the long-run queue discharge flow as the best representation for the bottleneck capacity since the flow rates are nearly constant, can be sustained for prolonged periods, and are replicated each day. Using the maximum flow rates just before the congestion onset is considered inappropriate for capacity estimation since these flows are unstable, highly variable, and persist only for short durations.

For application of the queue discharge capacity estimation method, the occurrence of an upstream queue is required. The use of a simulation tool enables us to create the conditions needed to perform this analysis. We use a 70 km/h speed threshold to distinguish between congested and non-congested conditions upstream the bottleneck.

The choice for an appropriate averaging interval
The duration of the smallest period in which the number of passing cars will be counted and aggregated - the averaging interval - is to a large extent arbitrary, and the results must be interpreted with this in mind. In particular, it is well known that very high rates of flow can be observed over very short periods, e.g., one minute, but they occur much less frequently over longer periods (see e.g., LEUTZBACH et al., 1993). Time intervals ranging from five to fifteen-minute are considered appropriate because the independency of the observations between the averaging intervals can be defended, local fluctuations are smoothed out while the maximum traffic volume can hold for more than the interval duration. The five-minute interval is selected for application in our capacity analysis.

The needed observation period
The total observation period consisting of multiple averaging intervals from which maximum flow observations will be determined can take, for example, two hours (e.g., during the morning or evening rush). For the capacity analyses, a hypothetical morning rush period of two-and-a-half hours will be examined.

4.3.4 Expectations about possible effects of AICC on capacity
This section considers the expectations about the possible capacity impacts as result of AICC deployment. These capacity impacts are highly related with microscopic changes in driver behaviour which have been hypothesised in section 4.2.

Motorway capacity is determined by the motorway density $k$ and speeds $u$ per lane. As the average gap distance per lane decreases at capacity conditions, the density will increase according to the relationship between density $k$ and average gap distance $s$ (in metre): $k=1000/s \ [\text{veh/km}]$. The general relationship between flow, density, and speed is given by the expression $q = ku \ [\text{veh/h}]$ with $u$ in metres/second (see e.g., MAY, 1990). At bottleneck capacity, this equilibrium relationship turns into $q_c = k_c \cdot u_c$ with index $c$ denoting the capacity
or critical value.

The lane capacity can differ among motorway lanes due to the vehicle fleet composition, and driver preferences such as the desired speed. The issue of lane use in relation to traffic demand is elaborated in the following.

![Graph](image)

**FIGURE 4.12** Lane utilisation downstream bottleneck as function of traffic flow rate (simulation results for two-lane motorway with an on-ramp)

*Possible changes in lane use*

As stated previously, the capacity, speed at capacity, and critical density may differ between lanes. The differences in the desired speed among vehicle-driver combinations are for a large part accountable for the distribution of user classes over lanes, and consequently, the lane utilisation. In particular the presence of heavy trucks, normally with desired speeds below 90 km/h, will affect the lane distribution and utilisation. In the following we will show that the lane utilisation is a function of traffic demand.

Figure 4.12 shows five-minute averages collected downstream an on-ramp bottleneck (using simulation) with 10% heavy trucks in the vehicle fleet, and no AICC-equipped vehicles. The figure also shows an indicative relationship between flow rate and lane use for the left (median) and right (shoulder) lane. At low flow rates, the majority of the drivers will use the right lane, since only a few trucks are present and lane changes are easily performed. The drivers will drive at their desired speed. With increasing flow rates, the lane distribution of the vehicles will shift to the left lane. The drivers now partly drive in constrained conditions and can not always drive at their desired speed.

From the figure it can be seen that the median lane carries about 60% of all the traffic just before the lane capacity has been reached. After the traffic breaks down and queuing follows upstream the bottleneck, the lane distribution is more balanced (the open triangles and squares in figure 4.12 represent the flows on shoulder lane and median lane respectively). This sudden shift can be explained by the dropped median lane capacity in the queue discharge situation. The resulting smaller speed differences between the median and shoulder lanes in the queue discharge situation explain the increased relative attractiveness of the shoulder lane.
The introduction of AICC may affect the vehicle fleet lane distribution and lane utilisation. This can be explained by the expected changes in gap distance and changes in the variation of the gap distance in the traffic when AICC is deployed. We refer to the causal diagram depicted in figure 4.1. Changes in the gap size distribution will typically influence the attainable speeds on the motorway lanes, which can affect the lane change motivation of the drivers. Also, the lane change opportunities for the drivers may be affected. It is possible that drivers experience more difficulties to change lanes due to the smaller gaps and reduced alertness or politeness of the drivers in AICC-equipped vehicles. The changes can be user class dependent: the median lane may be more attractive to drivers with vehicles equipped with AICC, since these drivers may minimise the number of lane changes. All these possibilities have to be tested.

We conclude that there are many interrelations between factors affecting the average gap distance per lane, lane density and speed, and thus lane and motorway capacity. This can be studied best by means of microscopic simulation. Outcomes of microscopic simulation are mainly macroscopic figures, which will be discussed in the following.

**Possible changes in the fundamental diagram**

The microscopic behaviour of drivers in a traffic flow can be aggregated into a diagram giving the relation between flow rate and density. Such a diagram can be constructed for a cross-section of a single lane or all lanes of a motorway. This macroscopic representation of a traffic flow is shown in figure 4.13. At low flow rates, drivers drive at their desired speeds. This state represents the free flow branch with a nearly constant speed. At high flow rates, the average speed decreases until the maximum flow has reached. A capacity drop is expected and results, after a short period of nonstationary conditions, in queue discharge flows at lower speeds and densities. A congested branch is observable at motorway sections upstream a bottleneck. It represents the queue-discharge flow from jam density to the critical density.

With the introduction of AICC the properties of the flow-density relationship might change. Figure 4.14 shows the potential changes of characteristic points in the flow-density relationship. We will address the expected changes in the following:
• **Free flow speed**: In case the desired speed of the drivers using an AICC system with a personalized headway setting increases, the free flow branch will be steeper (see fig 4.14). The average speed per lane will increase. When the desired speed distribution remains equal, the average speed per lane can increase due to the higher alertness and adequate control actions of the AICC design. This has been illustrated in figure 4.3. The headway setting, penetration rate and AICC use also affect the free flow branch characteristics. When the AICC-headway setting is smaller than drivers prefer in capacity conditions, the introduction of the AICC will increase the density and makes higher speeds possible.

• **Speed at capacity**: As the flow rate increases towards the capacity flow, drivers will experience constrained driving conditions in which the desired speed can not be achieved anymore for part of the drivers. The aspects expected to result in speed improvements in the free flow branch, also hold for the speed at capacity. However, lane change decisions are expected to change due to changed average speeds per lane. Therefore differences in lane utilisation per lane may evolve. The average speed in the bottleneck is likely to increase with AICC at headway settings equal to the drivers' preferred headways (see e.g. figure 4.4). The difference between the speed in the pre-queue and queue discharge capacity state will probably diminish with AICC, because driver behaviour of a supported driver will be more constant, independent of the traffic state. The same holds for the capacity values; at large penetration rates, the differences between pre-queue and queue-discharge maximum flows (capacities) are expected to disappear.

• **Critical density**: Figure 4.14 shows also the possibilities of changes of the critical
densities and critical speeds (‘speeds at capacities’).
We expect an increase in the density due to several factors we discussed in section 4.2
with the aid of figure 4.1. The average gap distance per vehicle per lane is expected to
decrease with an AICC system operating at a personalised headway setting. In addition,
when the AICC-headway setting is fixed and smaller than human drivers’ average
headway, the average gap distance per lane will reduce even more (and thus increase the
critical density). The average speed is also assumed to increase. The AICC-penetration
rate determines the magnitude of these changes.

In conclusion, we expect that with AICC introduction the current flow-density relationship
of motorways will evolve to a new diagram. Increases in average speed and critical density
are expected, especially in the queue discharge state. Consequently, differences between pre-
queue state and queue discharge state are expected to diminish when the AICC penetration
rate increases. These hypotheses are subject of our investigations in the rest of the thesis.

4.4 Flow stability in motorway lanes

4.4.1 Stability notion

Stability refers to the traffic flow of a line of vehicles after progression of a speed
disturbance started at a car in front. Definitions for the stability of a traffic flow generally
consider a single lane. In literature (e.g. CHANDLER & HERMAN, 1958) two types of stability
are considered. Local stability is concerned with the time variations of the response of one
car to a change in the motion of the car in front. On the other hand, asymptotic stability is
concerned with the manner in which a fluctuation of the motion of the lead car is propagated
don a line of vehicles.

We restate the definitions given by LEUTZBACH (1988):
• Local instability is defined as the situation in which a disturbance does not die out but
rather increases with time. A disturbance is defined as a change in a distance headway
resulting from the change in speed of the leading vehicle.
• Asymptotic or string instability is defined as the situation in which a disturbance grows
in magnitude as it propagates from vehicle to vehicle. Both forms of stability are defined
in terms of safe driving. A response can be either nonoscillatory, which is a damped
response and represents safest driving, or oscillatory, which can occur with or without
damping and is said to be unstable. Unstable flows can lead to collisions especially if the
line of vehicles is large.

On motorways, a shock wave indicates unstable behaviour and might result in rear-end
collisions, especially if gap sizes between following vehicles are at minimum desired
distances. However, a large intervehicle gap distance of one of the vehicles in a line of
vehicles might compensate oscillatory behaviour of the other vehicles.

It is desired to attain a stable traffic flow; this prevents the occurrence of rear-end
collisions and increases the travel convenience of the drivers involved (reduction of number
and severity of shock waves in the traffic flow). It is therefore also a desired property, if not
a requirement, of future longitudinal driver support systems.

A brief overview of past research and some of the findings are presented in section 4.4.2.
4.4.2 Investigations into lane stability

As has been found in earlier research (HOEFS, 1972; JAHNKE, 1982) actual driver behaviour is unstable. In the mentioned studies, a deterministic car-following model (developed by GAZIS et al., 1959, 1961) has been applied for the stability analysis. A comprehensive overview of past research efforts can be found in ZHANG et al. (1997).

The general form of Gazis' car-following model and findings of stability analyses are reported below.

An example of stability analysis

Consider a line of cars numbered from 1 (the leading car) to n (the last car). Let \( x_i(t) \) be the position of the \( i \)th car in the line at time \( t \). The driver observes the traffic state, makes predictions and makes a control decision based on experience and knowledge. The control action algorithm used by the above-mentioned researchers to study the stability is different to the model presented in section 2.4.3. It can be described as follows

\[
\dot{x}_i(t) = \alpha_i(t) \left[ \dot{x}_{i-1}(t-\tau) - \dot{x}_i(t-\tau) \right]
\]

(4.13)

where \( \alpha_i(t) \) is the sensitivity of driver-vehicle combination \( i \). In this model, the speed differential with the leading vehicle is the stimulus of the driver to make speed adaptations. The sensitivity \( \alpha_i(t) \) is given by

\[
\alpha_i(t) = \frac{c \dot{x}_i(t)^m}{(x_{i-1}(t-\tau) - x_i(t-\tau))^l}
\]

(4.14)

In these equations, dots denote time derivatives, \( \tau \) is the driver's reaction time while \( c \) is a positive coefficient of proportionality. Driver's reaction time is the time between state observation and performed control action. Parameters \( m \) and \( l \) are nonnegative constants (not necessary integers). The parameter values determine the characteristics of acceleration and deceleration levels while approaching or following a vehicle in front. For string stability analyses, the motion of the first vehicle in the string is normally taken to be given.

Four types of models can be distinguished (LEUTZBACH, 1988):

a. linear model (\( m=0, l=0 \)), sensitivity \( \alpha_i(t) \) equals constant \( c \);

b. non-linear model (\( m=0, l\neq 0 \));

c. non-linear model (\( m\neq 0, l=0 \));

d. non-linear model (\( m\neq 0, l\neq 0 \)).

According to ZHANG et al. (1997), stability considerations have been limited to the linear model, with some exceptions in which an adapted non-linear model has been investigated. LEUTZBACH (1988) reports that stability computations for the non-linear models are very difficult to carry through.

Findings

For the linear model (with sensitivity equals constant \( c \)), conditions for local and asymptotic stability were established in the past using Laplace transforms and Fourier analysis. The
qualitative properties of the solutions for local stability were found to be the following (see e.g., ZHANG et al., 1997):
1. If \( c \cdot \tau < \pi/2 \), the response is oscillatory with increasing amplitude;
2. If \( c \cdot \tau = \pi/2 \), the response is oscillatory with constant amplitude;
3. If \( 1/e < c \cdot \tau < \pi/2 \), the response is oscillatory with damped amplitude;
4. If \( c \cdot \tau > 1/e \), the response is non-oscillatory and damped;

The condition for a disturbance to be damped as it is propagated down a line of vehicles was found to be \( c \cdot \tau < 1/2 \) (see e.g., KOHLER, 1974).

From the stability analysis results above, it can be concluded that the local and asymptotic stability is affected by the time delay and the sensitivity to the stimuli in the car-following model. For example, a large time delay \( \tau \) with a large sensitivity \( c \) will result in unstable behaviour. Typically, small values for both parameters represent stable behaviour. Figure 4.15 illustrates the asymptotic stability criterion of the linear car-following model of eq. (4.13) graphically.

**General conclusions**
For other car-following models than equation (4.13), for example Helly’s model shown in section 2.4.3, the stability criterion may deviate from these findings. For example, since there are multiple sensitivity parameters involved or if the model is non-linear. Nevertheless, the negative impact of large time delays on stability remains. The asymptotic and local stability will depend on the combination of the time delay and sensitivity parameters.

We comment that the desired minimum gap distance is not explicitly taken into account in the described car-following model of eq. (4.13) and (4.14). This has already been reported by, among others, EISENBERG (1971). An adapted version of Gazis’ model that alleviates this essential shortcoming has been developed and analysed by LOW et al. (1998).

4.4.3 **Expectations about possible effects of AICC on flow stability**

For implementation in driver assistance systems, the applied car-following algorithm should control the vehicle towards a desired gap distance. Unfortunately, the model described in section 4.4.2 (equation 4.13) does not take into account the desired gap distance in determining a response and may therefore not be used in a longitudinal driver assistance system without adaptations (such as proposed by LOW et al., 1998). Helly’s model presented in section 2.4.3, however, is useful since it considers the gap distance explicitly.

When applying this car-following model, the stability criterion will now also depend on the safe distance gap setting parameters. It can easily be understood that a small gap distance setting between cars in a line of vehicles will easier result in unstable behaviour -
given a speed disturbance - than a large gap distance setting, assuming the same time delays and sensitivity parameters.

Next paragraphs discuss the impacts of car automation on stability, and give an example of a stable and unstable traffic flow using two time delay values of Helly's longitudinal car-following model presented in section 2.4.3.

**Fully automated car-following systems: impact on stability**

A great safety advantage of fully automated longitudinal driver assistance systems could be the string - or asymptotic - stability which can be achieved by a well-selected control system. In addition, for fully automated driver assistance systems the string stability should be a requirement for implementation and deployment, since it can be imagined that - if the driver task is overtaken completely - the public will not accept accidents happened as a result of malfunctioning or unfavourable control design of the automated system (KÖHLER, 1974).

The stability of a line of vehicles, equipped with fully automated, non-overrulable longitudinal driver assistance systems, has been analysed by, among others, SWAROOP et al. (1994). Two types of control systems were analysed, a constant spacing control and a constant headway control. A vehicle control model has been adopted, and string stability conditions have been derived. The authors report that the constant headway policy does not require inter-vehicle communication to assure string stability, whereas the constant spacing policy requires intervehicle communication for string stability. However, for the latter policy larger capacity gains can be achieved than with the constant headway policy.

**Assistance systems: impact on stability**

For early longitudinal driver assistance systems, which can be overruled by the driver at any time, the string stability is difficult to analyse analytically. A driver in the middle of a line of vehicles may intervene the system control and create an unstable situation by strong braking or recover a stable situation by delicate braking and temporarily accepting a smaller gap distance. Each driver may react differently under similar conditions. The reaction of drivers following a vehicle at a minimum gap distance, which is maintained by the assistance system, on the changing state of the lead vehicle - a sudden deceleration - is difficult to predict since there is little knowledge about the type and moment of reaction of drivers in borderline situations.

KOPF et al. (1997) investigate driver-vehicle interaction while driving with AICC in borderline situations: situations where driver intervention may be necessary. They conclude that the decision making on intervention could be modelled using the predicted minimum approach headway as a criterion, which turned to be about 0.7 s. The level of braking, and human errors in selecting the needed braking level, have not been assessed in the study.

Investigations of string stability of vehicles equipped with an informing support system show improved, more stable behaviour, according to JAHNKE (1982). For comparison, HOEFS (1972) and KÖHLER (1974) noticed that actual driver behaviour - without driver support systems - is characterised by unstable behaviour. JAHNKE (1982) confirms this phenomenon, but states that the overall effect on string stability is quite limited since his investigation showed that drivers drive unstable only a limited amount of time, and compensate unstable behaviour of other vehicles during the stable part of their trip. Van Arem found an improved traffic flow stability with AICC-equipped vehicles in the vehicle fleet using a shock wave criterion (VAN AREM et al., 1997).
Figure 4.16 exemplifies the stability notion using a numerical calculation approach on Helly's car-following model, eq. (2.9), applying a time delay of 0.6 s (and with velocity sensitivity $c_1=1.8 \, 1/s$, headway sensitivity $c_2=0.3 \, 1/s^2$ and a desired car-following headway of 1.2 s). The lead vehicle speed curve is shown by the thick line. The leader's vehicle speed drops from 100 km/h to 50 km/h in about five seconds (deceleration rate 0.3g), after which

FIGURE 4.16 Effect of lead vehicle disturbance on speed profiles of five following vehicles applying Helly's car-following model (time delay 0.6 s)

FIGURE 4.17 Effect of lead vehicle speed disturbance on speed profiles of five following vehicles applying Helly's car-following model (time delay 0.3 s)
the leader accelerates at 0.2g towards 100 km/h. The speed amplitude of the five following vehicles increases oscillatory during the deceleration and acceleration, so we may conclude this model does not exhibit asymptotic stable behaviour, although analysis of the intervehicle gap distances indicated that there were no rear-end collisions. The time delay applied here approximates human driver’s delay time according to the calibration of the developed simulation model (Appendix A).

Figure 4.17 shows a parameter combination that results in stable behaviour. Only the time delay has been reduced to 0.3 s, the other parameters are the same as applied in the latter example. It can be observed that the speed amplitude in the line of vehicles is damped quickly. Furthermore, no oscillatory behaviour is noticed. This example characterises the impact of a substantial reduction of the time delay \(\tau\). It can carefully be concluded that the introduction of AICC may result in a positive impact on the asymptotic stability, since relatively small time lags (smaller than 0.3 s used in the example) are expected with AICCs replacing the longitudinal driving task. This also may imply positive impacts on motorway traffic safety.

A stability analysis will not be conducted in the study, since our safety analysis takes into account the negative impacts of shock waves and flow instability. The safety assessment approach applied is outlined in next section 4.5.

4.5 Motorway traffic safety

4.5.1 Safety notion

The traffic safety notion expresses the level of safety of traffic participants in qualitative or quantitative terms (e.g. the number and severity of accidents on a specific road type). Traffic safety depends to a large extent on the road type and the presence of slow traffic participants. As the number of different traffic participants increases, and a separation between slow and motorized traffic is lacking, more dangerous situations with large speed differences can occur.

Speeds, and especially speed differences among traffic participants, are important factors affecting traffic safety. Generally, larger speed differences lead to more and more serious accidents. In addition, high speeds normally lead to more severe accidents due to the larger impact speed. When a driver and passengers in a vehicle colliding with a speed of 80 km/h, they have twenty times more chance to be killed than driving at a speed of about 30 km/h. Several studies indicate that a reduction of the average speed with 1 km/h will lead to a 3% reduction in the number of accidents. Additionally, the reduction of severe accidents and fatalities will reduce with 5% (SWOV, 1997). This indicates the importance of speed as an indicator of traffic safety.

Table 4.2 shows the fatality and accident probabilities for several road types in the Netherlands. It can be seen that motorways are relatively safe compared to the other road types. It is interesting to see the relative safety of 2x3 (or more) lane motorways compared to the 2x2-lane motorways. Apparently, additional lanes increase the overall safety expressed per vehicle-kilometre. We hypothesise that additional lanes on motorways result in a homogenisation of speeds and vehicle types within lanes. Smaller speed differences between adjacent lanes are also expected with extra lanes. As a consequence, the number of lane changes is expected to be less than at 2x2-lane motorways.
### Table 4.2: Probability of fatalities and accidents per road type in the Netherlands (1980-1986) [Source: SWOV, 1987]

<table>
<thead>
<tr>
<th>Road type</th>
<th>Fatalities per $10^4$ veh km</th>
<th>Accidents per $10^3$ veh km</th>
</tr>
</thead>
<tbody>
<tr>
<td>Motorway 2 x 3½-lanes</td>
<td>0.28</td>
<td>0.07</td>
</tr>
<tr>
<td>Motorway 2 x 2-lanes</td>
<td>0.4</td>
<td>0.08</td>
</tr>
<tr>
<td>Undivided highway</td>
<td>1.2</td>
<td>0.1</td>
</tr>
<tr>
<td>Rural roadway (restricted access)</td>
<td>1.55</td>
<td>0.31</td>
</tr>
<tr>
<td>Rural roadway (for all traffic)</td>
<td>5.16</td>
<td>0.86</td>
</tr>
<tr>
<td>Urban roadway</td>
<td>2.7</td>
<td>1.35</td>
</tr>
<tr>
<td>Residential street</td>
<td>0.75</td>
<td>0.75</td>
</tr>
</tbody>
</table>

Section 4.5.2 outlines relevant motorway safety studies and their safety assessment.

#### 4.5.2 Investigations into motorway traffic safety

It is expected that the introduction of new vehicle technologies will have both positive and negative impacts on traffic safety. We can distinguish direct safety benefits (such as enhanced driving performance and mitigation of crash consequences) and indirect safety benefits (e.g. reduced exposure, reduced driver stress and fatigue, reduced conflicts and variance in behaviour). Also, direct safety risks (driver distraction, overload, reduced situation awareness) and indirect safety risks (behavioural adaptation, loss of skill, etc.) can be distinguished. Impacts depend largely on the extent to which the support systems support drivers’ needs and if the systems are compatible with human capabilities and limitations.

In many cases, direct safety measures such as accident and fatality frequencies can not be obtained, among other things, since intelligent driver support systems are not yet widespread available. Since empirical collection of accident data is not an option, other methods for safety assessment are needed.

Among these are ex ante assessments with which the safety consequences of different vehicle fleet compositions relative to a base (do-nothing) case can be estimated. To this end, microscopic simulation models can be applied. With the application of microscopic simulation tools a variety of traffic safety indicators can be determined, such as the headway distribution, time-to-collision (TTC) distribution, or number and severity of shockwaves. The comparison of headway distributions at a cross-section gives an indication about the positive or negative shifts in traffic safety, assuming that small headways are relatively unsafe. Also, a comparison of time-to-collision distributions can be made to evaluate safety changes. Other safety indicators can be used as well, such as the number of shockwaves (e.g. VAN AREM et al., 1997), time-to-accident (TTA), post-encroachment-time (PET), deceleration-to-safety-time (DTS), see e.g. TOPP et al., (1996, 1998). Absolute safety effects are hard to derive with such comparative analyses. It may also be clear that traffic safety analysis with microscopic traffic simulation has a number of restrictions. Most important, driver behaviour in real motorway traffic is more diverse and less predictable than can be implemented within a model. Furthermore, microscopic simulation models mostly neglect parts of the lateral driving tasks, such as keeping the vehicle on the roadway. Despite these limitations, simulation can give valuable insights into relative changes of traffic.
flow safety.

For sake of assessing the safety impacts of future intelligent in-vehicle devices interacting with the driver, adequate safety indicators should be applied which express the safety notion into a comparative and understandable variable. Focus of next section 4.5.3 is the formulation and application of such new safety measures based on the time-to-collision notion. This implies that the lateral safety concerns are not taken into account. The time-to-collision indicator expresses only indirect safety concerns related with execution of the longitudinal driving task, and should be interpreted with this limitation in mind.

4.5.3 Safety assessment with an aggregated time-to-collision indicator

**Definition**
A safety indicator which has been applied beneficially in safety analyses is the time-to-collision. The Time-to-collision (TTC) concept was introduced in 1971 by the U.S. researcher Hayward. A TTC value at an instant $t$ is defined as *the time that remains until a collision between two vehicles would have occurred if the collision course and speed difference are maintained*, see e.g. TOPP et al. (1996). The time-to-collision distribution has been applied in several studies to identify traffic safety impacts (among others, FANCHER et al., 1997 and VAN AREM et al., 1997). The time-to-collision of a vehicle-driver combination $i$ at instant $t$ can be calculated with:

$$TTC_i(t) = \frac{X_{i-1}(t) - X_i(t) - L}{\dot{X}_i(t) - \dot{X}_{i-1}(t)} \quad \forall \; \dot{X}_i(t) > \dot{X}_{i-1}(t) \quad [8] \quad (4.15)$$

![Time-to-collision notation illustrated with vehicle trajectories](figure4.18)

where $\dot{X}$ denotes the speed in m/s, $x$ the position, and $L$ the vehicle length in metres. The time-to-collision notion is illustrated with two vehicle trajectories in figure 4.18. Depicted is a situation in which the lead vehicle $i-1$ brakes. After a reaction time $\tau$, subject driver $i$ starts a control action. According to expression (4.15), a time-to-collision value can only be calculated when a positive speed difference between the vehicles exists. Figure 4.18 shows the TTC-value at instant $t$, the moment driver $i$ starts braking. For calculation of a TTC-value, the speed differential at instant $t$ is assumed to remain constant during the hypothetical collision trajectories of the vehicles until instant $t'$ (shown by the straight dashed lines). The higher a TTC-value, the more safe a situation is.

**Critical time-to-collision value**
Safety-critical approach situations are characterised by small TTC-values. In applying the developed, improved safety indicators, a critical or *threshold value* should be chosen to
distinguish relatively safe and critical encounters. Hirst reports that a time-to-collision measure of 4 s could be used to discriminate between cases where drivers unintentionally find themselves in a dangerous situation from cases where drivers remain in control (Hirst et al., 1997). The study further describes a laboratory experiment into the design of a Collision Warning System. The results show that a TTC warning criterion of 4 or 5 s results in too many false alarms. A TTC-value of 3 s produced the least number of alarms, although in some cases critical situations were observed. Hogema studied the driver behaviour at an approach of a queue for non-supported and supported drivers in a driving simulator experiment (Hogema et al., 1996). He found a minimum TTC value of 3.5 s for the non-supported drivers, and 2.6 s for supported drivers. The 2.6 s value is regarded as a safety concern. Van der Horst reports even lower critical TTC values, however, based on approaches at intersections (Van der Horst, 1990).

Basically, two approaches can be observed in literature to determine time-to-collision values for safety assessments (see previous paragraph). One approach focuses on time-to-collision values of vehicles passing a cross-section of a roadway. The other approach deals with subject drivers who must drive during a certain time period, or follow a specific route in real-life traffic conditions or under controlled conditions in a driving simulator. The driving performance of the subjects (including time-to-collision) is continually measured, so that afterwards minimum time-to-collision values can be determined.

Our improved approach combines the two approaches which result into two new safety indicators (called TET and TIT). Instead of a single cross-section a specified road length is considered for safety analysis. With this approach, the occurrences of small time-to-collision values of all traffic participants, at any moment, can be taken into account. The analysis depends no longer on an arbitrary chosen cross-section.

A road section based time-to-collision indicator

For establishing the improved safety measures, we consider a road section between \( X_f \) and \( X_s \). Example trajectories of vehicles driving at a road section are shown in figure 4.19. The considered road section length is denoted with \( L \), the duration of the time period between \( T_f \) and \( T_s \) with \( H \). It is now possible to determine the time-to-collision profile over time, \( TTC_i(t) \) for each of the vehicles that use the road section, using expression (4.15). Such a time-to-collision value profile over time is shown in fig. 4.20.

Shown in figure 4.20 is the movement of a driver on a motorway lane. At instant \( t=0 \) the driver approaches a slower driving vehicle, so the time-to-collision value decreases with time. At a certain moment \( t_1 \), the subject decides to make a lane change. The driver is confronted with a new leader at a smaller gap distance. The time-to-collision values are smaller and reach quite unsafe values. The driver adapts his speed to increase the gap distance and reduce the speed differential. Between \( t_2 \) and \( t_3 \) no positive TTC values are apparent. The
lead vehicle is thus driving with a higher speed. However, at \( t_1 \), the subject approaches another lead vehicle. Drivers' car-following behaviour exhibits this oscillatory behaviour constantly, switching from a negative to a positive speed difference, in order to maintain a minimum desired gap distance. At \( t_6 \), the lead vehicle returns to the right lane, and a new lead vehicle is observed by the driver. The subject approaches this new leader without speed adaptations, so the TTC value decreases.

![Diagram of time-to-collision](image)

**FIGURE 4.20** Example time-to-collision profile of a driver-vehicle combination in motorway traffic (shaded areas represent safety-critical approach conditions)

In figure 4.20 a constant TTC threshold value (\( \text{TTC}^* \)) is indicated (horizontal line), together with shaded areas if drivers' TTC values drop below this threshold value. The TTC threshold value is a time-to-collision value which can be applied to distinguish safe and safety-critical approach situations.

From the example, we observe that the time-to-collision values for a single driver strongly vary over time. Based on such TTC-profiles, a number of more refined safety indicators may be derived. An analysis approach is developed in which the individual time-to-collision profiles are used in the determination of a useful time-to-collision exposition distribution. A full description of the developed safety indicators TIT and TET is given in the following.

**The TET-indicator**

The first indicator we will describe is called \( TET \), which stands for Time Exposed Time-to-collision. The duration of exposition to safety-critical time-to-collision values over a specified time duration \( H \) is used here as safety indicator. It is a summation of all moments (over the considered time period) that a driver approaches a front vehicle with a TTC-value below the threshold value \( \text{TTC}^* \), the latter is considered to be the boundary between safe and safety-critical approaches. Thus, the lower the TET value, the more safe the situation (on average over period \( H \)). This safety measure does not take into account the variation in safety levels of different Time-to-collision values below the threshold value.
For calculation of the TET indicator, it is needed to collect the position and speed of all vehicles entering and leaving the specified road section between $X_1$ and $X_2$, over time period $H$, from which trajectories (fig. 4.19) and time-to-collision profiles can be established. However, since data mostly is collected in discrete time, the TTC values will also be determined at discrete time moments (determined by time scan interval $\tau_{sc}$). For calculation purposes it is assumed that the measured TTC-values at an instant $t$ do not change during a small time step $\tau_{sc}$ (e.g., 0.1 s). For the considered time period $H$, there are $T=H/\tau_{sc}$ time instants $t$ taken into account in the calculation ($t=0, \ldots, T$). From fig. 4.20, it can be concluded that the $TET^*$ indicator for a subject $i$ can be expressed by:

$$TET_i^* = \sum_{t=0}^{T} \delta_i(t) \cdot \tau_{sc}$$

where $\delta_i(t) = \begin{cases} 0 & \forall \quad 0 \leq TTC_i(t) \leq TTC^* \\ 1 & \end{cases}$ [s] (4.16)

in which $\delta_i(t)$ is a switching variable. The subscript $*$ should be interpreted as 'indicator value calculated with respect to the threshold value'. Its value is 1 in case a driver $i$ at instant $t$ experiences a TTC value between zero and the specified threshold value $TTC^*$, otherwise, its value is zero. It can easily be understood that for a population of $N$ drivers ($i=1..N$), the total $TET^*$ is equal to:

$$TET^* = \sum_{i=1}^{N} TET_i^*$$ [s] (4.17)

The TET-indicator can also be calculated per user class, e.g., trucks and passenger cars, equipped and non-equipped, by adding an extra index and summation per user class.

**The TIT indicator**

One disadvantage of the TET indicator is that unsafe TTC values do not affect the TET indicator value. For example, the approach situation between $t_1$ to $t_2$, in fig. 4.20 can be considered to be more dangerous than the approach between $t_1$ and $t_2$. To take into account the impact of the TTC value in the safety assessment, the TIT indicator is developed:

The TIT (=Time Integrated Time-to-collision) indicator uses the integral of the time-to-collision profile of drivers to express the level of safety (in s$^2$). In continuous time:

$$TIT^* = \sum_{i=1}^{N} \int_{t=0}^{T} \left[ TTC^* - TTC_i(t) \right] dt \quad \forall \quad 0 \leq TTC_i(t) \leq TTC^*$$ [s$^2$] (4.18)

The shaded areas in fig. 4.20 represent situations in which the driver approaches the front vehicle with TTC values below TTC*. Since low TTC values represent more dangerous situations, it holds that the smaller the shaded area, the higher the risks on collisions. To be consistent with the TET indicator, the shaded area should be subtracted from the area below the threshold value, resulting in a time integral with an interpretable meaning. This area is shown in fig. 4.20 by a dark surface. A high TIT value means a large exposition time to duration-weighted unsafe TTC values, which is negative for road safety. The individual TIT for subject $i$ in discrete time can be calculated with:

$$TIT_i^* = \sum_{t=0}^{T} \left[ TTC^* - TTC_i(t) \right] \cdot \tau_{sc} \quad \forall \quad 0 \leq TTC_i(t) \leq TTC^*$$ [s$^2$] (4.19)

Summation over all vehicles ($i=1..N$) present in the simulation during time period $H$, results in the following discrete-time aggregate TIT definition (expressed in s$^2$):

$$TIT^* = \sum_{i=1}^{N} TIT_i^*$$ [s$^2$] (4.20)

The aggregate indicator values (4.17) and (4.20) hold for the population of all vehicles $N$, and depend on the considered time period $H$ (see fig. 4.19).

From the aggregate TET and TIT indicators, others can be derived, such as average value per vehicle, as well as the probability of safety-critical situations per time unit (see 6.6.3).
Construction of a TTC-frequency distribution

For the construction of a TTC-frequency distribution, which is useful for visual inspection and analysis of the impact of the threshold value on the indicator value, we distinguish TTC classes denoted with index \( k \). In our analyses, the size of the classes is set at \( a \) with the range of zero to \( MAX \) seconds TTC value. The boundaries of the TTC classes in the frequency distribution are therefore defined by \( TTC_k = (k-1) \cdot a \), where \( k = 1 \ldots MAX/a \).

The summed exposition time with TTC-values within a particular TTC-class \( k \) over period \( H \) for a driver \( i \) is calculated by:

\[
TET_i^k = \sum_{t=0}^{\tau_{sc}} \delta_k^i(t) \cdot \tau_{sc} \quad \delta_k^i(t) = \begin{cases} 0 &\text{if } TTC_k \leq TTC_i(t) < TTC_{k+1} \\ 1 &\text{otherwise} \end{cases} \quad [s] \quad (4.21)
\]

With expression (4.21), a frequency distribution of TET-values can be constructed per subject \( i \). More useful is a frequency distribution of the population \( N \), which can be calculated by summing over \( i \) for each class \( k \):

\[
TET^k = \sum_{i=1}^{N} TET_i^k \quad [s] \quad (4.21a)
\]

From eq. (4.21) it follows that the \( TET^* \) indicator for a subject \( i \) can be determined by:

\[
TET^*_i = \sum_{k=1}^{k^*} TET_i^k \quad \forall \ k = 1 \ldots k^* \quad [s] \quad (4.22)
\]

where \( k^* \) represents the index of the class corresponding with a TTC-value equal to the threshold value \( TTC^* \). The class index \( k^* \) can be calculated from \( k^* = TTC^*/a \). Similarly, the aggregate \( TET^* \) of the population \( N \) can be calculated with:

\[
TET^* = \sum_{k=1}^{k^*} TET^k \quad \forall \ k = 1 \ldots k^* \quad [s] \quad (4.22a)
\]

With the TET-values per class \( k \) the aggregate TIT indicator can be derived. The aggregate \( TIT^* \) indicator, see equation (4.20), can be derived from the TTC-frequency distribution. Graphically, it can be observed that for \( TIT^* \) holds (in \( s^2 \)):

\[
TIT^* = N \cdot T \cdot TTC^* \cdot \tau_{sc} - \sum_{t=0}^{T} \sum_{i=1}^{N} TTC_i(t) \cdot \tau_{sc} \quad \forall \ 0 \leq TTC_i(t) \leq TTC^* \quad [s^2] \quad (4.23)
\]

with the first part of the equation representing the area below \( TTC^* \) for time instants with a TTC-value meeting the condition \( 0 \leq TTC_i(t) < TTC^* \), and the second part representing the area below the curve (see fig. 4.20) for time instants meeting the same condition. This subtraction of areas results in the \( TIT^* \) indicator; it is equal to the area below the threshold value and above the TTC-profile, again for time instants meeting the previous mentioned condition. Eq. (4.23) can be formulated with the TET indicator by substituting \( TTC_i(t) \) according to:

\[
TTC_i(t) \cdot \tau_{sc} = \sum_{k} TTC_i(t) \cdot \tau_{sc} = \sum_{k} \delta_k^i(t) \cdot TTC_k \cdot \tau_{sc} = \sum_{k} TET_i^k \cdot (k-1) \cdot a \quad [s^2] \quad (4.24)
\]

The \( TIT^* \) calculation with the TTC-frequency distribution is less exact than using the vehicle trajectory approach since the exposition time of unsafe TTC values are aggregated into classes of TTC-values of width \( a \). Nonetheless, the method simplifies the data collection effort while the estimated indicator value is sufficiently accurate for assessing safety impacts.

The use of a frequency distribution is exemplified in section 6.6.3.

### 4.5.4 Expectations about possible effects of AICC on traffic safety

To what extent future driver support systems will contribute to a safety risk reduction or a
higher risk is currently an open question (BUNDESANSTALT, 1998), among others because of Wilde’s risk homeostasis theory (section 2.1). In this section, some considerations about the expected safety impacts are presented.

As stated in section 4.5.1, speed, and speed differentials are the most important indicators for safety changes, and may be applied in the analysis of safety effects of AICC. VAN AREM et al. (1995a) found that AICC introduction will decrease the average speed and standard deviation of the speed. Hoedemaeker (1997, 1999) found an increase of the average speed with AICC using driving simulator experiments. HOGEMA et al. (1996) reported a decrease of the desired speed of drivers using AICC. These changes were not transferred into safety impacts.

It is also obvious that the impacts on traffic safety will depend on the support system functional design (i.e., the headway setting), its learnability and its predictability, as has been pointed out by SCOTT (1997). Considering the AICC functional design of the first generation AICC-systems (section 3.5) several common situations on motorways are identified as potential safety risks:

- approaching a standing queue with high speed;
- driving near the acceleration lane of an on-ramp without anticipating on the vehicles wanting to merge;
- driving under capacity conditions while a sudden speed drop occurs (a shock wave) leading to speeds that are not supported by the AICC system.

These situations inhabit safety risks when we expect that AICC-supported drivers are less alert, rely on the system’s performance, or fail in supervising the longitudinal driving task accurately (also denoted with the ‘underload’-effect, described further on in this section).

The expected safety benefits of AICC-equipped driving follow from the smaller time delays, reduced errors, and reduced variance of errors in the state monitoring, estimation, prediction, decision, and control action performance (section 3.4). It is hypothesised that the introduction of AICC decreases the number of rear-end collisions while it also may reduce the severity of collisions in case they could not be avoided.

Although deployment of driver assistance systems could be countermeasures to prevent manual driver behaviour contributing to accidents, their usage may be accompanied by side-effects that might have a negative impact on the traffic safety (HEIJER et al, 1998). The potential side-effects are described in the following.

**Overload**

Overload in the driving task refers to the situation that the driver is unable to process all relevant information for executing the driving task. Overload may occur without telematic in-vehicle applications, however, the introduction of such applications makes overload more likely because of the required interaction with these systems. An example of overload is a warning signal of the support system (indicating that the driver should take over the driving task) while the driver is carrying out a lane-change manoeuvre. The relation between driving performance, workload and safety is a complex one. It is not clear what level of increase can be considered acceptable when using a support system. The requirement that workload may not increase at all is too simple since many support systems may increase workload in some situations and reduce the workload in other situations.

**Underload**

Driver underload is defined as the situation that the driver gets into a state of limited attention due to diverted attention or deactivation. The use of driver assistance systems might imply that less
attention of the driver is required in execution of the driving task. As a consequence, this may result in dangerous situations if the driver is suddenly warned to perform the task himself.

**Counterproductive behaviour adaptation**
Counterproductive behavioural adaptation is the phenomenon that a driver starts behaving in riskier ways because they are supported by a safety-raising application. Examples are the changes in driving behaviour as observed at drivers with ABS braking mechanism. A problem with counterproductive adaptation is how to assess the net effect of a safety device. Possible counterproductive behaviour with introduction of in-car telematics are an increased traffic participation (travel time reduction may attract new users), a shift in modal split or an increase in the total vehicle-kilometres driven.

For our simulation experiment the potential side-effects are neglected. We assume that drivers supervise the system’s control actions and interact timely. This modelling aspect is elaborated in Chapter 7.

### 4.6 Conclusions
Traffic flow quality can be specified by purposeful indicators which describe relevant aspects of the traffic flow operation for both drivers and motorway operators. Changes in the indicators are expected when AICC systems enter the public motorway. The possible changes depend on the assistance system specifications. Since the interrelations between capacity affecting factors are very complex, exact expectations about capacity changes are difficult to make. One could expect more alert, responsive behaviour using AICC, which, especially in combination with small headway settings of these systems, could lead to higher capacity levels. Besides the capacity analysis, the traffic safety is also selected for further analysis in our AICC-impact investigation.

From analysis of a simple car-following model it is found that lane capacity estimation based on safe distance strategies adopted by the drivers is not an appropriate approach to assess capacity levels on multi-lane motorways. The approach neglects the interaction between lanes, as well as acceleration and deceleration behaviour. However, the models are useful to describe a theoretical relationship between the desired gap distance and driving speed for a certain population, and can be used in microscopic models as input for the longitudinal control model. The approach can also be applied to calculate the theoretical maximum flow rate attainable with a specific safety distance control algorithm of AICC systems.

The average queue-discharge flow rate was shown the most appropriate estimation method and is selected for application in our impact assessment (described in Chapter 8). Condition for application of the method is that the capacity state of the bottleneck location must be achieved, which can easily be accomplished with a simulation tool.

Safety aspects also determine the traffic flow quality. Factors affecting safety are identified, such as speeds, speed differences, lane stability, driver’s underload, overload and behavioural adaptations. An extended Time-to-Collision indicator is developed to enable an approximate assessment of the relative safety impacts of AICC deployment.

Before quantifying these indicators under a variety of AICC scenario’s (including a do-nothing reference), findings from the literature about capacity impacts of driver assistance systems will be assembled and discussed in the next chapter.
STATE OF THE ART OF RESEARCH ON MOTORWAY CAPACITY IMPACTS

This chapter describes the state of the art of motorway capacity analyses dealing with longitudinal driver assistance systems and automated vehicle guidance concepts. The literature survey has been conducted to justify our study, learn from the weaknesses and shortcomings of existing studies, refine our study objectives, and define an appropriate experimental setup. The chapter provides insights into the variety of investigations conducted in this field and focuses on the study setup, the capacity estimation methodology followed, and capacity values derived. Chapter 6 proceeds with the discussion of the refined objectives and our enhanced experimental setup.

5.1 Introduction

Chapter 3 presented a categorisation of driver assistance systems. We distinguished driver assistance systems for the longitudinal driving direction that perform the task autonomously - by appropriate in-vehicle equipment - and non-autonomous systems. For the latter case, communication between vehicles and a road side traffic control centre is necessary to distribute position, speed and other relevant information to close vehicles. The two approaches have different implications for capacity analysis and infrastructural requirements.

The most simple autonomous driver assistance systems do not require dedicated lanes or special infrastructures, whereas the non-autonomous 'autopilot' and non-overrulable assistance systems require a strict division between automated and conventional vehicles. This chapter deals with these two types of system design, although the main focus is on the autonomous systems, such as AICC. We will show that there are several reasons why fully automated systems are not likely to appear on the road in the short term.

The implications of introducing of AICC-like systems for motorway capacity - and possibly impacts on relevant driver behavioural aspects - as reported in literature are described in section 5.2. The impacts of automated vehicle guidance concepts on capacity are presented in section 5.3.
5.2 Longitudinal driver assistance systems

A vehicle equipped with a longitudinal driver assistance system is able to replace the longitudinal driving task to some extent. The driver must execute the lateral driving task (such as lane-change decisions) without the aid of the system. The driver is still responsible for performing the complete driving task. The first assistance system expected to be available on the European market soon - on the S-class of Mercedes-Benz - exhibits these characteristics indeed (AUTOWEB, 1998).

Section 5.2.1 gives an overview of characteristics of early longitudinal driver assistance systems. Section 5.2.2 presents a literature study on the effects of AICC deployment on road capacity and driver behaviour classified according to field operation studies and simulations.

5.2.1 Characteristics of early longitudinal driver assistance systems

Present prototypes of longitudinal driver assistance systems are mostly designed with a limited acceleration range. It can be expected that the early assistance systems will show comparable characteristics. Some experiments have been conducted with the application of a maximal coast down deceleration, which is about 0.05 to 0.1g (BENZ, 1993 and FANCHER et al., 1994, 1996). Other studies have limited the deceleration values at about 0.2 to 0.3g to keep the decelerations comfortable (NILSSON, 1995, FARBER, 1996, VAN AREM et al., 1995a and BENZ, 1993, 1996). Hoedemaeker used the full available deceleration range of both overrullable and non-overrullable autonomous cruise control equipped vehicles in a driving simulation experiment (HOEDEMAEKER, 1999).

Some of these overrullable systems will assist the driver in automatically braking, though not in automatically accelerating towards a pre-set speed (REICHART et al., 1996). More extreme types of latter systems are referred to as Collision Avoidance Systems, since they will only intervene by braking in emergency situations (FORBES, 1994). Other systems only warn the driver in dangerous situations, the so-called Collision Warning systems (ASHER, 1997 and LANDAU, 1995). These types are not subject of our study because maintaining distance and speed is not assisted during normal driving conditions.

Another restriction in the operation of first generation longitudinal driver assistance systems is the operational speed range of the systems (see also section 3.5 1). Typically, reaching an upper or lower speed boundary will switch the system automatically off. Typical operational speed ranges are between 20-160 km/h (REICHART et al., 1996), 30-130 km/h (NILSSON, 1995), 35-150 km/h (AUTOWEB, 1998). The possible active speed range depends on several aspects, in particular of the maximum sensor range. The maximum sensor range and the maximum deceleration together determine the maximum driving speed at which a safe stop can be performed. According to the literature, the sensor detection range of AICC is about 80 to 150 metres, depending on weather conditions and applied sensor type.

The present vehicle transmission system could also determine functional minimum and maximum operating speeds. For example, HOEDEMAEKER (1997) uses a hand-gearred transmission AICC vehicle where the longitudinal controller is only active in the fourth gear. This experimental design could function over the full speed range, however, shifting gears will be inevitable to comfortably accelerate at low speeds. Subsequently, vehicles equipped with automatic transmission are most commonly applied as prototype or test vehicle, and
expected as the first models to be sold with AICC.

Furthermore, it is observed that today's available sensors - applied in prototype longitudinal driver assistance systems - cannot distinguishing a standing vehicle from its environment (NWAGBOSO, 1997). As an important consequence, when an equipped vehicle with an activated assistance system approaches the tail of a slow driving queue, the driver must intervene in order to avoid a collision. The system will not react on standing vehicles as long as the sensors are not capable of observing a standing object and interpreting it as a vehicle. A lower operational speed boundary of about 30 km/h is apparent in prototype assistance systems. The application of expensive video-imaging system is an option to solve this essential shortcoming of first generation assistance systems.

5.2.2 Impacts of driver assistance systems on capacity and driver behaviour

Field operational studies
This category of studies use mostly a number of specially equipped vehicles which are driven by subjects in real traffic. Driver behaviour can be measured directly, but the traffic conditions can hardly be manipulated. The usefulness of the outcomes of these field studies are therefore very limited for motorway capacity assessment. Nevertheless, the results can give an indication of changes in individual driver behaviour. There are quite a number of these studies conducted focusing on AICC use by subject drivers. Some of them are discussed in the following.

FANCHER et al. (1996) investigated differences between manual and automated control of headway. The study is based on 36 drivers. Each driver operated an instrumented vehicle that can be switched between manual and adaptive cruise control operation. Driving performance was measured in freeway operation. The variables include headway range, range rate, velocity, and acceleration/deceleration plus brake and accelerator pedal usage. The results show that there is a wide range of manual driving characteristics. The distribution of headway times for individual drivers is characterised by most likely values running from approximately 0.6 to 3.0 seconds.

The applied fixed beam sensor covered 3.6 metres width at a 70 metre range. The AICC system did not use the braking system to control speed. Headway and speed control was achieved using throttle modulation with the maximum deceleration being limited to the 'coast down' deceleration of the vehicle (approximately -0.05g at freeway speeds). The desired time headway was held fixed at 1.4 seconds in this study. Furthermore, the control algorithm operated at a 10Hz cycle rate. When there was a preceding vehicle detected by the sensor and the following vehicle was responding to the sensor measurements, the velocity command was calculated by the controller. Then, the actual speed of the controlled vehicle was compared to the speed command and if necessary, the gas pedal coast down deceleration was actuated to reach the desired headway setting.

Measurements show a great acceptance of the system: even though the driver has the option of driving without the AICC system in operation, most of the driving is done under AICC. Examination of the differences between manual driving and AICC driving shows that during manual driving vehicles are likely to travel at shorter headway values than 1.4 seconds. It was concluded that the properties of the headway control algorithm used in this study apply well to the average driver preferences.

The study gives little insight in achievable capacity values. When we estimate a
theoretical maximum flow based on the assumption of a minimum headway of 1.4 s and add another additional headway of about 0.2 s for the vehicle length, we derive a capacity value at highest of 2250 vehicles/hour per lane which is an acceptable value for today's traffic. Thus, we may not expect any improvement of motorway efficiency with the investigated AICC in comparison with manual motorway traffic.

FANCHER et al. (1997) present preliminary results from an intelligent cruise control field operational test. The one year test involved tracking the driving of more than a hundred randomly selected drivers. The drivers used the equipped vehicle between two and five weeks. The experimental design involved drivers age and experience with conventional cruise control. The Adaptive Cruise Control could be adapted by the driver with respect to the desired minimum headway (1.0, 1.4 or 2.0 s). Maximum deceleration authority is 0.07g. Safety benefits were investigated using safety measures for a variety of safety factors (headway following, attentiveness, unusual actions, and driver acceptance).

The authors observed that the AICC system has been used 39% of the time, whereas the conventional cruise control has been activated only 24% of the time it was available. Drivers consistently rate the Adaptive Cruise Control the highest for comfort, convenience, and driving enjoyment.

The empirical data shows a considerable amount of variability in the speed-headway relationship. Considering three subjects, the mean headway varied from 0.92 s for the most aggressive driver to 1.63 seconds for the most passive driver. It was found that the most aggressive driver exhibited the lowest standard deviation in headways. Another finding is that older drivers tend to prefer the 2.0 s setting, while younger drivers mainly select the 1.0 and 1.4 s setting when driving with the Adaptive Cruise Control.

Other results of the same field test are discussed by BURGETT et al. (1998). It was concluded that the 108 drivers learned to use the AICC quickly and to integrate the AICC driver assistance system into their individual styles of driving. Only 5 percent of the drivers reported that they would not use AICC. It appeared that drivers selected greater headway settings with assisted driving than headways kept while driving unassisted. Data from the operational test showed that, on average, drivers applied the brakes heavily (>0.25g) about 1.3 times for every 1,000 miles of driving. Therefore, an assistance system with a deceleration authority of 0.25g could manage almost all of the situations observed in practice. Exceptions are approach situations in which the lead vehicle decelerates.

REICHART et al. (1996) describe an experiment conducted during system design of the Adaptive Cruise Control (AICC) of BMW. Two different system layouts were compared in the experimental study:

AICC with automatic speed and distance control in a speed range of 20-160 km/h including braking up to -0.3g. Control capabilities of the driver are given by selecting a set-speed; braking of the driver deactivates the system.

AICC with an active gas pedal working in the speed range above 20 km/h. No automatic speed control is provided but the driver is assisted by tactile indication of the appropriate gas pedal position, realized with a variable additional counter force. The driver can easily override this recommendation but the system never will accelerate on its own. Automatic braking is available to the same extent as above, if the driver releases the gas pedal. Additional braking of the driver will not deactivate the system.
Chapter 5 - State of the Art of Research on Motorway Capacity Impacts

These two concepts were tested with 24 subjects on motorways under various conditions. The second concept with the active gas pedal scored best. The possibilities and the demand for individual parameterization of AICC control strategies were tested in a further experiment. Even if safety critical behaviour is avoided using AICC, there are still a large variety of system designs possible. For this purpose three parameters of an AICC control strategy could be modified during a sequence of test trials either by the test leader or by the test drivers themselves 1) headway setting 2) brake reaction point 3) braking force (gain factor for speed difference)

Each of the nine subjects drove 600 km under various test conditions. For the parameter headway a clear tendency was shown after approx. 100 km of testing, that each driver selected an individual adjustable headway in a range between 1.1 and 1.8 seconds. This parameter was easily understood by the driver. The preset value for system reaction in an approaching manoeuvre was only slightly modified by the subjects. The requested gain factor for braking in approaching a leading slower vehicle however, showed a clear tendency towards higher values if considered along the whole test cycle.

The authors conclude that with growing experience concerning vehicle dynamics and assistance capabilities a standard assistance system configuration may be no longer adequate. Individualization with regard to personal driving style and available vehicle dynamics could be necessary even within a given safety margin. We agree with this conclusion, but in our experimental setup the settings of the AICC parameters are controlled and specified in advance (Chapter 6).

KOPF et al. (1997) investigate the driver-vehicle interaction while driving with AICC in borderline situations (situations which may require driver intervention). An experiment has been carried out in real traffic on German motorways to study this behaviour. Second goal was to get findings about acceptence, risk feeling, and subjective predictability as function of driver types and AICC system design. Three designs are considered:

- soft setting: maximum deceleration 0.05g and fixed time headway of 2.1 s
- medium setting: maximum deceleration 0.1g and time headway of 1.8 s
- hard setting: maximum deceleration 0.3g, time headway 1.5 s.

Thirteen subjects took part in the experiments, divided into three groups: careful, medium and sportive drivers. Each subject had to drive five rides, and each ride was at least 130 km long. Two groups of situations were produced, a following-brake situation and an approach situation, with three different decelerations applied in the first group (0.05g, 0.25g and 0.45g), and three different speed differentials in the second group of situations (20, 40 and 60 km/h).

They found that with the 'hard' system design almost all situations were fully assisted by the system. With the 'soft' system the drivers brake themselves in almost all situations. The 'medium' system with the intermediate deceleration (0.25g) and speed differential (40 km/h) of the lead vehicle were the most interesting. Here, the frequency of driver braking intervention fall in the range around 50%. Decision making is difficult in this class of situations.

The frequency of braking actions decreased as the driving time increased in a ride. They rely more on the capability of the AICC with increasing experience. However, the decrease was not observed between two rides after a pause of about three days. This indicates that it was difficult to preserve the learning effect over a longer period of time.
The researchers found that the driver’s intervention decision depends on the predicted minimum time distance without driver intervention. They conclude that drivers brake only if the minimum time distance without intervention would be below a characteristic value, here about 0.7 s. Consequences for motorway capacity are not mentioned.

We expect that the AICC layout (deceleration authority) mainly affects the safety and has a negative impact on road capacity. We question the quite large headway settings chosen for the AICC’s since drivers prefer substantial smaller headways than the here tested smallest value of 1.5 s.

The results of the field studies are disappointing with respect to analysis of the possibilities of motorway capacity improvements. The study approach is not suited for capacity analysis, and microscopic data is affected by the non-controlled traffic conditions during the experiments. In addition, the tested AICC-systems have generally quite safe headway settings, automatically leading to negative conclusions with respect to attainable motorway capacities. We will not use a field study approach for studying our research objectives.

**Simulation studies**

There are basically two types of simulation studies. *Microscopic traffic simulation* studies use a theory about driving behaviour in order to assess traffic flow impacts. Differences in driver behaviour among vehicle types, such as the behaviour of drivers in AICC-equipped and non-equipped vehicles, is explicitly taken into account. Traffic conditions can mostly be controlled with a microscopic simulation approach.

*Driving simulator* studies focus on individual driver behaviour of a subject driver in a controlled traffic environment. All vehicles in a driving simulator drive according to a theory about driving behaviour, except the subject’s vehicle. Traffic flow analysis is not the objective of driving simulator studies. In addition, the driver behaviour theory of the vehicles in the traffic environment is mostly quite simple. Among others, differences in driver behaviour between AICC-equipped and non-equipped vehicles are not modelled. These studies are therefore not discussed here. Research into the capacity impacts of AICC-deployment, conducted with microscopic simulation, are reviewed in the following.

BROQUA et al. (1991) studied the changes in traffic flow that will arise from the introduction of driver assistance systems in mixed traffic situations. Their recommended safe distance law is based on an analysis of the different possible rules for setting safe distances. The ‘progressive’ strategy (see section 4.3.2) was identified as the most promising control algorithm for ICC. This is a quite optimistic selection with regard to safety considerations at higher speeds. We found the more safe ‘prudent’ strategy the best selection for deployment in AICC-controllers.

The assessment has been performed with the micro simulator SPEACS, and the simulation experiment was based on a two-lane 6 kilometre long motorway stretch. One important assumption is that the controlled vehicles try to use ICC as much as possible. The ICC is activated whenever such an equipped vehicle finds a preceding vehicle that can be followed. The simulation considers different percentages of equipped vehicles. Table 5.1 shows the estimated changes in capacity. Capacity increases for the ICC at 1.0 s headway setting, at 20% and 40% penetration. The ICC at 2.0 s headway decreases capacity for both equipment rates.

We question the representativeness of the conducted experiments, since the motorway
stretch did not include a bottleneck. In addition, the presented fundamental diagram shows a congested branch which is questionable under the given conditions. Also the adopted characteristics of the applied ICC-system are unclear (is the system overrullable or not?) and how human driver behaviour has been modelled.

<table>
<thead>
<tr>
<th>Penetration rate</th>
<th>Capacity increment</th>
<th>Critical density increment</th>
</tr>
</thead>
<tbody>
<tr>
<td>ICC 1.0 s</td>
<td>20%</td>
<td>+6%</td>
</tr>
<tr>
<td>ICC 2.0 s</td>
<td>20%</td>
<td>-3%</td>
</tr>
<tr>
<td>ICC 1.0 s</td>
<td>40%</td>
<td>+13%</td>
</tr>
<tr>
<td>ICC 2.0 s</td>
<td>40%</td>
<td>-6%</td>
</tr>
</tbody>
</table>

**TABLE 5.1** Capacity impacts of ICC under stationary traffic conditions (Source: Broqua et al., 1991)

SCHNITGER (1991) studied the influence of safety requirements on traffic flows. A stochastic microscopic model for driver following behaviour is taken as a starting point.

The applied car-following model in the simulation is Wiedemann's model which is based on driver's perception thresholds and sensitivity areas. The driver-vehicle behaviour is determined by a set of parameters, drawn from a distribution. The desired safe car-following distance was derived from kinematic equations.

The investigation was restricted primarily to the observation of passenger cars in order to keep the number of degrees of freedom as low as possible. The 1-minute interval maxima were compared with different scenarios of safe driving. The headway setting appeared to an important factor for the maximum throughput. Table 5.2 presents some capacity estimates from the study.

<table>
<thead>
<tr>
<th>Penetration rate</th>
<th>Capacity value (relative change)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ICC 1.0 s</td>
<td>100% 4,800 veh/h (reference)</td>
</tr>
<tr>
<td>ICC 1.5 s</td>
<td>100% 3,700 veh/h (-23%)</td>
</tr>
<tr>
<td>ICC 1.8 s</td>
<td>100% 3,100 veh/h (-35%)</td>
</tr>
</tbody>
</table>

**TABLE 5.2** Capacity values for a two-lane motorway without a bottleneck based on one-minute flow rates (Source: Schnitger, 1991)

The author concludes that the traffic volume of multi-lane carriageways under safety requirements will be below the maximum values measured nowadays. We question the representativeness of these outcomes since the study focusses on a motorway stretch without a bottleneck. Furthermore, the applied AICC system and its characteristics have been described insufficiently while only full equipment penetration rates have been studied.

Benz studied traffic flow effects of Intelligent Cruise Control (BENZ, 1993). The Autobahn Simulator was chosen to analyse traffic flow effects of introduction of ICC. Two ICC systems were investigated: informing and an overrullable assisting system.

The first system provides the driver with information about the actual situation in relation to a predefined optimal situation. During the approach, the deceleration is displayed. The optimal value is considered to be -0.1g. During following, the distance is displayed with the optimal value derived from a function for a safe distance. The display was chosen to be
analogue and similar to a speedometer.

The second system investigated was based on the same concept, however, it yields an intervention when the driver does not react: the system applies the brakes when the required deceleration reaches -0.2g. Stronger decelerations were excluded from the system.

Two cases of 0% and 100% equipped vehicles are described in the study. Results of the simulation show a minimal effect on average speed and density. It can only be stated that the variation range of speed is smaller for the 100% penetration case. Furthermore, it was found that ICC hardly influences journey speed. Capacity values have not been derived. However, the author states that at least no negative effect on capacity is to be expected, while safety is significantly improved.

We observe that the study examines assistance systems that are quite different to the expected first generation AICC vehicles. The tested systems provide information but do not actively support the longitudinal task.

Reiter (1993) studied the impact of driver support systems on traffic flows in his dissertation. Subject of the study is simulation of traffic flow with systems assisting the driver. The empirical background of the chosen Wiedemann model was based on measurements from 1972, therefore, new measurements using a special vehicle equipped with different sensors were collected for a new calibration of the microscopic model.

In the simulations, longitudinal systems with a headway setting of 1.5 s were investigated. Four classes of driver reaction on the warning longitudinal support system are distinguished:

- **Full reaction:** The warning given by the support system is fully accepted, the driver adapts his driving behaviour to the advised behaviour.
- **Partial reaction:** The driver accepts the warning signal, however, he accepts the advised value and behaviour only partial. His subjective safe headway lies between the empirical headway and the advised headway.
- **Relative reaction:** In this class of reaction, the driver accepts the system reaction but doesn’t accept the advised value. Therefore, the driver doesn’t change his approaching behaviour but increases his alertness. This will reduce the reaction time.
- **No reaction:** The driver doesn’t accept warning and advised value. He neglects the indications of danger and will drive further as if he has no such kind in-vehicle devices.

How many drivers in which situations can be categorised in any of these classes is yet unknown and will depend strongly on the parameter setting and user-interface of the intelligent system. Three driver acceptance scenarios were studied: 1. an equal distribution of reactions over the four classes, 2. a 50/50 distribution between full reaction and no reaction and 3. an 80/10/10 distribution between respectively full, partial, relative and no reaction.

The adopted penetration rates of equipped (so-called Intelligent Vehicles) in the vehicle fleet were 0%, 10%, 20%, 50% and 100%.

The simulation experiments consisted of a two-lane motorway stretch without bottlenecks. We question therefore the observed capacity and congested conditions, generated by the simulation model. With this set up, the capacity analysis cannot be conducted unambiguously. It is furthermore unclear how, among others, the interaction between driver and assisting system takes place.
Chapter 5 - State of the Art of Research on Motorway Capacity Impacts

Results (depicted in figure 5.1) show a decreasing trend with respect to motorway capacity at increasing penetration of the assisting support system. It was also noticed that there are less one-minute intervals with congested traffic conditions. The performance of the informing system shows less clear results. The frequency of congested intervals, even at high penetration rates, is one of the differences. The capacity value trend is more or less a constant, independent of the penetration rate when examining the low-acceptance scenario. The high-acceptance scenario, however, resulted in substantial lower capacity values, comparable to the assistance system.

![Figure 5.1 Capacity and 95-percentiles of capacity flows for the assisting system (1.5 s target headway, 1-minute intervals) (Reiter, 1993)](image)

Furthermore, the impact on the speed distribution was investigated. For both assistance and informing system it appeared that there were only small differences with the reference situation of 0% equipped vehicles. The mean value is about constant for both.

As could be expected, the headway distribution changed significantly. With an increasing penetration rate in the vehicle fleet the distribution of headways gets smaller and the mean increases slightly. This can be explained by the decreasing number of small headways in the range from 0 to 1.5 seconds with a decreasing proportion manually controlled vehicles. Table 5.3 summarizes some findings. In the column for the informing support system, the two capacity values correspond with a low and high response on warnings. We observe that the sensitivity to the headway setting is enormous. When the headway setting decreases from 1.5 to 1 s, the capacity change changes from -11% to +15%.

The study gives an indication of changes in capacity, however, we regret the limited attention given to the impact of the headway setting. Furthermore, the AICC characteristics are not described well, information about the deceleration authority and minimum supported speed is missing. The capacity estimation method is also questionable, since the study focusses on a uniform motorway section without a distinct bottleneck, while it uses maximum flow values instead of average values, making the capacity estimation strongly dependent on the chosen aggregation time interval.
<table>
<thead>
<tr>
<th>Penetration rate AICC</th>
<th>Informing system low response / high response</th>
<th>Assisting system</th>
</tr>
</thead>
<tbody>
<tr>
<td>0%</td>
<td>4,250 veh/h</td>
<td>4,250 veh/h</td>
</tr>
<tr>
<td>10%</td>
<td>+1% / -10%</td>
<td>+5%</td>
</tr>
<tr>
<td>20%</td>
<td>+5% / -6%</td>
<td>+5%</td>
</tr>
<tr>
<td>50%</td>
<td>-1% / -13%</td>
<td>-1%</td>
</tr>
<tr>
<td>100%</td>
<td>-1% / -16%</td>
<td>-11% (+15%)</td>
</tr>
</tbody>
</table>

TABLE 5.3 Capacity impacts of informing and assistance system (headway setting of 1.5 s using one-minute flow data) (Reiter, 1993) headway setting 1.0 s

Van Arem et al. (1995a) assessed the impact of AICC on traffic flow using the micro simulation model MIXIC. The AICC-systems are assumed to have a limited acceleration and deceleration range of between +0.3g and -0.5g. In situations where the AICC gives too small decelerations, the driver must overrule the AICC. The impacts were assessed using real traffic measurements as input (up to 7,000 veh/h for a three-lane motorway).

The desired safe time headway to the preceding vehicle has been implemented as a linear function of the current speed. For non-AICC vehicles the equation is extended with a square term. The AICC vehicles used in the simulation have the following characteristics: Type 1: a time headway at 1.0 s at 100 km/h. Type 2: a time headway at 1.5 s at 100 km/h.

These values should be compared with the modelled time headway of a driver without an AICC, which is about 0.6 s at 100 km/h according to the square function employed. As a consequence, AICC vehicles will not directly contribute to an increase of capacity by means of a reduced time headway. Only an indirect impact on capacity may exist through the reduction of speed variations in the traffic flow. For all simulations, the same motorway stretch was considered. It comprises three sections of one kilometre. Only the second section was examined. The experiments addressed the following varying conditions: the level of penetration (0%, 20% and 40%) and the AICC target headway setting at 100 km/h (1.5 and 1.0 seconds).

Analysis of the results shows that a small percentage of the AICC equipped vehicles has overruled their support system - which is to be expected since no bottleneck has been simulated. The model results give no direct answer whether the capacity value increases or decreases, since all simulation runs have the same traffic demand as input. Therefore, capacity changes could only be derived by observing other parameters, such as average speed as function of time (see figure 5.2). A moderate decrease of the

![Average Speed vs AICC Penetration](image)
average speed is found as the penetration level increases. The combination of a 40% AICC penetration level at 1.5 s target headway gives a relatively large decrease of the average speed. This is also the only combination that resulted in congestion on the simulated motorway.

Extrapolation of the speed-flow relationship resulted in dubious capacity estimates, which are unrealistic compared to currently observed one-lane maxima (see table 5.4).

<table>
<thead>
<tr>
<th>No AICC</th>
<th>20% AICC</th>
<th>20% AICC</th>
<th>40% AICC</th>
<th>40% AICC</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1.0 s</td>
<td>1.5 s</td>
<td>1.0 s</td>
<td>1.5 s</td>
</tr>
<tr>
<td>Capacity values</td>
<td>3,000 / 3,500</td>
<td>3,000 / 3,400</td>
<td>2,880 / 3,185</td>
<td>2,840 / 3,500</td>
</tr>
<tr>
<td>Relative change</td>
<td>0 / 0 %</td>
<td>0 / -3 %</td>
<td>-4 / -9 %</td>
<td>-5 / 0 %</td>
</tr>
</tbody>
</table>

Table 5.4 Overview capacity estimates for morning/evening peak (per lane) (Van Arem et al., 1995a)

Although the absolute capacity values are unrealistic, the differences may give an indication of a potential capacity increase of decrease. Analysis of the values shows a decreasing trend of the capacity value. The variation in values is enormous, so a conclusion from values here derived - for two peaks - can hardly be drawn. We question the usefulness of the results for improving knowledge about capacity impacts of AICC deployment.

Benz (Benz, 1996) describes some problems in the development of Intelligent Cruise Control. Apart from legal and liability issues there are still technological questions about ICC to be answered, like: What is a proper safety distance? How hard should the system decelerate? What sensor range is needed?

The study focuses on these three questions and presents a solution to obtain answers. A simulation tool (Autobahn Simulator) is applied to investigate the impacts of ICC parameter combinations. Together with partners in the automotive industry, several parameters (see table 5.5) and parameter sets were defined.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant headway [s]</td>
<td>1.1 1.3 1.8 2.2</td>
</tr>
<tr>
<td>Sensor range [m]</td>
<td>50 80 130 180 220</td>
</tr>
<tr>
<td>Max. Deceleration [m/s²]</td>
<td>-5 -1 -1.5 -2 -2.5</td>
</tr>
</tbody>
</table>

Table 5.5 Investigated ICC parameters (Benz, 1996)

For the investigation, a total of 4000 vehicles were simulated which travelled over the predefined stretches of German motorway, without bottlenecks. There were two penetration rates studied, namely 5% and 10% equipped cars.

The emphasis in the study was on driver interventions. Some logical findings emerged. It was found that the higher the desired speed of a vehicle the higher the probability that a driver has to intervene. The influence of the headway - ranging 1.1 to 2.2 s - on the number of interventions is limited. The influence of the maximum deceleration, however, is by far stronger than the influence of the headway. It was found that the higher the deceleration authority the fewer number of interventions. A deceleration authority above 0.2g seems to manage nearly all practical motorway situations.

The impact of the sensor range on the number of interventions is limited. The investigation proved that AICC needs to include the brakes in order to be effective. The
study doesn’t derive capacity values.

Another simulation study has been conducted by McDONALD et al. (1998). A fuzzy logic based microscopic simulation model was used to analyse the impacts of Autonomous Cruise Control on motorway traffic. The experiment focused on a three kilometre three-lane United Kingdom motorway with 15% heavy goods vehicles.

Assessment of the impacts of system parameters on traffic flow is the aim of the first part of the study. The AICC time headways included are 1.0, 1.5, 2.0 and 2.5 s, while the deceleration authority value ranged from 0g, 0.1g, 0.2g to 0.3g. Traffic demand varied in three levels: 3500 veh/h, 4500 veh/h and 5500 veh/h. We remark that this experimental set up, using fixed traffic demands, cannot generate reliable capacity estimates. The AICC penetration in part one is fixed to 60% of the cars. For part two of the study, the AICC time headway was fixed at 1.5 s while the deceleration authority value was fixed at 0.1g. It is unclear whether the system can be overruled or not. How this important aspect has been modelled in the simulation is questioned.

As can be expected on theoretical grounds, the journey time increases as the traffic demand increases. Also, a large AICC time headway setting results in larger travel times. Especially above values of 2.0 s, the travel time increases rapidly. The combination of an - extreme large - headway setting at 2.5 s and high traffic demand showed the largest journey times. Furthermore, it was found that the deceleration authority does not affect the journey time greatly. Even the 0g setting does not deteriorate the travel time much, compared to a setting at -0.3g.

The standard deviation of the speed is small for medium and low traffic demand. At these traffic flow rates, the impact of the time headway setting is relatively small. This is explainable, since the capacity has not been reached yet, and the drivers may drive at their desired speeds. With larger time headways, or a high traffic demand, some of the drivers will be constrained and no longer drive at their desired speed.

Part two of the study deals with the relation between AICC penetration, traffic demand and journey time. They found that with 100% equipment penetration the travel time increased significantly during high traffic demand. We must emphasise that a headway at 1.5 s has been assumed and explains this result, since this headway is larger than the human average on motorways in dense traffic near capacity. We expect a capacity decrease, which in turn is responsible for a travel time increase.

In our opinion, the study focussed on too large headway settings and gave no insight into capacity changes with the tested systems. Much of the examined speed and travel time changes were expected due to the large headway setting of the AICC systems. Furthermore, the study did not include a specification of some important AICC variables, such as the lower speed boundary, and driver behaviour with respect to conditions for overruling the system.

From the examination of the simulation studies it follows that capacity impact analyses have not yet concentrated on bottleneck locations in motorway networks. Also the applied capacity estimation methods are not defined well. We furthermore found that the design aspects of AICCs are neglected to a large extent in the studies. In contrast, we will analyse bottlenecks in motorway segments, a decision which we motivated in section 4.3. In addition, we will adopt a clearly defined and unambiguous capacity definition and measurement method. In our experimental approach also challenging headway settings at
values below 1.2 s will be included. The AICC systems to be tested will have different functional characteristics. The AICC systems will have different supported deceleration authorities and supported speed range. The simulation model which will be applied for the traffic flow analysis must be able to represent these operational characteristics, as well as the interaction between driver and AICC system. Chapter 6 will focus on the experimental setup in more detail.

5.3 Automated vehicle guidance concepts

In literature, much attention is given to Automated Highway Systems (AHS), which is an automated vehicle guidance concept embodying a part of a conventional motorway, a transition lane, and a reserved, dedicated lane for fully automated vehicles (TSAO, 1995, SHLADOVER, 1996, 1997). In the following, a brief explanation is given about the operation of such a AHS, based on a description given by IOANNOU (1997).

Firstly, the concept and characteristics of automated vehicle guidance are set out (section 5.3.1). The literature review is presented in section 5.3.2.

5.3.1 Characteristics of automated vehicle guidance concepts

In an AHS environment, the facilitated vehicles would firstly enter the motorway under manual control through conventional on-ramps. After entering the main line (the shared infrastructure) the equipped vehicles, intending to travel on the supported portion of the freeway, would first enter the transition lane under manual control. A check-in procedure is required to ensure that the vehicle is properly equipped and is in satisfactory operating condition. After a positive check-in procedure, the system would shift the vehicle in the automated mode. The automated vehicle would then enter the adjacent automated lane when an adequate merging gap becomes available. For vehicles aiming at back-shifting to manual control, essentially the reverse of this process would be followed.

Lane barriers between transition lane and the adjacent automated and manual lanes would physically separate automated and manual traffic. Strategically located openings in the lane barriers would allow vehicles to manoeuvre between the automated and manual portions of the motorway.

Figure 5.3 shows an example of the concept of a transition lane were appropriately equipped vehicles change to the assisted driving mode or, in case of leaving the motorway, to the manual driving mode. On the dedicated lane, drivers are not able to change to the manual mode independently, referred to as ‘non-overrulable’. Only under emergency situations this would be allowed. Vehicles entering the reserved automated lane are clustered into platoons. In platoons, vehicles drive at very small gap distance from each other, while the distance between platoons is quite large in order to prevent collisions between platoons.

The small and fixed intervehicle gap distances within platoons can only be maintained by communication between the vehicles and by in-vehicle sensors (SWAROOP et al., 1994). In case of a sudden deceleration of the leader of a platoon and failure of the communication between vehicles, the consequences of rear-end collisions will be very limited due to the small speed difference formed between consecutive vehicles, see for example HITCHCOCK (1994).
Apart from the Automated Highway Concept, there exist automated vehicle guidance concepts which assume autonomous operation of the vehicles. These vehicles are equipped with many sensors and can drive in traffic together with manually controlled vehicles. Some prototypes based on this principle are tested, such as the ARTS/AHS-prototype (NAKAMURA, 1995), the intelligent Jaguar, demonstrated at the 1994 Prometheus Board Members' Meeting on public motorways north of Paris (TRIBE et al., 1995), and the intelligent RALPH vehicle (Rapidly Adapting Lateral Position Handler) developed by the Robotics Institute of the Carnegie Mellon University. We question if this mix of fully automated and conventional vehicles should be allowed since drivers' expectations and actual behaviour of the automated vehicle may differ.

5.3.2 Impacts of automated vehicle guidance on capacity

Theoretical studies
The longitudinal and lateral throughput on an idealized highway was studied by HALL (1995b). The author uses deterministic approximations to model highway throughput, accounting for both longitudinal requirements and lateral requirements (i.e. lane changing). The objective of the study was therefore to develop a throughput model of a multiple-lane Automated Highway System with automated lane changes. The primary parameter of interest is the time-space requirement for a lane change manoeuvre on capacity. The interpretability of the model and the results derived can be questioned. Capacity values are not presented.

BROUCKE et al. (1996) proposed a traffic flow theory of automated highway traffic. The theory predicts the performance of an automated highway system (AHS) in terms of achievable steady state flows and travel times, which can be used to compare alternative AHS designs. In an AHS, all vehicles are under automatic control: the distance a vehicle maintains from the vehicle in front, its speed, and its route from entry into the highway to
exit, are all determined by the vehicle's feedback control laws. The centralized traffic management system for the AHS can directly influence the flow by issuing orders to vehicles regarding their speeds and routes. Those orders will be obeyed because the vehicles are programmed to do so.

The model may be suitable for representing traffic flow on an AHS but only after the characteristic operational parameters are known.

Broucke's theory is based on an activity model, the movement of a vehicle is conceptualized as a sequence of activities, such as entry, cruise, and exit, which are realized by vehicle control laws. The highway is viewed as providing the space necessary to carry out each activity. When there is insufficient space in one section of the highway, the rate of activity completion in the immediately upstream section must be reduced. Since the rate of activity completion is proportional to the speed, this causes a reduction in flow.

The theory is the basis for capacity and optimal plan calculations. The model has been illustrated with some examples, such as the implementation of Intelligent Cruise Control. It was found that the capacity of a single lane increases about linearly with the proportion of these semi-automated vehicles. However, the parameters determining the needed safe 'activity' space were chosen ad hoc, strongly affecting the

RAN and TSAO (1996a) studied the macroscopic traffic flow on a single-lane Automated Highway System. There are some important assumptions in the conducted traffic flow analysis.

1. All vehicles moving in a clustered formation (platoons, see figure 5.4);
2. The actual intra-platoon spacings do not vary with respect to time or speed;
3. Vehicles are automatically driven either at a constant speed or with a variable speed;

A platoon-following model is proposed. The length $L_k$ of platoon $k$, assuming a constant vehicle length $l$, is simply:

$$L_k = n_k \cdot l + (n_k - 1) \cdot s_{k,\text{intra}}$$

where $n_k$ is the number of vehicles in platoon $k$ and $s_{k,\text{intra}}$ is the constant intra-platoon spacing. See Figure 5.4.

A deceleration response of a following platoon $k$ is specified as occurring at time $t+\tau$ where $\tau$ represents the reaction time. This reaction time includes sensor delay as well as actuation delay. Since conventional human control is replaced by computer control, the reaction time could be much shorter (0.1 to 0.3 s) compared to the average human reaction time.

In some fully automated AHS concepts, movements of all platoons are closely monitored, commanded, and even completely controlled by the roadside control system. The authors stated that it is more likely that realistic AHS operational concepts will give platoons a high
degree of autonomy during platoon following for safety reasons. A conventional car-following model can be used as a starting point for designing and modelling platoon-following strategies, given the proven safety of manual driving.

The car-following models are useful to predict maximum achievable traffic flow under specified assumptions (see for example section 4.3.2). The in the study derived platoon-following model was applied to a single AHS lane without entering, exiting, lane changing, merging or diverging processes. The study distinguishes two operational concepts, which are the *speed constant* concept and the *speed variable* concept.

The potential speed-density curves for these concepts are depicted in figure 5.5. The constant speed concept exhibits a linear relationship and can be compared with the concept of a cable train. The variable speed concept has similar properties of manually operated motorways, but the characteristic points are shifted substantially.

Some results of the analysis are presented in table 5.6. As can be seen from the table, the capacity values depend strongly on the input parameters. However, this is still the most uncertain part of the AHS development. As indicated by the author, an intra-platoon spacing of 1 metre at a speed of 97 km/h means a headway of 0.037 seconds and seems a little bit too optimistic. It requires sensing and control systems operating at less than this time.

<table>
<thead>
<tr>
<th>Speed control</th>
<th>Free flow speed [km/h]</th>
<th>Jam density [veh/km]</th>
<th>Platoon size</th>
<th>Inter-platoon spacing</th>
<th>Intra-platoon spacing</th>
<th>Capacity value [veh/h/l]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ex. 1</td>
<td>Constant 97</td>
<td>162</td>
<td>20</td>
<td>50 m</td>
<td>1 m</td>
<td>11,392</td>
</tr>
<tr>
<td>Ex. 2</td>
<td>Variable 97</td>
<td>162</td>
<td>20</td>
<td>50 m</td>
<td>1 m</td>
<td>8,358</td>
</tr>
<tr>
<td>Ex. 3</td>
<td>Variable 97</td>
<td>162</td>
<td>1</td>
<td>5 m</td>
<td>1 m</td>
<td>6,303</td>
</tr>
<tr>
<td>Ex. 4</td>
<td>Variable 97</td>
<td>162</td>
<td>20</td>
<td>100 m</td>
<td>5 m</td>
<td>4,750</td>
</tr>
</tbody>
</table>

*TABLE 5.6 Examples of derived capacity values for AHS (Ran & Tsao, 1996a)*

It seems to us that the inter-platoon spacing was chosen ad hoc in the analysis. The choice for the inter-platoon spacing could depend, for example, on the platoon speed. A safety strategy could be applied to determine the minimal required safe inter-platoon spacing.
Simulation studies

In the study of Tساo et al. (1997), analytical models are developed to study the vehicle/platoon and gap distributions on individual AHS lanes. Based on these models, estimates for the time required for a complete lane change for several operating scenarios are provided. Also, the simulator SMARTPATH was modified and applied to study the effects of platooning and lane barriers on AHS capacity.

In most of the simulation test cases, the exit success percentage is well below 100%, which poses a major challenge to designing AHS operating strategies. Compared to the platooning lane-flow rule, the free agent rule results in lower exit success percentages. The presence of barriers results in lower longitudinal flow but makes little difference in exit success rate. This is because the lane changes are initiated well before the desired exits and, to accommodate the lane changes, the traffic has to slow down. The analytical study showed that the average lane-change completion time increases with the flow in the destination lane and, at high flow levels, the increase is at a higher rate than the flow.

Neither the analytical models nor the simulation models studied by Tsao adequately represent how a future AHS would be operated. More sophisticated operating strategies and models are required to optimize the capacity of an AHS, both in longitudinal and lateral direction. An exit success rate of about 100% is desired for practical use of the AHS.

They conclude that there exists a direct trade off between longitudinal and lateral capacities of an AHS. Therefore, in predicting the maximum achievable flow of the AHS, the amount of lane changes assumed and the lateral capacity required to accommodate the lane changes must be explicitly considered. In particular, using the longitudinal flow as the only measure for AHS capacity without any reference to the requirement for lateral flow is misleading.

We recall one interesting remark in the paper:

'Though the short spacing concept increases the longitudinal capacity, it may decrease the lateral capacity to such a degree that the lateral capacity becomes the bottleneck, and the longitudinal flow suffers as a result.'

This aspect not only counts for the AHS but also for support systems in mixed traffic.

Flow benefits of Autonomous Intelligent Cruise Control in mixed manual and automated traffic are assessed by Rao et al. (1993a). The potential flow improvements when only a proportion of vehicles on a highway are equipped with AICC are examined, and theoretical upper limits on flows as a function of pertinent variables are derived. Because of the limitations of the theoretical models, a simulator was used that models interactions between vehicles to give detailed information on achievable capacity and traffic stream stability.

The longitudinal support system applied is combined with the AHS platoon driving concept. Based on assumptions of average spacing between cars in platoons and average spacing between platoons, a theoretical model is developed for predicting the benefits. They assume that all vehicles equipped with AICC will drive with an activated system. One important quote from their conclusions is the following:

'Although derived flow rates appear impressive (an AICC lane capacity of 5,500 veh/hr) they are based on an extremely optimistic value for intervehicle spacing in platoons using AICC. This value (8 m) is too small and is unlikely ever to be implemented (...).'}
Indeed, at 90 km/h, this distance represents a headway of 0.3 seconds which seems too optimistic even when sensor technology improves. The ultra close spacings proposed in AHS concepts (1 m), to prevent relative velocity collisions, can certainly not be maintained with ACC based on sensors. Only cooperation (fast communication) between vehicles will possibly and eventually results in attaining these spacings.

The authors also conclude that the needed transition lane for feeding the automated lane can preferably not carry permanent flow, because the stream in the transition lane is very sensitive to vehicles moving in and out of it. Therefore, any capacity on the AIACC lane must be divided by two. Thus, if the dedicated lane capacity is 5,500 veh/h, the capacity of the dedicated and transition lane is on average 2,750 veh/h/1, which is only marginally better than the average maximum lane flows on today's motorways.

The topic of another study by RAO et al. (1993b) are the access and egress strategies of AHS. The claim of the paper is that the major source of capacity limitation in an intelligent highway environment will arise from behaviour of the traffic stream as vehicles attempt to join and leave the automated lanes. A simulator (SmartPath, see ESKAFI et al., 1995) was used for stability investigations. Assumptions about the behaviour and characteristics of automated vehicles are made. Simulations are based on a range of detection of 150 m, a sensor delay of 0.1s, an actuator delay of 0.2s, a comfort deceleration of 0.2g and an emergency deceleration of 0.5g. The maximum platoon size is set to twenty.

Speed of vehicles is specified such that single vehicles or platoons can stop before colliding with any vehicle decelerating in front of it. A speed of 25 m/s was applied. Three different policies governing entrance and egress from the automated lane were examined. They found that appropriate design of these strategies can improve the access and egress rates, achievable flows, and rider comfort.

CASTILLO et al. (1997) also try to quantify the capacity of an AHS taking into account exits and entrances to the dedicated lane. The authors mention network-related capacity limitations. For example, traffic on a freeway that reaches its destination downtown must be absorbed by the local city streets. Improvements of speed, flow, safety or other conditions on the freeway cannot increase the input flow of traffic to the city centre beyond the absorption capability of the destination zone. As a consequence, the capacity of automated highway systems must incorporate parameters regarding the capacity of the destination nodes.

An analysis of the AHS performance indicates theoretically large capacity values - potentially a factor six compared with conventional lanes - for a single platoon-based automated lane. This is only representative of an idealized scenario without lane-changes, entrances, or exits. The authors look at the latter factors as well and conclude, using assumptions about the merging processes (platoons must be split, vehicles must change to a manual driving mode), that very high values of capacity can be obtained even for moderately high values of the exit flow ratio. However, in the interval of 10 to 40% exit flow the capacity decreases significantly with increasing exit flow (capacity gain compared with a conventional motorway lane at 40% exit flow is between factor 1 and 3, dependent on average number of vehicles per platoon). They remark that locations where automated highways could be beneficial would likely exhibit a low exit flow ratio.
The Castillo investigation also included the impact of entering vehicles on the automated lane capacity. Unfortunately, this effect is essential for the AHS performance and should not be ignored according to the authors. Calculations showed reductions in capacity which are larger than the reductions related to exit flow processes. A value of 6,000 veh/h is mentioned as a potential realistic value for a single lane AHS if the exit flow is small. However, a small proportion of high flow rates is still quite large to be accommodated by a single (dedicated) off-ramp. The authors propose splitting of the exit flow from the automated lane into several streams and feeding these into different streets or highways. This is needed to prevent queuing on the automated lane. If for some reason the traffic flow collapses, the number of vehicles to store per unit time will be much greater than that of a conventional lane. In other words, the resulting queue will grow much more rapidly and will become much longer. The authors give an example: if two lanes of a four-lane conventional freeway are converted to AHS (one automated lane and a transition lane), and the capacity of the automated lane is four times that of a conventional lane, then the freeway as a whole has 50% greater capacity, but queues on the automated lane will grow four times as quickly and will be four times as long as on conventional lanes.

An economic comparison of a single-lane AHS and a three-lane freeway results in the conclusion that the cost of an AHS which is intended to serve the same flow as a three-lane freeway will only be less than the cost of that conventional freeway if the average trip lengths on the system are somewhat long: larger than 8 km to break even, larger than 24 km to save the cost of one freeway lane km.

Many researchers (CASTILLO et al, 1997, TSAO, 1995, RAN et al,1996, 1997 and 1998) noticed the importance of studying the consequences of vehicles leaving or entering a platoon and the dedicated lane, and strategies to deal with this traffic. The large pipe-line capacities possible on uniform lane sections for automated vehicles only, will heavily reduce with the presence and amount of merging vehicles. RAN et al. (1997) state that these strategies are critical to the success of AHS.

‘An AHS cannot survive without an effective urban interface strategy.’

Recent years, many researchers view AHS development as something that evolves from AICC deployment. It is speculated that, by gradually increasing the in-vehicle technology (advanced sensors, communication facilities) and adapting the infrastructural environment, the motor vehicle will be equipped with facilities enabling coordinated driving on dedicated lanes, see e.g. WARD, 1997, BENOUAR et al, 1997, HALL, 1997, STEVENS, 1995, 1997 and TSAO, 1998. We agree with the view of such an evolutionary development of AHS.

5.4 Conclusions

5.4.1 Longitudinal driver assistance systems

From the literature findings we conclude that extensive and accurate capacity analyses of driver assistance systems are lacking. Only a few headway settings are studied, without combining other AICC design variables such as maximum deceleration authority or minimum supported speed. Headway settings equal to, and even above 1.5 s are examined although on theoretical grounds this must automatically result in a capacity loss. Our experimental setup will include challenging headways below 1.5 s, as will be described in Chapter 6.

There are also comments on capacity estimation methods applied in the past research. Firstly, extrapolation of speed-density data is not a reliable approach. The derived capacity value depends too much on assumptions made about the critical density. Secondly, the use of aggregated one-minute data is not appropriate for determining practical capacity values.
Thirdly, capacity can only be measured unambiguously downstream a distinct bottleneck, while most attention has been given to uniform stretches without discontinuities. We will use a well-defined and consistent capacity estimation method which already has been described in section 4.3.3. The reliable queue discharge flow rate distribution method will be applied on several bottleneck types which are described in the following chapter. Furthermore, in our capacity analyses we will use an aggregation time interval of five-minutes which is sufficiently large to obtain robust, independently distributed maximum flows (section 4.3.3).

We observe that microscopic simulation has frequently been applied to assess traffic flow quality effects of longitudinal driver assistance systems. We will use a micro simulation approach in our traffic flow impact assessment as well.

Past research focussed mainly on uniform motorway links. In contrast, we will focus on motorway bottlenecks. The transferability of the reviewed models may be restricted since simulation of traffic processes near bottlenecks requires a specification of driver behaviour that is different from driver behaviour at uniform stretches. A microscopic model is required that takes into account driver behaviour at bottlenecks, such as merging and mandatory lane-changes.

It is also found that in past research the applied AICC models have been specified inadequately. A full description of the AICC operational characteristics should be incorporated in a microscopic simulation model in order to get realistic outcomes. For example, the AICC description should include a supported speed range and acceleration range, and driver behaviour with respect to AICC intervention and reactivation. We will include such a detailed description in the applied simulation model (Chapter 7).

5.4.2 Automated vehicle guidance

The assessed automated vehicle guidance studies focus particularly on Automated Highway Systems, as the most serious candidate for complete automation of the driving task. A considerable number of studies recall the importance of entry and exit processes, as decisive factor for attainable capacity gains.

The feasibility of AHS as beneficial alternative of urban motorway systems is doubted by several authors (see e.g. ZHANG, 1996). Although bottleneck sections can gain from automation, the introduction of the AHS concept seems not realistic for these locations due to the implementation cost of dedicated infrastructure. The demanded extra space for the AHS is needed at locations where space is scarce. In addition, sufficient vehicles should be equipped with the needed intelligence and electronics to utilise the dedicated infrastructure satisfactorily. Besides, the extra lane capacity created by adding an AHS-lane can only be utilised if supplementary traffic can enter and leave the motorways with the AHS facility. This will replace the capacity problem to the entrances and exits of the motorway system.

From these considerations, it appears that the focus of traffic flow investigation should be on short term driver assistance systems first. The implementation of AHS concepts will progress slowly due to the unclear advantages and large investments needed for deployment.

Next chapter will describe the experimental setup of our traffic flow impact assessment of AICC systems. The fully automated vehicle guidance systems are not investigated here further.
CHAPTER 6

EXPERIMENTAL SETUP OF AICC INVESTIGATION

A well-thought-out experimental setup, needed for adequately assessing traffic flow quality impacts of AICC-systems, is described in this Chapter. First, the research questions and hypotheses are restated in section 6.1. Section 6.2 provides a description of the design layout of the assistance systems to be tested. Section 6.3 continues with a discussion of the safe car-following headway parameter selection for the AICC systems under investigation. Other aspects of the experimental setup, such as the dependency of impacts with the penetration rate and motorway configuration, are described in sections 6.4 and 6.5 respectively. In conclusion, the methods and difficulties of the capacity and safety analyses are shown, concentrating on the reference situation for a two-lane main line with an on-ramp bottleneck (section 6.6).

6.1 Research questions and research approach

Before simulation experiments can be carried out, it is necessary to concisely describe the objective of these experiments, and select or develop a purposeful microscopic simulation model. We restate our research objectives, research questions, and related difficulties in section 6.1.1. The research approach is outlined in section 6.1.2.

6.1.1 Research questions

Many advantages of AICC have been hypothesised in the past but not established unambiguously yet, see e.g. BROQUA (1991), DAVID (1995), MINDERHOUD et al. (1996d). The impacts of supported driving on capacity, safety, comfort, and driver acceptance are still uncertain. Our main subject of research is estimating and assessing the potential capacity impacts of AICC deployment on motorways. In Chapters 4 and 5 we found that such an assessment should focus on bottlenecks in the motorway network. With respect to the deployment of driver assistance systems, or AICC, many questions about relationships between system layouts (e.g. algorithms and parameter settings) and motorway capacity can be formulated. With our knowledge about the design variables of AICC systems (see section 3.5.1), we decided to focus on the following relationships:
• impact of AICC headway setting on motorway capacity;
• impact of AICC system design parameters (such as deceleration authority, minimum speed, manual/automatic reactivation) on motorway capacity;
• impact of AICC presence in the vehicle fleet.

On theoretical grounds, expectations on changes in motorway capacity might be formulated, assuming the introduction of longitudinal driver assistance systems. Some hypotheses have been described in section 4.3.4 and will be recapitulated here.

Firstly, we expect that extremely large headway settings of AICC systems will deteriorate motorway capacity while extremely small headway settings probably increase capacity. Small headways imply a high traffic density, which is beneficial for high capacity levels. The impact of headway settings close to current observed average minimum headways (1.2 s) of drivers under capacity conditions is less obvious.

Another expected impact as a result of introducing AICC is the reduction of variation in gap sizes. In section 4.2 we hypothesised that this can contribute to a road capacity increase. We also foresee that AICC-equipped vehicles will approach the desired speed closer, thus contribute to a speed increase. This effect is envisaged when a small headway setting and an efficient car-following controller is applied in the AICC systems.

The impact of the various possible (combinations of) system layouts and parameters is quite difficult to estimate in advance. Only some indications on capacity impacts can be given. A small deceleration boundary implies that drivers must intervene more often than when large deceleration levels are supported by the system. More interventions imply less use of the AICC functionality, which may result in a decreased capacity. The same holds for a high value for the minimum supported speed and a low value for the maximum supported speed. Furthermore, the reactivation strategy of a system does also dictate the time drivers might use their assistance system. We hypothesise that when systems with small headway settings are used more frequently, the capacity value will increase.

Furthermore, the penetration rate will probably affect motorway capacity. The larger the percentage of the vehicle fleet equipped with an AICC with a small headway setting, the larger the capacity value will be. On the contrary, a large percentage of vehicles with large headway settings will decrease motorway capacity. Furthermore, at relatively small AICC equipment penetration rates, the effect on capacity - regardless the headway setting - will probably be very limited due to the majority of manually controlled vehicles.

Secondary impacts of the factors mentioned here are changes in lane speeds and densities, and as a consequence, in lane utilisation (the distribution of vehicles over the lanes).

Safety impacts that follow from AICC deployment are also part of the impact assessment study, but it is not the main issue to be tackled.

Next section 6.1.2 gives the motivation for using a microscopic simulation approach to study the capacity impacts of AICC.

6.1.2 Motivation for the use of a microscopic simulation model

In order to motivate our research approach, of using a microscopic simulation tool, the factors affecting motorway capacity levels are recalled here briefly. The capacity notion has been discussed in section 4.3 extensively.
Figure 6.1 shows a schematic overview of factors related to changes in capacity. Changes in vehicle fleet composition, driver population, changes in preferences (such as desired driving speed) and vehicle capabilities - added systems such as AICC - may cause changes in lane change desirability, lane change possibilities, and lane utilisation. A direct impact on capacity via changes in flow composition, speed and inter-vehicle gaps is also possible. Unfortunately, it is difficult to analytically estimate the separate or joint impact of these changes. For example, it was found that (little) rain may decrease the capacity of the left lane approximately 12%, whereas the overall capacity decreases only 1% due to a more balanced lane distribution (Seddiki, 1993).

Another example of the influence of lane utilisation on motorway capacity is capacity values observed on German motorways, which are substantially lower than observed at Dutch motorways. Very likely this is due to the unrestricted speed limit in Germany giving rise to a lane distribution which negatively affects the over-all performance (Hall & Brilon et al., 1994).

In order to cope with the complex interrelationships between the many factors determining roadway capacity a microscopic simulation approach is needed. Our literature study in Chapter 5 confirmed the appropriateness of the application of a microscopic traffic simulation tool to assess changes in traffic flow characteristics. Chapter 7 is dedicated to the selection of such a tool, and describes a driver behaviour theory that includes AICC system handling.

The thesis will proceed with the description of the setup of the simulation experiments, beginning with the selection of driver assistance designs in section 6.2.

6.2 Selection of driver assistance system designs

A range of driver assistance designs will be tested since it is expected that the variation in system design may result in different traffic flow qualities. Each assistance system design or
layout can be differentiated further and is called a *concept* when a headway parameter setting has been chosen (section 6.3). The systems are denoted with AICC (Autonomous Intelligent Cruise Control) according to the definition presented in section 3.5. Sections 6.2.1 to 6.2.5 describe the five AICC layouts and give reasons for applying the system layout in the experiments.

### 6.2.1 Normal AICC design

The ‘Normal AICC’ layout represents the first generation of autonomous in-vehicle longitudinal driver support system (figure 6.2). The system layout allows the driver to intervene at any moment. The support system must be reactivated manually after an intervention. Due to the still expensive techniques and methods for detection of stationary objects, this first generation support system will operate within a restricted range. First prototypes show a minimal operational speed of approximately 30 km/h (see e.g. NILLSON, 1995, AUTOWEB, 1998). The upper speed boundary is determined by the sensor range and deceleration authority. The value of 150 km/h is an average of maximum speed boundaries found in literature, and applied for testing the ‘Normal AICC’ design in a simulation environment.

![Operational characteristics of 'Normal AICC' design](image)

The ‘Normal AICC’ has also the restriction of limited deceleration capabilities of the first generation support systems. A medium deceleration authority of -3 m/s² 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 +1.5 m/s². Higher levels are quite uncomfortable for driver and passengers.

With respect to the described characteristics of the ‘Normal AICC’ some preliminary expectations can be drawn for driver behavioural changes. 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. The 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 under-utilisation of the system’s functionalities.

### 6.2.2 Extended AICC design

The ‘Extended AICC’ layout is an extension of the described ‘Normal AICC’ layout. In
addition, the ‘Extended AICC’ design has a functionality for automatically reactivating the system after a manual intervention has occurred (figure 6.3). In this way, temporary manual control is always directly followed by the support system control. For example, a driver may brake in order to reduce speed to let a vehicle merge in front. Directly after removing his foot from the brake pedal, the support system takes the vehicle control back again. The same holds for a temporary speed increase, for example needed to pass a slower vehicle or truck.

![Image: Operational characteristics of 'Extended AICC' design]

The automatic reactivation functionality added will probably increase the use of the assistance system. Manual driver control is minimised and under-utilisation of the system is avoided, although driver’s sovereignty and responsibility remain. It should be noted that we assume that drivers do not use the on/off switch of the system during the experiments.

6.2.3 Queue AICC design

Another AICC design proposed for testing is the ‘Queue AICC’, which is especially designed for supporting the driver in congested, stop-and-go traffic conditions. The support system functions are as described for the ‘Normal AICC’ layout, however, the sensor is able to detect stationary objects. The operational speed range of the AICC is 0 to 60 km/h, covering the speed range of congested traffic. Manual control is required during normal traffic conditions, at speeds above 60 km/h (figure 6.4).

![Image: Operational characteristics of 'Queue AICC' design]

We hypothesise that such a stop-and-go functionality could postpone the moment of breakdown and therefore possibly increase capacity. Apart from the foreseen positive
impacts on drivers’ perception of comfort using the ‘Queue AICC’, the queue length may be reduced due to the efficient speed and safe distance control of the system. Especially during stop-and-go traffic conditions, following a lead vehicle at a small gap distance is a difficult and uncomfortable task. Without a support system, relatively large gap distances are maintained in order to create a comfortable, smooth ride in congestion. A ‘Queue AICC’ could solve this inefficient driver behaviour by means of automatic vehicle control.

6.2.4 All Speed AICC design

The ‘All speed’ system layout supports the driver with his longitudinal driving task over the full speed range from 0 to 150 km/h, and applying a maximum deceleration of -0.3 g. Figure 6.5 illustrates the operational characteristics.

By supporting the driver over a large speed range, the ‘All speed’ design is a mix of the stop-and-go functionality of the ‘Queue AICC’ and the ‘Extended AICC’ layout. The observation of vehicles at all speeds may result in a further improvement of the traffic flow quality. In addition, the safety advantage in comparison with the ‘Extended AICC’ is quite clear. The ‘All speed’ AICC detects the end of a queue and extremely slow moving vehicles and will react upon this. The ‘Extended’ concept does not detect these vehicles: the driver should control the vehicle when observing such a dangerous approach.

6.2.5 Complete AICC design

The most sophisticated AICC layout conceived, is a system that supports the driver over the full speed range and without deceleration and acceleration limitations. Automatic
reactivation of the assistance system after manual intervention is also present. This layout is in the experiment referred to as ‘Complete AICC’. Figure 6.6 gives the characteristics schematically.

Introduction of such an advanced AICC design depends on costs, legal aspects and driver acceptance. In addition, these issues can only be studied appropriately when another characteristic of the AICC has been determined: the time headway setting. The next section focusses on this important design parameter.

6.3 Selection of headway parameter settings

Generally, drivers can hardly maintain a constant speed for long periods, are inconsistent in their approaching behaviour and drive at varying car-following distances (see e.g. Hogema, 1995 and Hoefer, 1972). Driving with an AICC makes it possible to maintain constant, small, minimum car-following distances for long periods.

![Figure 6.7 Relation between average minimum gap size and driving speed](image)

Empirical findings allow us to formulate a function for desired minimum gap distance and driving speed (see e.g. Vermij, 1992). By dividing a gap distance by the driving speed, the headway value results. Figure 6.7 exemplifies both relationships using empirical data (Vermij, 1992). On the left vertical axis the desired gap distance in metres is depicted, while on the right vertical axis the desired headway in seconds is depicted. The horizontal axis shows the speed of the following vehicle.

For speeds in the range of 40 to 130 km/h, the desired minimum gap relationship can easily be represented by a single parameter: the desired minimum time headway. For ease of comparison, the time headway constant is used to indicate the gap distance setting for the AICC concepts.

Considering all possible headway settings for all AICC concepts would result in a too large number of system concepts which must be simulated and analysed. Therefore, a purposeful
selection has been made. The range of possible headway settings is bounded by a minimum value of 0.8 s, since smaller values are considered to be unsafe for the type of overrulable AICC-designs considered. Furthermore, the 0.8 s setting is approximately the lowest acceptable headway when dealing with comfort aspects, as has been found in driver simulator experiments (De Vos et al., 1996).

The upper boundary of the time headway is determined by one of the goals of AICC, namely to realize a capacity increase. Theoretically, the capacity cannot increase when all vehicles drive at a car-following distance of approximately 1.4 s. The 1.4 s value is therefore selected as largest headway value in our experiments.

Table 6.1 presents an overview of the characteristics of the support systems to be tested. Empty cells mean that the corresponding AICC-design with a certain headway setting has not been included in the analysis. The last column with penetration rates is explained in section 6.4. A total of ten AICC-concepts is taken into account in the experiment.

<table>
<thead>
<tr>
<th>AICC-design</th>
<th>Speed range [km/h]</th>
<th>Acceleration range [m/s²]</th>
<th>Reactivation option</th>
<th>Headway [s]</th>
<th>Penetration rate [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal</td>
<td>30 - 150</td>
<td>-3 / +1.5</td>
<td>manual</td>
<td>0.8</td>
<td>✓ ✓ ✓</td>
</tr>
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<td></td>
<td>1</td>
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<td></td>
<td></td>
<td>1.4</td>
<td>✓ ✓ ✓</td>
</tr>
<tr>
<td>Extended</td>
<td>30 - 150</td>
<td>-3 / +1.5</td>
<td>automatic</td>
<td>0.8</td>
<td>✓ ✓ ✓</td>
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<td>1.4</td>
<td>✓ ✓ ✓</td>
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<tr>
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<td>-3 / +1.5</td>
<td>automatic</td>
<td>0.8</td>
<td>✓ ✓ ✓</td>
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<td>1.4</td>
<td>✓ ✓ ✓</td>
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<tr>
<td>All speed</td>
<td>0 - 150</td>
<td>-3 / +1.5</td>
<td>automatic</td>
<td>0.8</td>
<td>✓ ✓ ✓</td>
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<tr>
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<td>automatic</td>
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</table>

Table 6.1: Overview of AICC-concepts selected for experimental traffic flow impact analysis

A 'Normal AICC' design with a 0.8 s headway has been rejected as possible system setting since some preliminary simulations showed rear-end collisions during shock waves, indicating that such small headway setting in combination with the restricted deceleration capabilities and a manual reactivation function is not an asymptotically stable (section 4.4). This system design can be considered as a safety hazard.

6.4 Selection of AICC equipment penetration rates

One could expect that the magnitude of impacts depends on the penetration rate of AICC equipment. Therefore, impacts should be studied at several levels of equipment penetration. The literature survey gave some indications for analysing the following equipment penetration levels (Reitter, 1994).

- 10% equipment rate (indication of effects on a short term);
- 20% equipment rate (indication of effects on a mediate term);
- 50% equipment rate (indication of effects on a long term);
- 100% equipment rate (a theoretical end stage: maximum achievable impacts)

These penetration rates are selected in our simulation study.

In each experimental scenario (combination of AICC concept, penetration rate, and road configuration) a number of user classes are distinguished. The user classes present in the vehicle fleet and the user class distribution, depend on the scenario characteristics (the AICC
penetration rate and investigated AICC concept). The experimental and reference scenarios deal with the following user classes:

- passenger cars not equipped with a support system;
- trucks not equipped with a support system;
- trucks equipped with a ‘Normal AICC, headway 1.2 s’;
- passenger cars equipped with an AICC system corresponding to the experimental scenario.

In all experimental scenarios a heavy truck percentage (for equipped and unequipped trucks) is applied of about 10%. Focus is on the passenger cars, although the small portion of trucks in the traffic flow will also be equipped with an assistance system. To limit the many factors affecting changes in road capacity, it is assumed that trucks will be equipped with the ‘Normal AICC’ design with 1.2 s headway setting. The percentage of equipped trucks is in each scenario the same as the percentage of equipped passenger cars.

The ten AICC concepts considered for passenger cars will be studied at the four penetration equipment rates proposed, resulting in a total of 41 experimental scenarios for each of the three bottleneck cases. The situation in which no AICC-equipped vehicles are present is referred to as reference case.

A simulation is carried out by gradually increasing the traffic demand at the origins from the beginning to the end of the simulation time. There are no vehicles generated at the origins if this is physically impossible. The simulation duration was set at 2.5 hours, including approximately one hour congestion upstream the bottleneck (congestion onset depends on the experimental scenario). All experiments end in congested conditions. Capacity estimates are based on data collected during the last ten 5-minute periods at the downstream detector, since during this period upstream queuing exists in all experiments. The queue discharge distribution method is applied to estimate the capacity value (section 4.3.4).

Next section 6.5 presents the three test locations applied in the simulation study.

### 6.5 Motorway bottlenecks in the experiments

With respect to earlier research into the relationship between driver assistance system design and motorway capacity, we seriously criticize the lack of a clear bottleneck location and capacity estimation methodology. One can only assess road capacity reliably downstream such a bottleneck under the condition that the traffic demand is sufficiently high (i.e., queuing observed upstream the bottleneck). Our experiments involve three different bottlenecks; a two-lane with on-ramp, a three-lane with on-ramp, and a weaving section.

For a correct data interpretation, it is also necessary to collect flow rates as if they are independently drawn from an identical distribution. A five-minute time interval will be used as aggregation period in the experiments 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.

In the following, we give a short description of the bottlenecks selected for the simulation experiments.
6.5.1 Two-lane main line with on-ramp

Figure 6.8 shows the road geometry of a scenario which will be applied in the simulation experiments. An on-ramp, of 250 m length, is located at 2500 metre after the beginning of the segment. Detectors, measuring flows and speed aggregated every five minutes, are located one km before and one km after the on-ramp. The downstream data is applied in the capacity analysis, the upstream detector is used to check the needed congestion state for the analysis.

![Diagram showing road geometry of two-lane main line of motorway with on-ramp](image1)

FIGURE 6.8 Road geometry of two-lane main line of motorway with on-ramp

The left lane demand level increases from 1,000 to 2,500 veh/h, the right lane flow increases from 1000 to 2,000 veh/h, and the on-ramp flow increases from 500 to 1,800 veh/h. Other mixes between main line and on-ramp demand may affect the moment of flow breakdown. Appendix B gives the traffic demand input of all the tested bottlenecks.

6.5.2 Three-lane main line with on-ramp

The three-lane version of the on-ramp bottleneck is depicted in figure 6.9. The location of detectors and on-ramp are the same as for the two-lane main line.

![Diagram showing road geometry of three-lane main line of motorway with on-ramp](image2)

FIGURE 6.9 Road geometry of three-lane main line of motorway with on-ramp
6.5.3 Symmetric weaving section

Weaving sections are important factors for capacity restrictions in today's motorway networks. At these locations, a proportion of the traffic from two main lines should make a 'weaving' manoeuvre to the desired destination. A weaving section bottleneck is therefore quite different compared to an on-ramp bottleneck. The symmetric weaving section analysed in the simulation study (figure 6.10) has the same number input lanes as output lanes.

![Diagram of weaving section](image)

**FIGURE 6.10 Road geometry of weaving section of a motorway**

Detectors are located 500 metre before the beginning of the weaving section and 1000 metre downstream the end of the bottleneck. The weaving proportion is 30%. Appendix B gives additional information about the traffic input.

Section 6.6 gives an example of the capacity and safety analysis for the two-lane with an on-ramp bottleneck with non-equipped vehicles.

6.6 Analysis of reference scenario with SIMONE

A capacity analysis will be carried out for the scenarios described in this chapter, using the microscopic simulation model SIMONE which will be described in detail in Chapter 7. In Chapter 4 it was decided to estimate a capacity value based on the average down-stream flow rate (based on five minute interval measurements) during the presence of an upstream queue. The investigation also includes the pre-queue capacity, but it turned to be impossible to make a reliable estimate with the available data from a single simulation run. Fortunately, the queue-discharge capacity is a more practical value for traffic engineering applications since the queue discharge situation can be attained for longer periods (CASSIDY et al, 1999).

Besides the capacity analysis, a safety analysis is performed. The approach focuses on the occurrence of safety-critical situations with respect to potential rear-end collisions, using a time-to-collision measure.

This section gives a selection of the traffic flow impact and capacity analyses (sections 6.6.1 and 6.6.2) and safety analyses (section 6.6.3) for the reference scenario for the two-lane with an on-ramp bottleneck. Some general findings on the significance of the results
will be used in order to limit the calculation effort and simulation runs for the other scenarios. The reference scenario analyses of the three lane on-ramp and weaving section were performed analogously, the outcomes of which are included in Chapter 8.

6.6.1 Speed-flow relationships

Figures 6.11a and 6.11b show for the reference situation of the two-lane main line with on-ramp (thus without AICC-equipped vehicles) the speed-flow relationships for respectively the upstream and downstream detector. The relationships are shown for each lane separately and for the cross-section as a whole.
As can be seen in figure 6.11a, congestion occurs after a while, and speeds of 30 km/h are observed during this period. The capacity state of the on-ramp bottleneck has been reached at that time, and as can be noticed in figure 6.11b, the queue discharge maximum flow rates are ranging from 4,100 to 4,400 veh/h. A clear difference between maximum flow rates of the pre-queue state and queue discharge state is not found (thus no capacity drop), however, the speeds at queue discharge capacity are somewhat smaller.

The estimated speed-flow relationships show a good resemblance with empirical speed-flow relationships observed for two-lane motorways near an on-ramp location (see e.g. Appendix A). The estimated motorway capacity is also in agreement with capacity values found in practice (see e.g., SCHUURMAN et al., 1993 and BOTMA et al., 1998a) and in a literature study on empirical capacity values (MINDERHOUD et al., 1996b).

6.6.2 Stochasticity of maximum flows

It is well documented (see e.g., MINDERHOUD et al., 1997) that actual driver behaviour on motorways is of a stochastic nature, such that observed maximum flows at capacity show a clear distribution. To consider this Stochasticity in motorway driver behaviour, five simulations runs were conducted with five different random seed values. Thus, all experimental conditions were equal except for the composition of driver/vehicle combinations in the flow. The fifty maximum flow rates collected during these randomized runs are used in a statistical analysis, see Appendix D. The standard deviation of the sample is 1.9 % (81.5 veh/h) of the mean (4,285 veh/h). A conducted chi-square test gave support to the assumption of a normal distribution of maximum flows (p>0.95). A histogram of the maximum flows is depicted in figure 6.12.

![Histogram of 50 maximum flow rates observed in 5 simulation runs](image)

To limit the number of simulations, we considered to perform just a single simulation per AICC-type, per penetration rate. Therefore, the relation between the number of simulation runs and accuracy of the capacity estimate was investigated (see appendix D).
The location of the mean can be improved by performing multiple runs. Our analyses showed that the coefficient of variation of single runs is 0.6% on average, whereas the overall c.o.v. is only 0.27%. A single run containing ten maximum flow observations can already give sufficiently accurate information with respect to our objectives, which is discrimination between AICC types. Assuming equal standard errors in all the experimental cases, a (two-tailed) statistical analysis showed that differences observed between two means are significant with a 95% confidence level if the difference is larger than approximately 1%. This accuracy level implies that estimated capacity changes of AICC scenarios, compared to the reference mean, are not significant between -1% and 1% of the reference mean.

The increase in the calculation effort to gain more statistical evidence on differences does not increase the practical value of the outcomes, see Appendix D. Positive or negative capacity changes of at least 1% will result in substantial travel time changes, in which we are interested.

6.6.3 Safety analysis

Besides the assessment of impacts on capacity, an analysis is conducted for assessing safety impacts. There exist currently a number of indicators to quantify the level of safety in a traffic stream, such as Time-to-Collision, Post-Encroachment Time, Time-to-Accident, Deceleration to Safety Time, see VANDER HORST (1990) and TOPP et al. (1996, 1998). Our analysis is based on the Time-to-collision (TTC) indicator, which is commonly used as a safety indicator. Normally a single TTC-value is calculated by dividing the actual following distance by the relative speed to its predecessor, giving the time left before colliding with the front vehicle if the speed difference remains unchanged. Our approach, which is described in section 4.5.3, uses an aggregated TTC-measure that focus on a motorway segment length and the vehicles on this segment given a specific time period.

We developed two related time-to-collision safety indicators, TET and TIT, which can advantageously be applied in the micro simulation analysis of motorway safety. Two related safety indicators are presented here. We may standardize the aggregate TET and TIT indicator value into an average value per vehicle, denoted with $\overline{TET}$ and $\overline{TIT}$ respectively:

$$\overline{TET} = \frac{TET'}{N} \quad [s/\text{vehicle}] \quad (6.1)$$

It is the expected average duration that a vehicle encounters an unsafe situation.

$$\overline{TIT} = \frac{TIT'}{N} \quad [s^2/\text{vehicle}] \quad (6.2)$$

The average $TIT^*$ per vehicle expresses the expected duration-weighted exposition to unsafe TTC-values (over time period $H$).

These average indicators still include the time period over which the indicator value has been determined. To overcome this dependency, an indicator $P^*$ can be established, expressing the probability that a vehicle encounters a safety-critical approach situation, which is defined as a moment with a TTC-value between 0 and TTC* second. The TET* probability per vehicle is therefore:

$$TETP^* = 100 \cdot \frac{\overline{TET}^*}{H} \quad [%] \quad (6.3)$$
The probability indicator can be interpreted as the percentage of time that a random driver on average drives with TTC-values below the threshold $TTC^*$. This indicator is calculated by dividing the average indicator value of equation (4.17) by the maximum attainable time period (thus $H$).

Analogously, the $TTI^*$ probability indicator can be calculated with:

$$TTIP^* = 100 \cdot \frac{TTI^*}{TTC^* \cdot H} \quad \text{[\%]} \quad (6.4)$$

in which the $TTI^*$ is divided by the theoretically maximum attainable $TTI$ indicator value per vehicle (thus $H \cdot TTC^*$).

The following paragraph presents an example of the frequency distribution of the TET indicator for the reference case. See also MINDERHOUD (1999a) for other examples.

**Illustration of derived TET indicator: a TTC-frequency distribution**

If we divide the time-to-collision range in classes with $a=0.25$ s, a TTC-frequency distribution of the aggregate indicator value $TET$ per class $k$ can be calculated according to eq. (4.21a), and shown graphically. This procedure has been applied in the following example. Figure 6.13 shows the calculated TTC-frequency distribution for a simulated two-lane motorway with an on-ramp bottleneck. Only the two main lane lanes are included in the analysis. On the x-axis the TTC range between 0 and 7 s is depicted, on the y-axis the exposition time per TTC class is shown. For a class $k$, the exposition time ($TET$ indicator) is calculated according to equation (4.21a). Also shown in fig. 6.13 is the cumulative exposition to unsafe TTC-values. For the cumulative distribution, the values on the y-axis correspond with the aggregate $TET^*$ indicator value, assuming a threshold TTC-value on the x-axis.

![Figure 6.13 Exposition time versus Time-to-collision (two-lane motorway without equipped vehicles)](image-url)
The three second threshold is considered an adequate measure for discriminating dangerous approach situations from acceptable situations, as has been observed by Hirst et al. (1997). In our example, the safety indicator $TET^*$ with a threshold TTC-value $TTC^*$ of $3 \text{ s}$ results in a value of approximately $19.5 \text{ s}$. See fig. 6.13. Nevertheless, other TTC-threshold values can be applied. From the figure, it is evident that the largest proportion of unsafety is found on the right (shoulder) lane.

The calculated aggregate $TET$ indicator value of $19.5 \text{ s}$ implies that during the two-and-a-half-hour simulation run only about nineteen seconds of potential dangerous situations have occurred with TTC-values below $3 \text{ s}$. Assuming that a total of 10000 vehicles is generated in the simulation, the average exposition time $\overline{TE\overline{T}}$ of safety-critical TTC-values is $19.5 \times 10^{-4} \text{ s}$ per vehicle.

The probability (denoted with $TETP$) that a driver is confronted with an unsafe situation is relatively small. In our example, the simulation time is 9,000 seconds and about 10,000 vehicles traversed the observed motorway segment. The percentage of time that a random vehicle in the given simulation experienced unsafe conditions is then $2.2 \times 10^{-7}$ on average. This probability is quite small. Even if a driver experiences a situation with a small time-to-collision value, this will mostly not result in a rear-end collision.

It is speculated that AICC-systems improve the driving performance and reduce the safety risks, due to quick response behaviour, less errors, etc., so we may select a smaller threshold value $TTC^*$ that expresses the attainable safety levels realistically. The adequate threshold value depends on all the design characteristics of the AICC-system and how the traffic safety eventually will be influenced by these features. In Chapter 8 attention is given to this issue, but we illustrate the importance of the definition of an appropriate $TTC^*$ value at this point of our discussion by means of fig. 6.14. The figure shows a TTC-frequency distribution similar to figure 6.13, generated by simulation for a future situation with the presence of AICC-equipped vehicles ('Extended AICC' design at 0.8 s headway).

![Exposition time versus Time-to-collision (two-lane motorway with 100% Extended AICC equipped vehicles, target headway 0.8 s)](image)

FIGURE 6.14 Exposition time versus Time-to-collision (two-lane motorway with 100% Extended AICC equipped vehicles, target headway 0.8 s)
From figure 6.14, the impact of the threshold value on the exposition time is obvious. The smaller the TTC threshold value, the smaller the overall exposition time TET\(^*\) (indicated by the cumulative distribution). It is also found that the largest unsafety is found on the left lane using a 3 s TTC threshold value. But applying a 2 s threshold value changes the proportion of unsafe TET values. In case of a 2 s threshold value, the right lane has a higher TET value than the left lane.

The TET indicator value is especially useful in a comparative analysis of scenarios. The TIT indicator while being more adequate, is more complex to determine, while being more difficult to interpret its meaning. In addition, the threshold value adopted in studies differs largely, affecting the safety assessment substantially. Although the TIT is theoretically a preferable indicator, the TET indicator is preferred for the use in comparative studies in which simulation tools are applied to generate trajectories. Due to the simplifications and uncertainties in modelled driver behaviour, the benefits of the more complex TIT approach seem small.

The selection of an appropriate TTC-threshold value applied in the TET value determination is essential for comparative safety analyses. It is found that a change of the threshold value affects the level of unsafety of a particular scenario, as well as the unsafety distribution over the lanes. In our experiments, a constant TTC threshold value of 3 s will be applied for the safety analysis, regardless the system design or road configuration.

6.7 Conclusions

This chapter described the study setup, illustrated the stochasticity of the capacity variable, and presented the use of the safety indicators. The study setup is a simulation approach in which ten AICC-systems are tested. The AICC-systems to be tested differ in their support functionality and car-following distance setting. Three relevant bottleneck situations will be investigated. Based on the analysed reference scenario, it is concluded that a single simulation run is adequate to estimate a capacity value for a scenario with 95% level of confidence using a 1% margin compared to the reference capacity. This accuracy is sufficient for our research goals, since we are particularly interested in capacity gains (or losses) of more than 1%, thus with a significant impact on capacity and leading to substantial travel time benefits. A comparative safety analysis is conducted based on the summed exposition durations of time-to-collision values in the range 0 to 3 seconds, the so-called TET indicator.

Next chapter deals with the description of the simulation model applied for the traffic flow analysis of the distinct AICC-systems.
CHAPTER 7

DRIVER BEHAVIOUR IN THE MICROSCOPIC SIMULATION MODEL SIMONE

A dedicated microscopic traffic simulation instrument has been developed and applied to assess traffic flow impacts of AICC penetration in the traffic fleet composition. This chapter deals with driver behaviour modelling and the development of the SIMONE simulation model. Driver modelling is an important aspect of the study, since the simulation outcomes are to a large extent defined by the implemented algorithms representing driver and AICC system behaviour. Section 7.1 starts with an introduction into microscopic traffic modelling. Section 7.2 focusses on common traffic situations at uniform motorway segments and discontinuities. Several common situations are distinguished and a generally applicable theory about driver behaviour is discussed. Section 7.3 gives a description of the execution of the driving task based on this theory. Here, the model simplifications are emphasised. Section 7.4 considers the model input requirements and output characteristics. The model will be applied in conducting the experiments previously described in Chapter 6, while the results of the analysis will be presented in Chapter 8.

7.1 Introduction

A microscopic simulation study will be conducted to analyse the traffic flow impacts of AICC introduction. This chapter deals with the issue of microscopic modelling of motorway traffic with and without AICC-equipped vehicles. This introductory section briefly describes what a microscopic model is (7.1.1), summarizes the requirements of the model we want to use in our experiments (7.1.2), presents an overview of existing models (7.1.3) and describes the evaluation procedure and decision to develop a new model (7.1.4).

7.1.1 Microscopic traffic simulation models

A traffic model is said to be microscopic when it distinguishes individual driver-vehicle combinations that as single entities progress along a road or network according to a theoretical behavioural model (TRB SPECIAL REPORT 165, 1998). A microscopic model is
the operationalisation of a theory about individual driver behaviour in relation to its driving environment. Macroscopic and mesoscopic models are not considered in our study due to the more aggregate input requirements, vehicle progression mechanisms, and limited level of detail.

A driver-vehicle combination in a microscopic model can make decisions with respect to speed changes, lane changes, and routes, based on its actual situation, objectives and preferences. The control decisions of all the vehicle-driver combinations present in a microscopic simulation are made at regular time intervals, simultaneously or sequentially (see e.g., AYCIN et al., 1999). During a simulation, vehicles are generated according to statistical rules at specified moments at the sources (origins) of the modelled road network.

Some microscopic models focus on complete networks, including motorways and urban roadways with traffic lights. Other microscopic models concentrate on single motorway sections of limited length. In this class of models, we distinguish models that are able to represent motorways with and without bottlenecks. This distinction is important, since extended driver behaviour should be modelled when there is an on-ramp, off-ramp or weaving section. Some examples of microscopic models concentrating on motorways will be given in section 7.1.3.

7.1.2 Requirements for model application

Our objective is the assessment of capacity and safety changes on motorways with AICC equipped vehicles in the vehicle fleet. We require a microscopic simulation model since changes in driver behaviour, induced by AICC operation, are expected which for analysis purposes should be represented by individual driver-vehicle combinations. The microscopic model must adequately describe the behaviour of vehicles equipped with or without driver assistance systems driving on a motorway. The interaction between driver and AICC system should be specified realistically, preferably based on expected driver behaviour.

Another requirement is the ability of the model to mimic driver behaviour at geometric bottlenecks, such as an on-ramp, off-ramp and weaving section. This implies a model structure that makes a clear distinction between mandatory lane changes (lane changes made to reach the destination) and discretionary lane changes (lane changes made to improve drivers' speed). A distinction between user classes must also be made, in order to represent different driving behaviour of, for example, trucks and passenger cars.

The introduction of AICC-equipped vehicles demands the introduction of a new user class with deviating driving behaviour characteristics. In addition, since time delays for performance of control actions will be much smaller with AICC systems than with human driven vehicles (section 3.4), separate time delay settings for user classes must be possible.

For capacity analysis, the input of the model should consist of time-dependent and varying traffic flow demands at origins. Detectors should be placed at the required locations according to our capacity estimation method.

An important point is that the microscopic model needs to be calibrated and validated. A model is useless if the model parameters and behavioural parameters are not specified correctly. With respect to traffic simulation, the difficulties of developing, calibrating and using microscopic models will not be discussed within the framework of this study. A good description of the weaknesses of microscopic modelling of traffic flows is given by BRACKSTONE et al (1995).
7.1.3 Review of existing microscopic simulation models

We need a microscopic simulation model that fulfills our requirements addressed in section 7.1.2. An existing model may be used, possibly adapted, or a new model may be developed dedicated to our research goals. We will therefore briefly discuss candidate microscopic models in the following, without the intention of being exhaustive, after which a decision will be motivated with regard to the use of a specific model in our experiments (section 7.1.4).

- WIEDEMANN's model, which is more or less the origin of many microscopic simulation models developed later (WIEDEMANN, 1974). The model is not designed for AICC representation. REITER (1993) shows an adapted version that can simulate AICC and other driver support devices in cars. However, driver interaction with the AICC system is not clear. Additionally, only uniform motorway stretches can be simulated. LUDMANN (1998) describes the PELOPS model, which belongs to the family of the Wiedemann's model approach, and shows an example of an AICC simulation experiment.

- CARSIM and its improved successor INTELSIM (BENEKOHAL et al., 1988). AYGIN et al. (1999) apply a new model structure designed to model AICC-equipped vehicles together with non-equipped vehicles by using a continuous time frame (simulation time steps do not restrict the reaction of drivers). Applications and results of the new model - using AICC vehicle types - are yet not available.

- INTRAS, FRESIM and CORSIM (see e.g., HALATI et al., 1997), family of Wiedemann's modelling approach, are not designed for AICC representation. Based on these models, the Dutch version of FOSIM has been developed (see e.g., VERMEER, 1991, 1992). FOSIM does not take into account AICC-equipped vehicles at the moment.

- MIXIC is another Dutch model with a very high microscopic level of detail for the engine and pedal use (VAN AREM et al., 1995b). Especially developed to simulate mixed traffic with AICC-equipped vehicles, but not capable of representing motorway bottlenecks such as on-ramps.

- ARCHSIM was developed and calibrated by INRETS, France (CREMER et al., 1998, DONIKA et al., 1998). It can be connected to a driving simulator which allows a human driver to participate in an interactive traffic simulation. Modelling of AICC is possible. First studies are underway and will focus on uniform motorway stretches.

- SPEACS, which was developed within the European DRIVE program in order to obtain traffic flow impacts of AICC (BROQUA et al., 1991), is capable of simulating traffic on a motorway stretch, however, without bottlenecks.

- AUTOBAHN SIMULATOR was developed and applied by BENZ (1993, 1996). The model focuses on uniform motorway stretches, not on bottleneck locations.

- FLOWSIM, developed by the Transportation Research Group at the university of Southampton. The model uses fuzzy-logic to describe driver's decisions and can simulate, among others, a mixed traffic composition with AICC-equipped vehicles (McDONALD et al., 1998). Capacity analysis and modelling of motorway bottlenecks such as on-ramps is currently impossible.

- SMARTAHS, a micro simulation model developed at PATH institute (university of Berkeley) that can simulate (partially) automated vehicles, such as AICC, on a single lane (GODOBOLE, 1999, RAO et al., 1993a, 1993b, ESKANI, et al., 1995).

None of the models have currently been applied for a realistic capacity analysis of motorway discontinuities with a mixed (intelligent and conventional) traffic flow composition. Since bottlenecks are the determining elements of network capacity in a motorway network we
concentrate on capacity analysis of such bottlenecks, which is one of our research objectives (see Chapter 6).

7.1.4 Motivation to develop a new microscopic model

A dedicated microscopic simulation model has been developed of which the modelling effort will be summarized in this Chapter (see also MINDERHOUD, 1998). We restate our arguments for developing a new model instead of adapting an existing one. We firstly considered to adapt an available simulation model for meeting our objectives. Two relevant Dutch models were considered: FOSIM and MIXIC. After evaluation of the characteristics of the models and estimation of the needed changes, it has been decided to make a new purposeful microscopic model.

Application of FOSIM with respect to the simulation of motorway traffic with the mentioned new generation vehicles has the following problems:
- No driver support system functionality is currently available.
- Stochastic properties in driver behaviour are limited (e.g. car-following parameters, desired speed differences between drivers).
- Simulation time scan interval determines driver delay, while specification of deviating driver/system delay times for (intelligent) user classes is currently no option.
- No separation between simulation time scan and driver’s observation interval, or, in case of AICC: sensor observation interval time.
- Application of different longitudinal control strategies for different user classes is not possible. In addition, the control strategy used in the current version has only a few changeable settings (anticipation time variable and parameters in desired distance function).

Adaptation of the FOSIM model to incorporate the behaviour of intelligent vehicles appeared a labourious effort, since it requires a complete change of processing structure with respect to the introduction of delay time differences and perception time differences among user classes. Furthermore, the graphical user interface does not meet the current requirements with respect to easy-to-use and a quick design of geometric road configurations.

Although specifically designed to handle driver assistance systems, the MIXIC model does not meet a number of the above-mentioned requirements either. Major disadvantages of the model are the following:
- The model lacks the possibility to simulate different geometric elements of a motorway (such as on-ramps and off-ramps).
- Capacity analysis based on observation of maximum flow rates is currently not possible, since the input of traffic demand is based on real-life traffic measurements.

The development of a new model was considered the best approach to deal adequately with the study objectives within our time constraints. A dedicated microscopic simulation model, denoted with SIMONE (Simulation model for Motorway traffic with Next generation vehicles), was developed for current and expected future motorway traffic representation. In the model, AICC-equipped vehicles of a certain vehicle type are specified as a user class based on the similar vehicle type user class without such an assistance system. Traffic processes beyond motorway facilities, such as connections with lower (non-
motorway) road networks, are neither considered nor analysed in this investigation. The SIMONE model is implemented using behavioural rules, by means of (nested) IF ... THEN ... statements. This structure can easily be modified, new behavioural rules can be added, while the implemented behavioural rules can easily be understand for outsiders.

Chapter 2 gave a comprehensive description of a driving task execution theory. However, for the development of the dedicated simulation model, not all the driving tasks are considered or implemented. Only the longitudinal and lateral driving tasks with respect to the interaction of other traffic participants are modelled. Other tasks, such as longitudinal and lateral control with respect to the position on the roadway are not considered in the simulation. The strategic navigation task (vehicle’s route to the destination) is input of the simulation model.

In the following sections, the operationalisation of the theory outlined in Chapter 2 is described, in particularly focussing on the longitudinal and lateral control decisions of drivers’ while driving on a motorway link with other vehicles present.

### 7.2 General assumptions on driver behaviour in SIMONE

Motorway networks can be represented by a collection of links connected by nodes. These links are geometrically uniform road segments; only at so-called discontinuities (or bottlenecks) the road geometry changes, such as at on-ramps, off-ramps, merging or diverging zones. In addition, bridges and tunnels can be regarded as discontinuities as well. A more elaborated study into this subject can be found in (Boekholt et al., 1996).

The difference between uniform motorway segments and discontinuities is important since in almost all cases motorway capacity is limited at these merging or diverging zones. The roadway capacity and flow breakdown phenomena can only be examined by observing flows at geometrically uniform downstream and upstream motorway segments near a discontinuity. Consequently, attention must be given to the traffic processes at both uniform links and discontinuities.

The conceptual model of driver behaviour at common traffic situations is described in this section. The theory in this section has been adopted by SIMONE, consequently, the implementation of some of the most elementary driver behaviour aspects is outlined also.

First the traffic processes on uniform motorway links are analysed and described (section 7.2.1). We limit our discussion to eight situations which are selected using the speed difference with other vehicles as main indicator. In the considered cases, the subject vehicle experiences different traffic environments where several control decisions are possible. These possibilities are given, and the most appropriate control decision is identified using our professional judgement. Assumptions are made to facilitate model development. These assumptions are provided and explained. Secondly, the processes near bottlenecks are explored (section 7.2.2). Basic assumptions of performing the driving task on motorways will be described, followed by model assumptions and simplifications made. The handling of AICC-equipped vehicles is incorporated in our discussion. Section 7.2.3 summarizes the driving behaviour assumptions of drivers using an AICC-equipped vehicle.

Other descriptions of driver behaviour theory exist, see e.g. Wiedemann (1974) and Vermeij (1992). Our description uses a more structured approach while some characteristic
7.2.1 Driving on uniform motorway links

Driving behaviour of a subject driver-vehicle combination at uniform motorway links is affected by the positions of the observed other vehicles and by stimuli such as relative speed and distance. Several combinations of vehicle position and relative speed will be used to describe the most likely control decision of the subject driver. We assume that drivers observe the position and speed of vehicles on the same and adjacent lanes. On the contrary, an AICC-equipped and activated vehicle can only observe and make decisions using the relative speed and distance to a vehicle on the same lane, but not to vehicles on adjacent lanes. In the description of our driver theory, we assume that drivers try to drive at their desired speed if the traffic conditions allow this. Furthermore, we assume that drivers and AICC systems can only observe stimuli within a certain distance boundary, denoted with perceptible range and sensor range, respectively.

Table 7.1 gives an overview of eight important traffic situations which can be distinguished on homogeneous motorway stretches and will be discussed in the following. The classification is based on a subject vehicle-driver combination driving on lane \( j \) observing speed differences with vehicles on adjacent lanes, and observing the speed difference with the direct vehicle in front on its own lane. Situations a, b, c and d. in table 7.1 assume the absence of a right adjacent lane \((j+1)\). Situations e, f, g and h. in table 7.1 assume the absence of the left adjacent lane \((j-1)\) of the subject driver. More situations are possible by combining the presence of both the left and right adjacent lane, but this would lead in a too large number of situations.

<table>
<thead>
<tr>
<th>Subject observes on left adjacent lane ( j-1 ) :</th>
<th>Subject on lane ( j ) observes on lane ( j ) :</th>
<th>Subject observes on right adjacent lane ( j+1 ) :</th>
</tr>
</thead>
<tbody>
<tr>
<td>a. a safe speed difference or no vehicle</td>
<td>a safe speed difference or no leader</td>
<td>no lane ( j+1 )</td>
</tr>
<tr>
<td>b. an unsafe speed difference</td>
<td>a safe speed difference or no leader</td>
<td>no lane ( j+1 )</td>
</tr>
<tr>
<td>c. a safe speed difference or no vehicle</td>
<td>an unsafe speed difference</td>
<td>no lane ( j+1 )</td>
</tr>
<tr>
<td>d. an unsafe speed difference</td>
<td>an unsafe speed difference</td>
<td>no lane ( j+1 )</td>
</tr>
<tr>
<td>e. no lane ( j-1 )</td>
<td>a safe speed difference or no leader</td>
<td>a safe speed difference or no leader</td>
</tr>
<tr>
<td>f. no lane ( j-1 )</td>
<td>a safe speed difference or no leader</td>
<td>an unsafe speed difference</td>
</tr>
<tr>
<td>g. no lane ( j-1 )</td>
<td>an unsafe speed difference</td>
<td>a safe speed difference or no leader</td>
</tr>
<tr>
<td>h. no lane ( j-1 )</td>
<td>an unsafe speed difference</td>
<td>an unsafe speed difference</td>
</tr>
</tbody>
</table>

TABLE 7.1 Classification of common traffic situations

In case the relative speed is such that the subject vehicle approaches a vehicle in front, this is denoted with "unsafe speed difference". A safe speed difference is handled as if there is
no vehicle observed in front (thus assuming a sufficient gap distance). Zero speed difference (following and lead vehicle drive with the same speed) is for simplicity neglected in this analysis.

A subject experiencing a situation described in table 7.1 may perform different control decisions. The possible control decisions and expected control decision are described in the following for each of the situations a. to h. In many cases, we had to use our professional judgement in defining behavioural rules since only a few, limited sources about driver decisions are available.

a. Subject experiences free driving conditions

Assume a situation in which a driver travels on the motorway. Within the driver’s perceptible range, no other vehicle in front is observed. In practice, this situation may occur at night (figure 7.1). What behaviour might be expected from this person?

- It is likely that the driver selects a right side driving lane (dedicated by legislation [e.g., in the Netherlands RVV 1990, article 3]).
- It is very likely that the driver selects a driving speed that is a compromise between legislation (speed limits), prevailing roadway and weather conditions and vehicle capabilities, and own preferences (such as safe driving, environmental friendly driving, etc.).

Since no vehicles in front are observed, the speed selection of the subject is unaffected by driving behaviour of other traffic participants. The subject driver experiences unconstrained driving conditions, which means that he is not hindered by other vehicles. Therefore, the selected driving speed in this situation is denoted with desired speed, and this definition is applied throughout the report.

In practice, it is possible that a driver adapts his desired driving speed during his travel along the motorway. Knowledge about this behaviour is lacking, which however, is not essential for the objectives of the simulation model, since road capacity is generally reached at speeds below the desired speed of most traffic participants. Furthermore, a traffic simulation model will focus at a small part of a motorway network - distances of about 1 to 15 km - thus individual drivers are present in the network for only a few minutes. During such a period, a constant desired speed may be assumed. A more detailed modelling of desired speed adaptations during a trip is therefore not necessary.

We assume that a subject in an AICC-equipped vehicle will select the same desired speed as he would have done if the system was not available. An assistance system has also a limited perceptible range (which depends on the sensor) for observing vehicles in front. Under normal weather conditions, this range will be smaller than that of a human observer.
However, under foggy conditions, the sensor may observe vehicles in front which cannot be seen by a human driver.

In conclusion, modelling driver behaviour should include a *perceptible range* and a *desired speed* per driver. For driving with an AICC system, a similar *sensor range* and *desired speed* should be used. We assume that the desired driving speed of a driver does not change when driving on a motorway segment of limited length, e.g., ten kilometre, and does not change when driving with an AICC system. A driver or assistance system will always try to achieve the desired driving speed. Furthermore, the *lane selection* of a driver - in case of an empty roadway - is the right lane.

b. *Subject experiences constrained conditions due to vehicle on lane j-1.*
Assume a situation similar to the latter. However, now a vehicle on the left adjacent lane (j-1) drives at a slower speed than the subject vehicle (as depicted in figure 7.2). How will a driver react upon this?

- It is likely that the driver adapts his driving speed, since passing the vehicle on the right - under normal traffic conditions - is not allowed according European traffic legislation [In the Netherlands, see RVV 1990 article 13].
- It is also possible that the driver anticipates on this slow driving vehicle by making a lane-change already in advance in order to pass the vehicle on the left side without reducing his driving speed.

This situation is sometimes noticeable in low density traffic conditions. In the model development, we assume that drivers do not anticipate slow driving vehicles on a left adjacent lane in order to make a - double - lane change timely. However, the other decision

![Figure 7.2 Subject observes a vehicle on left adjacent lane](image)

is supported: drivers will try to *adapt their speed* to the driving speed of the neighbour vehicle. The exact elaboration of this adaptation process is presented later (section 7.3.3).

The same holds for drivers using an AICC system. We assume that the subject driver-vehicle combination will react with a speed adaptation to limit the relative speed for passing the vehicle on the right. But since an AICC-system does not react on vehicles on adjacent lanes, and driver intervention is needed for left lane speed adaptation, the speed adaptation will probably be less extreme or be postponed, compared to a driver in a non-equipped vehicle.
c. **Subject experiences constrained conditions due to vehicle on lane j**

Figure 7.3 shows a driver following a predecessor in front on the same lane $j$. Furthermore, there are vehicles present on the left adjacent lane $j-1$. We assume that the average speed of the neighbour vehicles on the left adjacent lane is higher than the own driving speed.

This situation is expected to occur on motorways frequently. A vehicle in front - on the same lane as the subject vehicle - drives slower than the subject vehicle. What behaviour can be expected in such a situation? Two responses are hypothesised, and possibly executed simultaneously:

- The driver's acceleration response depends on how the gap distance changes per unit time and what the actual gap distance is, compared with his own perceived safe car-following distance.
- Since the left lane speed is higher than his own speed, a lane change to the left lane is an attractive alternative in case the desired driving speed has not been attained. In addition, a lane change decision can be made during the approach at large distances (in the change from free driving to following).

Some consequences follow from the analysis of situation c. First of all, it is obvious that a driver will adapt his speed when approaching a slower vehicle at distances within his perceptible range. Secondly, it is likely that drivers' response to approaching slower vehicles at a large distance is quite different compared to responses at small gap distances. A so-called longitudinal control strategy will take care of appropriate approaching behaviour towards the vehicle in front. Since we assume that each driver has a perceived safe car-following distance which he attempts to maintain, a desired distance function must be determined and modelled together with the longitudinal control strategy. Driver responses which are mainly based on the leader's behaviour are denoted with the longitudinal control task (see figure 7.3.2). Such a control strategy and desired following distance function is clearly apparent by AICC systems, since aim of the system is to assist in the longitudinal driving task.

Furthermore, we conclude that lane changes to the left lane are only considered if the left lane speed (based on some sample vehicles in front) is sufficiently higher than vehicle's own speed and if this speed is smaller than the desired speed (section 7.3.6). Nonetheless, and in addition to the described situations, we expect that most drivers accept speeds that are slightly smaller than their desired speed so that they do not consider a left lane change. To model this behaviour, a speed indifference threshold will be introduced.
A lane-change can also be considered when approaching a vehicle at large distances. This lane-change motivation, although mainly occurring at small traffic flow rates and therefore less important for capacity analysis, will also be modelled. A time-to-collision threshold of 7 s can be introduced for this purpose, see e.g. Rekersbrink (1995).

Lane-change motivations and lane-change decisions are not assisted by the use of an AICC system. Therefore, it can be assumed that lane-change decisions will be unaffected, but fully made by the human driver. It is possible that drivers in an AICC-equipped vehicle prefer to drive on left-side lanes to limit the number of lane changes, or make a lane-change earlier than a driver normally would do. These aspects will be neglected.

d. Subject experiences constrained conditions due to vehicles on lane j and on lane j-1

In this case, a lane change is not an appropriate decision since it will not optimize a driver's situation (with respect to increasing travel speed). A constrained driver will probably react by a speed adaptation.
- It is likely to expect a deceleration in order to adapt the current driving speed to the driving speed of the vehicles in front in the left lane;

We expect that the magnitude of the response will depend on the driver's own driving speed and relative speed with left lane vehicles. During congested conditions (low speeds, queuing) it is allowed to pass vehicles on the right, but normally with adapted speed differences only (see section 7.3.3). Furthermore, we assume that some proportion of the drivers will not pass vehicles on the right even in stationary congested conditions. The same holds for drivers in an AICC-equipped vehicle. However, the acceptable relative speed may be higher since system intervention is not a desired action.

e. Subject experiences free flow conditions on lane j while vehicles on lane j+1 drive faster

Assume a traffic situation where a vehicle drives, as depicted in figure 7.4, at the second most right lane. The behaviour of the driver depends on his own driving speed, the distance and speed of the leader on lane j and the speed of vehicles on the left lane. The speed of the vehicles on the right adjacent lane j+1 has a minor impact on his behaviour. Passing of vehicles on the left side j-1 is allowed although safety considerations may affect the accepted speed differential with the right lane during passing.

Generally, we can assume that all drivers try to maintain the most right lane, or will return to a right adjacent lane very soon after a lane change. Such a right lane change will only be accomplished if a driver expects little or no disadvantage at all from this decision (see section 7.3.7). This lane change behaviour is also expected to hold for drivers with an AICC-equipped vehicle.
Since in the situation above the observed vehicles in front drive faster, no disadvantageous conditions are created for either of the possible responses: stay on the current lane or make a lane change to the right. Therefore:

- It is likely to expect that the driver decides to make a right lane change if the gap distance (to front and rear vehicle on the right lane) is sufficient, since this is according to legislation and does not result in a disadvantageous situation.

f. **Subject experiences free flow conditions on lane \( j \) while vehicles on lane \( j+1 \) drive slower**

In case the observed vehicle on the right lane drives slower, the decision to return to the right lane depends on how large the unsafe speed difference is, and how long it will take to make a new - left - lane change in case he returns to the right lane directly. The gap distance to the observed vehicle on the right lane is therefore important. Other aspects, such as the vehicle type may also affect the decision (see section 7.3.7).

- It is possible that a driver decides to make a right lane change, but only if there is a very large (time) gap, otherwise, the driver probably stay on the current lane;

g. **Subject experiences constrained conditions by vehicle in front while vehicles on lane \( j+1 \) drive faster**

It is quite predictable that if the subject on lane \( j \) observes a slower driving vehicle in front while the right lane speed is larger, a right lane change decision motivation will be apparent.

- It is likely to expect a right lane change in case a sufficient safe speed gain and gap distance are available.

h. **Subject experiences constrained conditions by vehicle in front while vehicles on lane \( j+1 \) drive slower**

In this situation (a combination of situations f. and g.), the vehicle directly in front drives slower and the right lane vehicle in front drives slower than the subject vehicle. When we assume that there are no lane-change possibilities to lane \( j-1 \), two responses are possible: stay on the current lane \( j \) or go to the right lane \( j+1 \).

- It is likely that the driver maintains the current lane and decelerates.
- However, if the current driving speed is smaller than the right lane vehicle speed, a lane-change to the right may be considered;

Simultaneously with the decision to plan a lane change, a driver estimates the feasibility of a lane change. We assume that a driver tries to perform a lane change safely, and therefore estimates the risks of performing a lane change and compares these risks with his personal
perception of acceptable behaviour. For modelling purposes, the elements of a lane change decision are assumed to be made separately. The desirability and feasibility of a lane change are evaluated separately. Moreover, the feasibility of a lane change is evaluated only if the desirability has been determined, a modelling approach described by GIPPS (1986). This approach limits the calculation effort. BRACKSTONE et al. (1998) give insight into factors affecting the lane change decision. They find that there are multiple combinations of factors that can explain the lane change decision of individuals.

Lane changes to the right are more complicated to model than left lane changes, since it is a consideration which includes legal aspects. Right lane changes are not performed as a result of comfort and speed optimization decisions only: drivers may return to the right lane and accept a constrained driving situation. Section 7.3 deals with the operationalisation of the discussed conditions in the simulation model.

7.2.2 Driving at discontinuities

Discontinuities mostly operate as bottlenecks in motorway networks with high traffic demands since at these locations lane changes are required - for a proportion of the traffic - to reach destinations safely and within the geometric constraints of the roadway. Moreover, these so-called mandatory lane changes show deviating behaviour compared with so-called discretionary lane changes (see e.g. AHMED et al., 1995) which are encountered at uniform motorway stretches. The mandatory lane changes have a major impact on road capacity: as traffic demand increases, the traffic flow will break down near the bottleneck area first.

Other congestion causing factors are road accidents and road construction works, which are not discussed here, although the traffic processes are comparable to bottleneck situations. Traffic processes and driver behaviour of involved vehicles at merging zones (a.), diverging zones (b.) and weaving zones (c.) are analysed in the following.

a. Processes near merging zones

At merging zones, such as an on-ramp (see fig. 7.5), driver behaviour of vehicles entering the main line differs significantly from that of vehicles already driving on the main line. We describe the behaviour of both groups of drivers, and start with the vehicles on the main line.

Drivers on main line

If a driver on the most right side lane \(j\) observes a vehicle in front on the acceleration lane \(j+1\) wanting to make a lane change to the left (fig. 7.5, driver1), three reactions are hypothesised. The driver has typically the following response options: 1) stay on the current lane and anticipate on an oncoming lane-change by decelerate to create a sufficient gap, 2) make an anticipatory lane change to the left side lane \(j-1\) in order to create space for the merging vehicle. 3) maintain the same speed and lane. Advantage of the second decision is the limited speed adaptation required. The third option of the driver is according the right-of-way legislation in Europe. This behaviour is however not encountered frequently since it can obstruct the on-ramp flow and is unsafe for the drivers because sideward collisions can easily occur. In addition, many drivers assume right-of-way for merging traffic.
The type of resulting decision depends on the lane change possibilities. If no lane change to the left is possible, the gap creation is executed based on several assumptions about the needed gap and own preferences with respect to comfortable decelerations: the driver will try to create a sufficient gap size (both in time and space) with limited effort and limited reduction in speed.

Drivers using an AICC system have to decide if they want to intervene in the system’s longitudinal vehicle control to create a sufficient gap manually. An AICC cannot determine if a vehicle on an adjacent lane wants to merge in front, whereas a human driver can predict this behaviour quite well. If the drivers decide to create a larger gap in front, the AICC will be overruled. If the driver decides to make an anticipatory lane change, the AICC system does not have to be overruled in case the lane change can be performed directly without speed adaptations.

Drivers on acceleration lane

The behaviour of the merging vehicle (fig 7.5, driver 2) is another important element in the traffic processes near on-ramps. According European traffic regulation, the merging vehicle should give right-of-way to the vehicles on the main line. We expect that such drivers try to select an appropriate gap from the available gaps (in practice, only one or two gaps are potential target gaps), adapt their speed, and position their vehicle appropriately along the gap (see section 7.3.4). It is observed that drivers try to merge as soon as possible in the main line flow (SCHUURMAN et al., 1993). After 150 metres of the beginning of the acceleration lane the majority of the drivers has entered the main line. Some hypotheses are formulated below:

- It is likely that drivers will take more risk and accept less comfortable conditions in order to find an appropriate gap as they move towards the end of a merging zone;
- Drivers try to minimise their effort in approaching a gap: drivers prefer to make a lane change without reducing their speed;

The drivers using an AICC system will, in most cases, overrule the system while preparing a lane change on an acceleration lane with dense traffic on the main line. An AICC is not arranged for gap search tasks, but observes only vehicles directly in front. On an acceleration lane, this means that the system tries to accelerate to the desired speed, also when the main line traffic is congested. In such situations, the gap selection and speed adaptation must be carried out by the human driver.
In summary, at a merging zone, two different driver behaviour processes can be distinguished. Firstly, anticipatory behaviour of vehicles on the main line in order to let vehicles merge into the main line without being hindered. Secondly, gap search, positioning, and gap acceptance behaviour of merging vehicles (behaviour sometimes denoted with 'nosing', since drivers cut in by putting the nose of the vehicle in a target gap). Starting point in modelling these types of behaviour is the assumed minimal effort drivers want to spend on creating respectively finding a gap. All the mentioned behavioural aspects are incorporated in the simulation model.

b. Processes near diverging zones
At diverging zones, such as off-ramps, some proportion of the traffic wants to exit the motorway. Drivers are informed by traffic signs, thus anticipate on the oncoming motorway exit by already lane-changing to the most right lane in advance.

In comparison with the traffic processes at merging zones, behaviour of drivers leaving the motorway (figure 7.6) is similar to vehicles entering the motorway. Again, anticipatory behaviour is assumed for vehicles observing an oncoming lane change to their own lane. However, this anticipatory behaviour now does not include lane changes to the left, since drivers know that the event is temporary, only until the vehicle has left the motorway.

In addition to anticipatory behaviour near a merging area, it is assumed that drivers observing an oncoming lane change (to the right) do not consider an anticipatory lane change to the left. We assume that the gap creation processes, thus drivers' politeness, is similar to gap creation processes at a merging zone. Supported drivers have to overrule their AICC system for the gap creation process.

We furthermore assume that drivers with AICC are alert and - if needed - make lane-changes timely in order to leave the motorway at an off-ramp (navigation task).

![Figure 7.6 Diverging zone traffic processes](image)

c. Processes near weaving zones
At weaving sections, two main lines merge together and form new main lines. See for example figure 7.7. Other weaving section configurations on motorways are possible, for example an two-lane main line with an on-ramp directly followed by an off-ramp (i.e. acceleration lane and deceleration lane are not separated).

At weaving sections in a motorway network, a proportion of the traffic must perform lane changes to reach their destination. A weaving section can function like a merging zone or a diverging zone, depending on the proportion (and direction) of weaving flow. However,
in most cases another type of traffic process can be observed at such a discontinuity. This so-called weaving process can be described as follows. A driver on lane \( j \) wants a lane change to the left adjacent lane \( j-1 \) while an adjacent driver on lane \( j-1 \) wants a lane change to lane \( j \) (in the same gap).

![FIGURE 7.7 Weaving zone traffic processes](image)

Which type of behaviour can be expected?
- Each driver tries to adapt his speed in order to find an appropriate gap to execute a lane change (similar to the traffic processes at an on-ramp);
- If the gap on the adjacent lane is sufficiently large, a lane change is started;

These two responses are most likely to occur. However, eventually this could result in a totally blocked (deadlock) situation in case two drivers adapt their speed to null. Therefore, there are other, additional considerations in individual driver’s decisions:

**Anticipatory behaviour restriction**
The following behavioural rule is hypothesised:
- Below a specific (individual) minimum speed, decelerations needed for gap creation will not be made.

This behaviour is expected since at low speeds (e.g., below 10 km/h) the car-following gaps are very small, so the creation of a sufficient gap for merging vehicles will take quite some time, and possibly requires to stop the ‘polite’ driver for some seconds. Although anticipatory behaviour is assumed to be present, it is not assumed to occur that drastic. It is more likely that at a certain minimum speed, the gap creation will be performed solely by postponing possible acceleration, instead of decelerating to zero speed.

**Gap search behaviour restriction**
Vehicles actively searching for a gap, or positioning to a selected gap in order to perform a lane change, are assumed to have a minimum driving speed also. The following assumption has been made:
- Below a specific minimum speed, decelerations needed for gap positioning behaviour will not be made.

This minimum speed allows these vehicles to progress along a queue slowly and trying to find an acceptable gap or find a polite driver creating a gap. Stopping the vehicle entirely, in order to wait for a gap coming along, is not an expected behaviour for gap searching drivers without predecessors.

An additional behavioural aspect in weaving traffic behaviour is a possibly enlarged acceptance of a relatively small front gap during the weaving manoeuvre. Since drivers
know that the gap distance during the lane change is only temporarily short, it may be assumed that drivers accept smaller distances during these lane change conditions.

To summarize the findings and their implications for model development: Traffic processes near weaving sections can be described with anticipatory and active gap positioning behaviour such as can be observed near on-ramps and off-ramps as well. An activated AICC system should be overruled in most cases of anticipatory behaviour and actively gap searching. In addition, we assume that minimum speed thresholds are apparent in human driver behaviour. This modelling approach prevents the event of dead-lock situations. Driver politeness is assumed to be present on a large scale, but execution of a comfortable trip remains first priority.

7.2.3 Driving with an AICC system

Modelling assumptions with respect to the use of AICC systems are needed to analyse traffic flow impacts realistically. This section restates the assumptions about AICC use (as described in the previous sections), gives assumptions about the conditions needed to take over vehicle control, and assumptions about the conditions required to intervene in the AICC-system control. At last, the reactivation conditions are described.

The SIMONE model has been specifically designed to allow for a range of AICC system designs. The assumptions discussed here hold for all system designs.

Assumptions about AICC operation and AICC use

An AICC-equipped vehicle with an activated system can only observe and make decisions regarding the relative speed and distance to a vehicle on the same lane, but not to vehicles on adjacent lanes. Furthermore, an AICC-equipped vehicle with an activated system can only support the driver with the longitudinal driving task with respect to the observed leader on the same lane (i.e. headway keeping and speed adaptation). Lateral control tasks, such as lane-change decisions have to be performed by the driver. An AICC system will have a limited perceptible range, denoted with sensor range. Vehicles or obstacles beyond this range can not be observed.

With respect to the use of an AICC system, the following assumptions have been made for the model development:

- A driver of a vehicle equipped with an AICC will use the offered assistance as much as possible within the operational boundaries.
- We assume that a driver using an AICC system will select the same desired speed as he would have done if the system was not available.
- Individual differences in the man-machine-interaction (intervention moments, accepted deceleration level) are expected, but will not be incorporated since even knowledge about average behaviour is hardly assessed.
- Support systems cannot be switched off. One could assume that drivers in equipped vehicles have bought the system with the purpose to use the assistance options at maximum. Nevertheless, the system can temporarily be overruled if the driver decides to do so.
- If an AICC system reaches its operational boundaries, we assume that the system warns the driver after which the control will be taken over by the driver directly.
- The assistance system will be in the stand-by mode (idle), if the operational boundaries
have been reached and the driver has taken over control.

- We assume that a system (component) malfunctioning is a rare event, which will not be modelled. Such cases will therefore not affect the overall system functioning in the simulation study.
- Although time delays - needed to switch from support mode to manual mode - may possibly be increased due to reduced alertness, in the model we assume that drivers are attentive and alert and constantly ‘in-the-loop’. They can react within their defined normal time delay.

**Assumptions about conditions needed for taking over vehicle control**

The first generation AICC systems can not support the driver fully with the longitudinal driving task. In some situations, the driver have to take over the vehicle control. From the AICC system layout the following conditions for driver control can be distinguished:

- If the speed drops below minimum supported speed.
- If the speed exceeds maximum supported speed.
- If the minimum acceleration has been reached.

A warning signal is assumed to be given in these three situations, alerting the driver to take over the longitudinal control tasks since system’s capabilities have been reached. For modelling purposes, it is assumed that the driver indeed takes over the vehicle control directly, with a normal time delay, after such a warning signal. In addition to these three conditions, the driver may decide voluntary to take over control of the system. For example, if the driver does not accept the support system driving behaviour performance. This is described in the following.

**Assumptions about conditions needed for system intervention**

A driver can always overrule the AICC system, for example, when the driver experiences unsatisfactorily behaviour of the system. We will present some of these conditions in the following.

- Driver’s comparison of the assistance system’s driving behaviour with his mental model’s outcome about the desired task performance may result in a decision to overrule the support mode. The implementation of this aspect in SIMONE is described in the text box.

The assumed conditions for overruling the AICC and the followed modeling approach, can be summarized as follows (see figure 7.8 for an illustration). A minimum acceleration/deceleration threshold of +/- 0.1g is used:

1. **Situation indicates danger.** In case the desired deceleration according to driver’s mental model exceeds the deceleration calculated by support mode settings increased with 30%.
2. **Situation represents uncomfortable behaviour of support system.** In case the desired deceleration according to driver’s mental model is smaller than the deceleration calculated by support mode settings decreased with 30%.
3. **System accelerates too quickly according to driver’s perception and preferences.** In case the desired acceleration according to driver’s mental model is smaller than acceleration calculated by support mode settings decreased with 30%.
4. **System accelerates too softly according to driver’s perception.** In case the desired acceleration according to driver’s mental model is larger than acceleration calculated by support mode settings and increased with 30%.
In the conditions one to four shown in the text box, drivers’ compare their desired manual longitudinal behaviour with the performance of the support system. One can assume that a driver accepts some differences, but the system should not response too ‘hard’ or too ‘soft’ compared with driver’s own perception on how the car-following task should be executed. Little knowledge is available about accepted differences. After some preliminary experiments, differences plus or min 30% have been assumed to be acceptable by the average driver.

Besides this aspect, in the model development there has been taken account of the following situations that occasionally request driver intervention:

- In case the acceleration determined for a needed left lane speed adoption - estimated by the driver - is smaller than the acceleration determined by support mode settings. However, to make this condition less strict, an additional acceptance threshold is introduced.
- In case the driver of a supported vehicle observes a vehicle with a mandatory lane change request directly in front on an adjacent lane, and a deceleration is needed to create a gap manually.
- In case the driver of a supported vehicle must make a mandatory lane change - driver is searching for a gap - and an acceleration (positive/negative) is needed which is smaller than the support system has determined based on its car-following algorithm.

Important, but yet an unknown and unexplored aspect in the man-machine interaction is the - probably enlarged - acceptance to pass left lane vehicles driving with slower speed. It was during calibration of the model found that the speed difference acceptance modelling has an important impact on the simulation results. For the supported drivers, a slightly increased acceptance behaviour is modelled since we assume that drivers dislike overruling their support system as speeds on the left lane drop.

The list of reasons to overrule the system described here is extensive compared to
conditions implemented and documented in other simulation models handling AICC-equipped vehicles, see e.g. VAN AREM et al. (1995b). We observe that in other available simulation models coping with AICC systems (see Chapter 5), it is unknown if and when drivers may overrule the AICC-vehicle control. A complete specification of conditions implemented in SIMONE for system deactivation is desirable to represent future driver behaviour with support systems realistically, and to interpret simulation outcomes accordingly.

Assumptions about conditions needed for system reactivation

The decision to resume the AICC system depends on what type of support system the vehicle is equipped with: the automatic reactivation type or the manual reactivation type (MINDERHOUDE et al., 1998). These types are considered to be deployed in the near future, and therefore incorporated in the simulation model. For both types hold: the system cannot be resumed if the actual speed or actual acceleration level is not supported by the AICC system.

- Automatic reactivation type
  A vehicle equipped with a longitudinal support system with an automatic reactivation functionality, driving in the manual mode, will automatically return to the support mode directly after the subject driver stops its intervention. Thus, when the driver stops braking, the system returns to the assisted driving mode.

- Manual reactivation type
  The manual activation of a support system depends on the actual acceleration and the time expired since starting the manual control. If the acceleration on a specific moment is negative and less than coast-down deceleration, a driver will not activate the support system to take over the longitudinal driving task. We assume that during deceleration of a vehicle the traffic conditions are not appropriate to turn on the system. For modelling purposes, it is assumed that the assisted driving mode will be restarted when each of the following conditions is met:
  Actual acceleration is positive or near zero, while the time expired since the moment of starting the intervention or since the last coast down deceleration (-0.05g) is more than a predefined fixed threshold value (about 10 seconds).

Although it is expected that the first Adaptive or Intelligent Cruise Control systems in vehicles will have a manual resume function, the automatic reactivation option will probably have a more substantial impact on the road utilisation and is therefore already incorporated in the experimental setup and simulation model to assess its impacts on traffic flow (see also section 3.5.3).

7.3 Implementation of behavioural rules in SIMONE

The execution of the driving task of supported and non-supported drivers in the simulation model SIMONE is based on the control theory presented in Chapter 2. This control model for driving task execution has shortly been discussed in section 7.3.1. The behaviour of equipped and non-equipped vehicles is modelled identically, except the parameter values and
time delays differ, while extra tasks are introduced when driving in an equipped vehicle.

Basically, drivers' control decision $u^*(t)$ to observed stimuli on instant $t-\tau$ can be categorised into two types:

- speed adaptation decision;
- lane change decision.

The theory and modelling approach of speed adaptation in motorway traffic are described in sections 7.3.2 to 7.3.5. Analysis of traffic processes on motorways led to the assumption that drivers may adapt their speed for the following situations:

- observation of a direct leader on current lane (7.3.2);
- observation of vehicles in front on a left lane (7.3.3);
- observation of a vehicle on the right adjacent lane searching for a gap (7.3.4);
- motivation to perform a lane change (7.3.5).

An AICC will only support the first speed adaptation driving task, thus based on observations of the direct leader on the current lane (sections 7.3.2). Lane change decisions and gap acceptance considerations, which are the same for drivers with equipped and non-equipped vehicles, are described in sections 7.3.6 to 7.3.8 respectively. The extra subtasks introduced when driving in an AICC-equipped vehicle are implemented according to the assumptions made in section 7.2.3.

### 7.3.1 Control model

The SIMONE model, which will be described in this section, is a newly developed microscopic traffic simulation model. During a simulation run vehicles will move from their origin to their destination according to the implemented driver behaviour theory, which has been described in sections 7.1 and 7.2. Origins are sources of traffic and can be specified by the designer of a road configuration (a so-called scenario). A scenario consists of:

- specification of road configuration (number of lanes, on-ramp, etc.);
- selection of needed user class profiles;
- specification of traffic flow demand at origins;
- specification of origin – destination relations;
- specification of user class distribution at origins.

Traffic flows in the simulation model can be time-varying and can be specified for each origin separately.

In the model, drivers (and assistance systems) make state observations $y(t)$ at regular time intervals. However, a driver will normally have a broader view on the traffic environment than an AICC system, that typically observes only the range in front of the equipped vehicle. In the model a driver observes own lane $j$, left side lane $j-1$, and right adjacent lane $j+1$. An AICC system, however, only observes lane $j$.

The state observations $y(t)$ of a human driver involves, among others, the position and speed of vehicles on the adjacent lanes and on the current lane restricted by the observation range. Own position and speed are observations too. Flashing turn indicators are essential elements in the state observation since it indicates lane-changes, but are not modelled.

Several stimuli are applied in the prediction and evaluation of possible control decisions $u(t)$ from a control set $U$. An individual objective function $J_i$ is minimised to select the optimal control decision. Preferences and control objectives, embodied in the objective
function, affect the decision largely. Typically, the control decision $u^*(t)$ contains two responses: a speed adaptation and lane change decision. The responses - which are executed simultaneously - are constantly updated at regular time intervals. The actual execution takes place after a specific time delay. The stimulus-response control structure is applied in the simulation model.

Figure 7.9 shows the structure of the SIMONE model for representation of the driving task. The elements shown in the figure are described shortly in the sequel.

FIGURE 7.9 Main structure of the SIMONE model. Each time scan the system's state which includes all vehicles actual present in a simulation, is evaluated according to this flow diagram.

**Time scan interval**

The driver theory described in section 2.4 is based on a continuous time frame and has to be adapted in order to be applied for a discrete-time simulation model. In a microscopic simulation model, a time scan interval is the time period in which the state of the system (i.e., all vehicles present in the simulation) is updated. The processes depicted in figure 7.9 are performed at regular intervals during the whole simulation time. A time scan interval
\( \tau_{sc} \) of 0.1 s is chosen to capture the vehicle movements in detail. Longer time scan intervals restrict a realistic representation of AICC-equipped vehicles, since AICC systems can observe and react within such small time delays. A time scan interval of 0.1 s may even be too large in the case of shockwave delays, but it is considered an acceptable compromise between calculation effort and level of detail, see e.g. KöHLER (1974).

Although the applied time scan is small, the acceleration and state change considerations of an individual driver-vehicle combination can be adjusted at larger time intervals, which must be multiples of the 0.1 s time scan frequency. These time intervals are further denoted with update time interval, symbol \( \tau_{u,new} \) (user class dependent delay for new state update). Figure 7.10 illustrates the introduced time notions.

**Update time interval**

The update time interval \( \tau_{u,new} \) of a driver is the time interval for updating the actual state. At a certain update time moment \( t \), the observation, prediction and decision process leading to a control action will be started according to the conceptual model described in section 2.4. The update time interval notion is shown in Figure 7.10. Clearly, the update time interval is a multiple of the time scan interval \( \tau_{sc} \). Minimum value of update time interval equals the time scan interval.

The update time interval \( \tau_{u,new} \) of a driver-vehicle combination \( i \) belonging to user class category \( u \) (\( i \in u \)) depends on the user class characteristics. For a user class with drivers using their AICC-systems a small update time interval will be apparent due to the system and sensor characteristics (e.g., repeated state observations every 0.1 s).

The selection of an update time interval is also a trade-off between simulation speed and accuracy of the results. Although we assume that human drivers make state observations unconsciously and likely have a small update interval time, to accelerate the simulation speed we had to select an update time interval of 0.3 s for manually controlled vehicles. For AICC-equipped vehicles an update time interval of 0.1 is selected.
From figure 7.10 it also follows that the user class dependent update time interval $\tau_{i,\text{new}}$ contributes to the total delay time $\tau_i$ as has been elaborated in section 2.4. This total time delay includes the state observation, prediction, decision, and actuator delay. However, the introduced update time interval $\tau_{i,\text{new}}$ is not a behavioural parameter, but a model parameter. In order to approximate the behavioural time delay parameter $\tau$ as introduced in section 2.4, another model parameter $\tau_{i,\text{ad}}$ has been introduced. This parameter expresses the additional delay which must be added to the update interval time. The parameter $\tau_{i,\text{ad}}$ is a user class dependent model parameter but an individual disturbance is introduced between drivers within a user class. The delay time $\tau$ for a driver $i$ from user class $u$ is now formulated as follows (fig. 7.10):

$$\tau_i = \tau_{i,\text{new}} + \tau_{i,\text{ad}} \quad (i \in u) \quad (7.1)$$

Both $\tau_i$ and $\tau_{i,\text{ad}}$ are thus random variates (and therefore underlined).

In many studies (Forbes, 1994, Tijerina, 1995), it was found that the braking reaction time differs strongly between drivers. Therefore, differences in time delays among drivers in a user class $u$ are assumed. Therefore, a truncated normal distribution is assumed for the driver population. Driver differences are introduced with the mean and standard deviation of parameter $\tau_{i,\text{ad}}$:

$$\tau_{i,\text{ad}} = \max (\tau_{i,\text{sc}}, \frac{N(\mu(\tau_{i,\text{ad}}), \sigma(\tau_{i,\text{ad}}))}{}) \quad (i \in u) \quad (7.2)$$

A user class dependent mean $\mu$ and standard deviation $\sigma$ is specified for the individual additional time delay parameter $\tau_{i,\text{ad}}$. The right side of the distribution is limited by the time scan interval. The parameter value is rounded to a discrete value based on a multiple of the time scan interval, thus $\tau_{i,\text{ad}} = k \cdot \tau_{i,\text{sc}}$ (where $k=1,2,\ldots$).

Since a driver only starts the state observations, prediction and control decision process at the regular time intervals defined by $\tau_{i,\text{new}}$, driver behaviour at intermediate time scans is similar to the response calculated last update moment. We will illustrate this. One time scan interval after the last update moment, the state can be changed significantly (e.g., leader decelerates heavily) but the reaction on this state change can be determined at the following update moment and after completing the overall time delay. Therefore, the so-called maximum delay time (indicated in fig. 7.10) is defined by:

$$\tau_{i,\text{max}} = \tau_{i,\text{new}} + \tau_{i,\text{new}} + \tau_{i,\text{ad}} - \tau_{i,\text{sc}} \quad (i \in u) \quad (7.3)$$

For example, if an update time interval of 0.3 s and an additional delay time of 0.2 is chosen, the resulting time delay $\tau_i$ will be in the range of [0.5 to 0.7 s].

The selection of the update time interval of a user class is important for modelling driver behaviour. It must be selected simultaneously with other behavioural and model parameters of that particular user class. Changing the update interval time without checking other driver behaviour parameters, especially the longitudinal control strategy parameters, may result in unrealistic driver behaviour.

**Vehicle state**

A vehicle in the SIMONE model is characterised by one of the following lateral states: *normal, positioning* or *executing lane change*. Potential state changes are checked at
regular time intervals (fixed at 1.5 seconds). The vehicle state determines the route in the flow diagram, as shown in figure 7.9.

- **Normal state**
  In case of the normal state of a vehicle, only speed adaptation calculations are performed.

- **Gap positioning state**
  In case of the gap positioning state, the vehicle-driver combination receives a mandatory or a discretionary lane change request and evaluates gaps.

- **Execute lane change state**
  The execute lane change state is used during a lane-change execution. After completion (about 3 seconds) the vehicle state changes to the normal state.

**Speed adaptation calculations**

The speed adaptation calculations are based on several modules, each module giving a minimum required acceleration for a part of the longitudinal driving task. Eventually, the minimum value is selected from all modules. This value is stored temporarily until the delay time of the corresponding driver-vehicle combination has been elapsed. These modules are depicted in fig. 7.9 and deal with the following aspects:

- **Vehicle constraints**
  Based on the vehicle acceleration and deceleration characteristics (as specified for the corresponding user class) acceleration and deceleration boundaries are determined as function of the current driving speed of the vehicle. Responses simultaneously calculated in the other modules should be within the defined range.

- **Speed adaptation to achieve safe gap distance**
  Central in the calculation is this longitudinal control or car-following routine, in which a control strategy is applied based to maintain a safe gap distance to the leader (section 7.3.2). AICC-equipped car drivers are supported with this part of the longitudinal driving task.

- **Speed adaptation to left adjacent lane speed**
  Another module calculates a speed adaptation needed to prevent passing slower vehicles on the left adjacent lane. This is essential for representing European driving behaviour and legislation. Nonetheless, passing vehicles is possible during congestion and can also be observed if the needed speed adaptation requires too large deceleration (section 7.3.3).

- **Speed adaptation to create gap**
  A speed adaptation to create a gap is needed if there is a vehicle directly in front on an adjacent lane with a mandatory lane change request (section 7.3.4).

- **Speed adaptation to search gap**
  Optional, if the vehicle-driver combination should change lanes due to a mandatory lane change request, a speed adaptation for searching a gap might be needed (7.3.5).

**7.3.2 Speed adaptation to achieve safe longitudinal gap distance**

For maintaining a safe gap distance to an observed leader on the same lane, a longitudinal control strategy is applied. This control strategy and embodied safe distance model
determine the road capacity substantially, as has been demonstrated in section 4.3.2. It is an important part of the simulation model since the majority of the control decisions are based on the position and speed of a vehicle in front (relative to the driver’s own position and speed). It consists of a leader selection process, minimum desired distance preference, and the actual speed adaptation calculation. The procedure holds for drivers with a non-equipped vehicle and for AICC-equipped vehicles as well.

**Leader selection**

It is assumed that a subject vehicle observes the traffic environment at regular time intervals, as described in section 7.3.1. During the state observation the subject determines which vehicle is at a close distance in front - not necessarily on the same lane. A subject vehicle takes into account the presence of vehicles on the adjacent lanes, thus observes three lanes at maximum. A vehicle directly in front on subject’s current lane, or possibly performing a lane change from or towards subject’s current lane, is referred to as the leader of the subject vehicle (figure 7.11). The subject vehicle is also called ‘follower’.

![Leader and follower definition. A leader can have more than one follower, but a follower can not have more than one leader.](image)

In SIMONE, all drivers have a leader. In case no vehicles are observed within the observation range of the driver a dummy vehicle is assumed to be located at the driver’s maximum visible range. The driver’s visible range is a user class dependent parameter, and its maximum value ranges from 50 m (foggy conditions) to 500 m (clear weather). For an AICC, the maximum sensor range will be approximately 150 m.

To illustrate the leader-follower approach, see fig 7.12. In the figure, a subject follower and its leader are depicted. The shown candidate leaders drive in the normal state and are not considering a lane change. The leader and follower state, identified with the arrows, can be either normal or lane changing. We assume that a driver estimates the distance towards all vehicles directly in front driving at (or lane changing to) his own lane (or adjacent lanes in case the driver is executing a lane change himself) and determines which vehicle is the nearest. Observation of flashing turn indicators is needed to determine the lane-change state of a vehicle. Eventually, after evaluation of the distances towards these candidate leaders, only one leader is selected: this is the vehicle on which driver’s responses are based in our simulation approach. A similar procedure is assumed to be valid for an AICC system, taking into account the limited sensor range. The AICC sensor observes potential leaders in front on the current lane, observes lane-changing vehicles as they move to the current lane, while a filter selects the (critical) leading vehicle according to predefined rules.
Eight basic car-following situations, regardless the number of lanes (and some restrictive conditions) are taken into account in the leader determination (see figure 7.12). The modelling approach in SIMONE is according to this classification of leader-follower situations.

It should be remarked that despite the selection of a single leader, other vehicles will have an impact on driver’s longitudinal driving behaviour as well, for example, when vehicles on the left side lane drive slower, or when another vehicle wants to merge in the front gap of the subject. Such cases are treated separately in the SIMONE model and discussed in the following sections.

In the following list (see text box) the eight follower-leader situations shown in figure 7.12 are described.
A. The vehicles are not in a lane change state. This situation occurs most of the time. The vehicle directly in front on the same lane is leader.

B. Vehicle in front changes lane from the follower's driving lane to another driving lane. The follower considers this vehicle to be a leader until half of the lane change execution is performed.

C. Follower changes lane, vehicle in front stays on current lane. The vehicle in front is a leader until half of the lane-change of the follower is executed. A new leader is selected after this time (probably according to situation D).

D. Follower changes lane. Nearest vehicle in front on target lane becomes leader directly after starting the lane change execution (Only in case the distance to the vehicle in front on the same lane is smaller than the distance to the vehicle in front on the target lane).

E. Follower stays on current driving lane. Vehicle on adjacent lane executes lane change towards follower's lane. Directly after starting the lane change execution, this vehicle is specified as leader.

F. Both vehicles are executing a lane-change towards the same target lane. The vehicle in front can be a new leader if it is the nearest candidate (as depicted).

G. Weaving manoeuvre type 1: Follower changes lane to adjacent lane, while another vehicle in front, not on the follower's lane, also executes a lane-change (which can be to the same adjacent lane or to the current follower's lane). This vehicle in front is a candidate leader directly after starting its lane change execution. In the situation as depicted here, the candidate is actually the leader.

H. Weaving manoeuvre type 2: Follower changes lane to another target lane than the vehicle in front. The vehicle in front is a candidate leader. In the situation as depicted here, the candidate is actually the leader.

Minimum desired distance gap

As described in section 4.3.2, most theories about driver behaviour on motorways assume a driver's desire to drive at a minimum acceptable distance from its leader (see e.g., Wiedemann, 1974 and Vermuijs, 1992). A desired distance gap function is used as a reference gap in many longitudinal control strategies. A function formulation related to car-following distances was adapted from earlier findings (see e.g. Vermuijs, 1992, Van Arem et al., 1995b). This function is defined as follows:

\[ s_{i,\text{min}}(t) = I_i + \eta_i(t) \cdot (m_i z_i(t) + z_2 \dot{x}_i(t)^2) \quad (i \in u) \]  \hspace{1cm} (7.4)

The parameters in equation (7.4) are the following:

- \( I_i \): length of vehicle \( i \), which is equal to the user class parameter \( I_i \) [m]
- \( \eta_i \): congestion factor with value between 1 and 1.5, which depends on perceived traffic state by driver \( i \) and his speed at moment \( t \)
- \( m_i \): safety margin of vehicle \( i \), which is equal to the user class parameter \( m_i \) [m]
- \( z_i \): gap distance parameter of vehicle \( i \), which is related to a user class parameter and an individual disturbance factor [s]
- \( z_2 \): gap distance parameter of vehicle \( i \), which is equal to the user class parameter \( z_2 \) [s^2m^{-1}]

In the SIMONE model, the desired minimum gap distance \( s_{i,\text{min}} \) of driver \( i \) is partly individually determined by parameter \( z_i \). This parameter expresses to a large extent the desired headway of a driver. In the simulation model, it is defined by two other parameters: the additional delay time parameter \( \pi_{a,d} \) (see equation 7.1) and a model parameter \( \pi_{a,s} \), which is a user class parameter expressing the extra 'headway' margin above the driver's overall delay time.
\[ z_{il} = \xi_{i,ad} + \pi_u \quad (i \in u) \] (7.5)

This approach is followed because the probability of rear-end collisions increases significantly if the delay time parameter is larger than the \( z_{il} \) parameter. It was therefore decided that the dependency between desired minimum gap and the reaction delay should be incorporated in the model. Note that the update time interval affects the overall delay time, but has no impact on the desired distance gap function. An additional stochastic delay time \( \xi_{i,ad} \) with a mean of 0.1 seconds, together with a margin time \( \pi_u \) of 0.45 seconds (thus \( z_{il} \) equal 0.55) suits well for presenting driver behavior under normal weather conditions. However, it is generally assumed that the car-following distance increases, and average speed drops, under non-ideal weather conditions.

Expansion of desired gap distance during congestion

Differences in the preferred minimum desired gap distance function are found when we compare congested traffic flow conditions with non-congested conditions, see DIJKER et al (1997a). In order to model this behavior, we use a proportionality factor instead of the application of different distance functions. We decided for such an approach to make the calibration and interpretation of the minimum desired distance function easier.

The proportionality factor \( \eta_i \) in the desired minimum distance gap function, eq. (7.4), is set one for a driver \( i \) when he perceives non-congested conditions. From calibration of the model it was found that the factor should be approximately 1.4 when a driver perceived congested conditions. We also found that the factor depends on the driving speed. If a driver \( i \) perceives congested conditions, the following holds for the congestion factor:

\[
\eta_i = \begin{cases} 
1.4 & \forall \ x_i > 80 \text{ km/h} \\
\eta(x_i) & \forall \ x_i \geq 20 \text{ km/h} \\
1 & \forall \ x_i < 20 \text{ km/h}
\end{cases}
\] (7.6)

The congestion factor parameter is a user class dependent parameter since it may be possible that this value differs between user classes in different traffic scenarios. The employment of the factor in the simulation is elaborated in the following text box.

A driver in a simulation perceives congested conditions when he observes an average mean speed of a sample vehicles present over a road length equal to 6 s headway in front on the same lane, which is below 70 km/h while his speed is below 50% of his desired speed. The model initially assumes non-congested conditions for vehicles generated at origins. When a driver perceives congestion directly downstream the origin, the vehicle enters the simulation in a congested driving state. A driver might experience congested conditions during the simulation, or vice versa, notice a change back to the non-congested state. A driver changes back to the non-congested state if he drives at 95% of his desired speed again, while the average speed of the vehicles in front exceeds 95% of his desired speed.

A vehicle-driver combination using an AICC system will not adopt the desired gap distance in congestion as long as the system is active and assists the driver. The first generation AICC-systems will use only a single gap distance function for all traffic conditions (thus with a congestion factor equal one). After driver intervention the driver will adopt his own preferences with respect to the desired minimum gap distance. In the SIMONE model, vehicles' congestion state can be made visual during a simulation run.
Longitudinal control and car-following model

Helly's car-following model (PAPAGEORGIU, 1991), which is applied in SIMONE and other models (BROQUA et al., 1991, VAREM et al., 1995b), is based on equation 7.7. This equation is similar to the equation in the example given in section 2.4.3. The model tries to minimise distance difference and speed difference of subject vehicle \( i \) with respect to the lead vehicle \( i-1 \) according to the specified parameter values. In addition to a single leader, a driver may react upon changes in driver behaviour of other vehicles in front of the leader vehicle. This aspect has been neglected; several studies indicate the limited benefits when using two vehicles in front in determining a speed adaptation (PAPAGEORGIU, 1991).

\[
a_i(t) = \frac{c_1}{s_{\text{ad}}(t)} \left[ \dot{x}_{i-1}(t-t_i) - \dot{x}_i(t-t_i) \right] + \frac{c_2}{s_{\text{ad}}(t)} \left[ x_{i-1}(t-t_i) - x_i(t-t_i) - s_{\text{ad}}(t-t_i) \right]
\]

(7.7)

During implementing and testing this algorithm, it became clear that at low speeds, especially during stop-and-go traffic, the model generates many rear-end collisions. We found that during acceleration of the lead vehicle the algorithm should not use the same relative speed \( c_1 \) sensitivity parameter. Therefore, the value of this sensitivity parameter is made dependent on the relative speed sign. In other words, if the leader drives faster than follower, then \( c_1 \) is set to a value approximately half of the initial value.

Table 7.2 gives an overview of the applied parameters of the adopted, but modified Helly car-following model. Four parameter cases describe the manual longitudinal driver task. As can be seen in the table, individual differences in the longitudinal control are introduced for approaching conditions only, to limit the number of parameters and complexity in the calibration phase. Mathematically, the driver parameter \( c_{t_u,\text{neg}} \) for a negative speed differential is based on a normal distribution with the driver's user class parameter \( c_{t_u,\text{neg}} \) as mean and a coefficient of variation of 7%:

\[
c_{t_u,\text{neg}} = N(c_{t_u,\text{neg}}, 0.07 \cdot c_{t_u,\text{neg}})
\]

(7.8)

The \( c_{t_u,\text{neg}} \) parameter value is about half of parameter \( c_{t_u,\text{pos}} \) because during an approach situation (leader slower) a driver is more alert in keeping his minimum desired gap distance to its leader.

In contrast, the \( c_{t_u,\text{pos}} \) for a positive speed differential is specified as a user class parameter which is driver independent. This parameter is essential for describing driver behaviour in queue discharge flow conditions in which drivers accelerate to their desired speeds.

<table>
<thead>
<tr>
<th>Speed leader slower</th>
<th>Speed leader faster</th>
</tr>
</thead>
<tbody>
<tr>
<td>Follower experiences free flow conditions</td>
<td>( c_{t_i,\text{neg}} )</td>
</tr>
<tr>
<td>Follower experiences congested conditions</td>
<td>( c_{t_i,\text{neg}} )</td>
</tr>
</tbody>
</table>

TABLE 7.2a Application of \( c_1 \) parameter in car-following model as function of relative speed and congestion state

The \( c_2 \) parameters are all user class dependent. When a driver experiences congested conditions, the \( c_2 \) parameter expressing the distance error sensitivity, the parameter value
is set to a quarter of the value in free flow conditions. Thus, drivers will slowly reduce gap distance errors in congested conditions.

<table>
<thead>
<tr>
<th>Speed leader slower</th>
<th>Speed leader faster</th>
</tr>
</thead>
<tbody>
<tr>
<td>Follower experiences free flow conditions</td>
<td>$c_2 u$</td>
</tr>
<tr>
<td>Follower experiences congested conditions</td>
<td>$0.25 \cdot c_2 u$</td>
</tr>
</tbody>
</table>

TABLE 7.2b Application of c2 parameter in car-following model as function of relative speed and congestion state

Threshold speed values are introduced to model the minimum observable relative speeds (about 1 km/h). This ensures a more realistic representation of human driving and AICC-sensor characteristics.

For the longitudinal controller of the AICC systems, the parameters $c_1$ and $c_2$ were estimated taking into account the smaller delay time and smaller update time interval. Only one pair of parameters has been determined for application under all traffic conditions. Our global calibration goal was to achieve similar behaviour of the AICC system’s longitudinal control and human driver’s longitudinal control, using an equal minimum desired distance function. Other objectives may be applied in order to determine these important parameter values.

Figure 7.13 shows graphically the principle of the calculation procedure with the longitudinal controller. Near the desired minimum gap distance, small speed differentials are accepted, thus no acceleration needed, which is shown by the small rectangle. Minimum and maximum accelerations are restricted by driver preferences and vehicle characteristics (see MINDERHOUD, 1998).

![Graph showing gap distance and speed difference](image-url)

FIGURE 7.13 Example acceleration calculation in the distance-speed differential plane using the two-regime linear longitudinal controller (free flow state with $c_1_{pos}=2.0$ s\(^{-1}\), $c_1_{pos}=1.0$ s\(^{-1}\), $c_2=0.1$ s\(^{-2}\))
7.3.3 Speed adaptation to left lane speed

In Europe and many other parts of the world, traffic regulation is such that passing of vehicles on the right-hand side is not allowed under normal traffic conditions. In practice, this means that at driving speeds above approximately 100 km/h drivers will not accept a speed difference with the left lane. It is known that at lower speeds this is not fulfilled strictly: in congestion drivers accept larger speed differences between lanes.

This phenomenon is incorporated in the SIMONE model by adapting vehicle speed to the left adjacent lane speed. With respect to our modelling approach, we assume that:

- A driver adapts his speed smoothly as soon as he observes lower speeds at the left adjacent lane.
- A driver anticipates on situations he will encounter about two to five seconds ahead on the left side lane applying the actual speeds.
- During congestion larger relative speeds between lanes are accepted.
- Maximum speed differences can temporarily be larger than the acceptable speed difference during the speed adaptation process.
- A driver does not adapt to speed differences between own speed and the speeds on the right adjacent lane.

\[ \ddot{x}_{i,\text{left}}(t) = 2 \cdot \frac{\dot{x}_i(t) - \dot{x}_{\text{left}}(t - \tau) - v_{i,\text{av}}(\dot{x}_i)}{T_{\text{uat}}} \quad (l \in u) \quad (7.9) \]

where:
- \(\ddot{x}_{i,\text{left}}\) : deceleration response with respect to left-side lane speed \([\text{m/s}^2]\)
- \(\dot{x}_i\) : speed of subject vehicle \(i\) \([\text{m/s}]\)
- \(\dot{x}_{\text{left}}\) : observed speed on left side lane \([\text{m/s}]\)
- \(v_{i,\text{av}}\) : acceptable speed difference with left side lane (threshold) \([\text{m/s}]\)

Based on these considerations, a speed adaptation process has been developed to relax driver's speed on lane \(j\) to the average left adjacent lane \(j-1\), taking into account a small accepted speed differential. The applied acceptable speed difference as function of subject's speed, is depicted in figure 7.14. So far, nothing is known about this relationship, so we assume for simplicity that this relationship holds for all user classes and does not differ between individual drivers.

A speed adaptation is calculated only if the speed differential between subject's own speed and left lane speed (based on a sample of vehicles in front on lane \(j-1\)) exceeds an acceptable speed difference.
\[ T_{\text{rel}} \] relaxation time for left lane speed adaptation (calibration parameter) [s]
\[ \tau_{i} \] overall time delay vehicle \( i \) [s]

A relaxation time \( T_{\text{rel}} \) (which is a user class parameter for calibration purposes) of about three seconds results into a smooth speed adaptation. Speed differences with the left side lane will normally be compensated by comfortable engine braking, so a maximum deceleration of approximately \(-0.07g\) is used. However, if a vehicle is searching for a sufficient and acceptable gap on the left adjacent lane, a larger deceleration of \(-0.35g\) is used. This deceleration is larger since the speed difference between the vehicle and the left side lane must be reduced directly to execute the lane change safely and timely.

### 7.3.4 Speed adaptation to target gap on adjacent target lane

The gap selection and speed adaptation process is initiated if a vehicle needs a lane change with no appropriate gap available directly. The driver of the vehicle will then try to reach an existing gap by *positioning* his vehicle along this target gap with minimum effort. The driving speed needs to be adapted in order to reach the desired relative position to the target gap in the near future and to minimise the speed difference between own vehicle and target lane speed. The vehicle on the target adjacent lane can help the driver by creating a sufficiently large gap size. This so-called anticipatory behaviour is described in section 7.3.5.

The calculation of the needed acceleration or deceleration is based on the positions and distances indicated in figure 7.15. The following text box describes the approach used.

---

**It is assumed that there are only five suitable relative positions towards a lane-changing vehicle may move. The final decision is made after evaluation of the relative advantages. The positions are the following:**
- a gap in front of the direct front vehicle on the adjacent lane (distance to cover is denoted with \( \Delta x_{\text{front}} \)).
- a position directly behind the front vehicle with some margin (distance is denoted with \( \Delta x_{\text{lead}} \)).
- a position exactly between leader and follower (not depicted in the figure 7.15).
- a position directly in front of the rear vehicle, with some margin (distance to cover is denoted with \( \Delta x_{\text{rear}} \)).
- a position directly behind the rear vehicle, with the needed minimal margin, distance to cover denoted with \( \Delta x_{\text{rear}} \).

Depending on the presence of the vehicle in front and/or rear vehicle on the target lane, the vehicle positioning accelerations can be determined. Not all five relative gap positions are considered, since some options are no realistic alternatives (see for a detailed description MINDERHOUD, 1998).

---

The distance \( \Delta x \) to be traversed to a desired relative gap position can be calculated according to the distance depicted in figure 7.15. However, there must also be taken account of speed differences and even acceleration differences between the vehicles involved. Let us denote the actual relative distance to desired position \( \Delta x_{\text{gap}} \), the speed \( \dot{x} \) and acceleration \( \ddot{x} \) then we can calculate the needed acceleration \( \ddot{x}_{\text{gap}} \) to reach the position with, \( (i \in u) \):

\[
\ddot{x}_{\text{gap}}(t) = 2 \cdot \left( \frac{\Delta x_{\text{gap}}(t - \tau_{i}) - \dot{x}_{i}(t - \tau_{i})}{T_{\text{rel}}} \right) + \ddot{x}_{\text{car}}(t - \tau_{i}) - \ddot{x}_{i}(t - \tau_{i})
\]  

(7.10)
where

\[
\begin{align*}
\dot{X}_{i, \text{gap}} & \quad \text{acceleration response vehicle } i \text{ to reach target gap [m/s}^2] \\
X_{i} & \quad \text{speed of vehicle } i \text{ [m/s]} \\
\Delta x_{\text{gap}} & \quad \text{distance to target gap} \\
\dot{X}_{\text{tar}} & \quad \text{observed speed on target lane [m/s]} \\
\ddot{X}_{\text{tar}} & \quad \text{observed acceleration on target lane [m/s}^2] \\
T_{\text{rel2}} & \quad \text{relaxation time for left lane speed adaptation (calibration parameter) [s]} \\
\tau_i & \quad \text{overall time delay vehicle } i \text{ [s]}
\end{align*}
\]

Variable \( \dot{X}_{\text{tar}} \) denotes the average speed of the considered vehicles on the target lane, while \( \ddot{X}_{\text{tar}} \) the average acceleration of the involved vehicles on the target lane. \( T_{\text{rel2}} \) is a relaxation parameter, determining the time duration and smoothness of the speed adaptation response. It is a user class dependent parameter.

Since acceleration and deceleration levels are limited, the gap search duration can require more time than specified by the relaxation time parameter.

Expression (7.10) applying on the selected distances to reach the target gap results in an equal number of acceleration responses. These acceleration responses are compared using their absolute values, and the distance of which a minimum response is required is selected as control decision. Practically, this means that a driver chooses to accelerate towards a position in a gap on the target lane which he can reach with minimum effort.

7.3.5 Speed adaptation to anticipated merging

In case a vehicle wants to change lanes but has not an acceptable gap available immediately, the vehicle on the adjacent lane - directly behind the mandatory lane changing vehicle - can create a sufficient gap by decelerating. This behaviour is often observed near on-ramps and other locations. In DIJKER et al. (1997a), it was found that nearly all drivers create a
sufficient gap for a vehicle with a mandatory lane change request on an adjacent lane.

To create a sufficiently large gap size, the anticipating vehicle must in some cases decelerate or postpone accelerations. This behaviour is denoted with *defensive gap positioning* since it is a defensive reaction on expected manoeuvres of other vehicles. The needed gap creation deceleration level is calculated based on the following assumptions:

- The driver wants his future leader at a minimal margin ahead, so he will take measures to prevent a situation with less gap distance.
- The driver estimates the needed accepted gap time headway and tries to create this gap headway to let the vehicle merge in front smoothly.
- The driver anticipates on the needed gap size (metres) which should be sufficient to let the vehicle merge, and tries to create such a minimal gap distance.
- At extremely low speeds, decelerating can result in stopping in order to let another vehicle merge in front. Since this is not acceptable, at speeds below 5 km/h the gap creation is accomplished by postponing gap positioning decelerations and car-following accelerations.

Based on these assumptions, the speed adaptation of the anticipating vehicle can be determined. Similar to equation 7.9, the needed deceleration can be calculated. Positive accelerations are not relevant in the defensive positioning mode. The deceleration is limited by the lane change acceleration parameters of the user class (with a deceleration of about 0.1g).

### 7.3.6 Lane change decision to a left lane

This section starts with some general notions on lane change behaviour. After this introduction the conditions to execute a lane change to a left lane is discussed. Section 7.3.7 presents the lane change decision conditions to a right side lane.

**Two types of lane changes**

An important element of the lateral driving task is the decision to switch lanes. The difference between *mandatory* and *discretionary* lane changes is essential for driver behaviour. We describe these two types in the following. This difference equally holds for lane changes to the left and right.

- A mandatory lane change request is given to a vehicle if it is in a so-called *shunt zone* and if this area determines that the vehicle should make a lane change. The vehicle-driver combination should make the lane change in order to reach the destination. On/off ramps, lane drops, and weaving sections are examples of a shunt area. Since these lane changes must be made to reach a destination, they are performed with an increased risk acceptance compared to a discretionary lane change (see figure 7.16).

- In case a driver is not subject to a mandatory lane change request, a *discretionary* lane change is possible in order to comply with comfort, speed or safety objectives. Simultaneously with the longitudinal driving task, lane change options are evaluated, as long as no mandatory lane change is required.

The location (lane, position) and delineation of a shunt zone depends on the application at hand and is defined by the user of the model. The characteristics of a shunt zone are described in the following.
**Shunt zone for mandatory lane changes**

An example of a shunt zone is shown in figure 7.16. The shunt zone at the right lane drop is divided in two sections. The end of the upstream section is denoted as soft wall. In this section, drivers can receive a mandatory lane change request. It depends on the user class type and destination of the driver if a driver actually must change lanes. In the example in figure 7.16, all drivers have to change lane to the left hand lane. In case a driver passes the soft-wall and enters the second part of the shunt zone (for example, since the driver has not an available acceptable gap along) the driver starts decelerating. The gap search is still ongoing, but a deceleration is needed to prevent the vehicle from leaving the motorway unintentionally at the end of the shunt zone.

For modelling purposes, it is assumed that drivers always start a lane change when they have reached the hard-wall, thus the end of the shunt zone, even if no appropriate gap is apparent. This may result in a collision course, but prevents a situation in which drivers stop and ‘park’ their car at the end of a shunt area, waiting for a sufficient merging gap.

**Structure of the lateral control task execution**

In the simulation model, the motivation of drivers to start a discretionary lane-change, or to start a mandatory lane change are determined at regular time intervals (specified at 1.5 seconds). This is denoted with the term lane change desirability. At these moments, which can differ between drivers, the model uses the flow structure as shown in figure 7.17. In words, the algorithm performs following sequence:
1. Check if the vehicle is on a shunt zone and if the vehicle should perform a mandatory lane change.
2. If the vehicle must not perform a mandatory lane change, check if the driver wants a discretionary lane change to the right lane.
3. If discretionary lane change to right lane is not possible, check if driver wants a discretionary lane change to the left lane.
4. If no lane changes are possible or wanted, the vehicle state returns to, or stays, normal.

**FIGURE 7.17 Algorithm for determining lane change desirability (mandatory or discretionary) in SIMONE**

Evaluation of the lane change desirability (motivation) and evaluation of the lane change feasibility (opportunity) are modelled strictly separated. Conditions for performing a discretionary lane changes are different for a left lane change and right lane change decision. The left side lane change conditions will be discussed in the sequel of this section.

**Lane change to a left side lane**

First condition needed to initiate a discretionary lane change request to a left target lane is the existence of this lane and its accessibility, i.e., there should be no lane barriers present. It is furthermore needed that there is no shunt zone on the left adjacent lane where lane-changing to the right is mandated for the vehicle's user class or drivers with a prescribed destination.

When these basic conditions are met, a driver prepares a left lane change if evaluation of the situation shows benefits. The following sets of conditions were specified during the model development and in the calibration phase:
a. Subject experiences a time-to-collision value to current leader on lane $j$ that exceeds the predefined threshold value, which is about 8 s.

- Vehicle speed of potential new leader on left lane $j-1$ is larger than subject’s speed plus an additional speed difference threshold (about 5 km/h)

b. Subject’s distance to current leader is below 2 s headway (car-following situation)

- Vehicle speed of potential new leader on left lane $j-1$ is larger than subject’s speed plus an additional speed difference threshold (about 5 km/h)

- Subject’s vehicle speed is below subject’s desired speed minus an additional speed difference threshold (about 5-10 km/h)

Condition set $a.$ is mainly incorporated for fast approaching vehicles (mostly during low traffic flow rates), which enables making a lane change without reducing speed. Condition set $b.$ is especially useful for most of the car-following situations under moderate and heavy traffic demand.

Notice that it has been assumed that if a driver drives 5 km/h slower than his desired speed and is following another vehicle at the desired headway the driver accepts this situation and adjust his speed to the leader’s speed. However, if the threshold value is exceeded - for example if the leader’s speed drops - the driver will prepare a lane change accordingly (condition set $b.$ has been met). Figure 7.18 shows two situations where lane changes to the left side lane are considered.

![Figure 7.18 Examples of discretionary lane change decisions to the left lane](image)

The speed difference threshold is a parameter that controls the lane change frequency. If it has a high value the rate of lane changing is limited. It represents the desired ‘gain’ from making a lane change to a left lane, and contributes to a traffic composition with fast vehicles on the left lane. This parameter is defined per user class. Although a driver may consider a discretionary lane change, its actual execution will be performed only after a positive gap acceptance procedure. Table 7.3 presents the conditions which are applied for the left lane desirability checking. The two rows indicate the two condition sets under which the gap search procedure actually will be performed.
where:

\( \dot{x}_{i-l} \) : speed of leader [m/s]

\( \dot{x}_i \) : speed of subject vehicle [m/s]

\( v_{ide} \) : subject's desired speed [m/s]

\( \Delta v_{thr} \) : speed differential (threshold) for starting lane change [m/s]

\( s_i \) : subject's distance to leader [m]

\( TTC_i \) : time-to-collision to leader i-l [s]

\( TTC_{left} \) : time-to-collision threshold value for left lane change [s]

### 7.3.7 Lane change decision to right lane

First requirement for a lane change to the right is the existence of a right target lane. It is furthermore needed that there is no shunt zone on this target lane where a mandatory lane-change to the left is required for the user class at hand.

Legislation (in Europe and other countries outside Europe) requires that drivers should use the most right (shoulder) lane, if this is possible under the prevailing conditions. For the execution of a lane change to return to the right-side lane, the underlying idea is that a driver will only return to the right adjacent lane if this will not result in a disadvantageous situation (see e.g. figure 7.19). Based on this requirement, four sets of conditions are defined for starting a lane change to the right:

a. - Vehicle speed of new leader on right side lane \( j+1 \) is smaller than subject's speed;
  - Subject's time-to-collision to the observed new leader on the right lane \( j+1 \) is larger than a TTC threshold value (about 30 seconds);
  - There is sufficient distance to the new leader, expressed as a time headway (5 seconds) and speed-independent minimum gap size;

b. - Vehicle speed of new leader on right target lane exceeds subject's speed;
  - Subject's vehicle speed is near desired speed;
  - There is sufficient distance to new leader (about 1 s headway);

c. - Vehicle speed of new leader on right target lane exceeds subject's speed;
  - Subject's speed is below own desired speed;
  - There is sufficient distance to new leader (about 2 s headway plus a speed-independent constant distance);

d. - Subject's speed is equal to leader's speed on right lane;
  - There is sufficient distance to new leader (100 metre)
In the model calibration phase, we found that acceptance of condition set a. is mostly fulfilled in moderate dense traffic, lane change decisions made based on acceptance of condition set b. are especially encountered in light dense traffic while conditions c. are important during moderate and heavy dense traffic. For the latter, two situations with slightly adapted sets of conditions are distinguished, set c1 for large speed differential and set c2 for a small speed differential with the observed leader on the right lane (see table 7.4).

As described in section 7.3.1 and shown in figure 7.9, a vehicle changes to vehicle positioning state if a set of lane change conditions has been met. In the gap acceptance procedure, the availability of an acceptable safe gap is investigated. Since this investigation includes, among others, the rear gap distance from the potential new follower on the adjacent lane, this aspect of feasibility of a lane change has not been embodied in the lane-change conditions addressed previously. The gap acceptance decision making is discussed in next section 7.3.8.

Table 7.4 gives the condition sets for performing a right lane change. Each row indicates a set of conditions which have to be met in order to start the gap search procedure.

<table>
<thead>
<tr>
<th>Set</th>
<th>Speed difference</th>
<th>Desired speed</th>
<th>Distance gap</th>
<th>Time-to-Collision</th>
</tr>
</thead>
<tbody>
<tr>
<td>a.</td>
<td>$\dot{x}_i &gt; \dot{x}_i^{\text{safe}}$</td>
<td>$\dot{x}<em>i &gt; 0.95 \cdot v</em>{\text{den}}$</td>
<td>$s_{\text{right}} &gt; 30 + 2.5 \cdot \dot{x}_i$</td>
<td>TTC_{right} &gt; TTC_{br}</td>
</tr>
<tr>
<td>b.</td>
<td>$\dot{x}_i &lt; \dot{x}_i^{\text{safe}}$</td>
<td>$\dot{x}<em>i &gt; 0.95 \cdot v</em>{\text{den}}$</td>
<td>$s_{\text{right}} &gt; 1 \cdot \dot{x}_i$</td>
<td></td>
</tr>
<tr>
<td>c1.</td>
<td>$\dot{x}_i &lt; \dot{x}_i^{\text{safe}} - 0.7$</td>
<td>$\dot{x}<em>i \leq 0.95 \cdot v</em>{\text{den}}$</td>
<td>$s_{\text{right}} &gt; 30 + 1.8 \cdot \dot{x}_i$</td>
<td></td>
</tr>
<tr>
<td>c2.</td>
<td>$\dot{x}_i^{\text{safe}} - 0.7 &lt; \dot{x}_i &lt; \dot{x}_i^{\text{safe}}$</td>
<td>$\dot{x}<em>i \leq 0.95 \cdot v</em>{\text{den}}$</td>
<td>$s_{\text{right}} &gt; 30 + 2.3 \cdot \dot{x}_i$</td>
<td></td>
</tr>
<tr>
<td>d.</td>
<td>$\dot{x}_i = \dot{x}_i^{\text{safe}}$</td>
<td>$s_{\text{right}} &gt; 100$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 7.4 Right lane-change desirability conditions
Complementary to table 7.3 we define:

- $x_{i-1 \text{ right}}$: speed of potential leader $i-1$ on right lane $j+1$ [m/s]
- $s_{k \text{ right}}$: subject’s distance to potential leader on right lane $j+1$ [m]
- $TTC_{k \text{ right}}$: subject’s time-to-collision value to leader on right lane $j+1$ [s]
- $TTC_{thr}$: time-to-collision threshold value for right lane change [s]

### 7.3.8 Gap acceptance decision making

The conditions for accepting a gap in the target lane are a combination of safety and efficiency considerations. A lane change is executed if all these conditions are met. For most of the criteria reference to figure 7.15 is made. After a positive gap acceptance decision, the lane change manoeuvre will be executed directly.

The following conditions are defined for the gap acceptance decision in case of a discretionary lane change.

1. Firstly, there should be a gap directly aside the vehicle in the target lane, otherwise the driver will not start a lane change manoeuvre.

2. The gap aside of the vehicle must be large enough. If the gap size, expressed in the net time headway of the adjacent rear vehicle to the adjacent front vehicle, is smaller than a predefined threshold value (about 1.4 seconds) a lane change will not be executed.

3. The desired lane change must be executed sufficiently safe for the driver. For this condition, the time-to-collision indicator is used. If the time-to-collision between driver and his new leader is below a threshold value (about 8 seconds) a lane change is not started.

4. The lane change must be sufficiently safe for the new follower (the rear vehicle on the adjacent lane). For operationalisation of this criterion, the Time-to-Collision indicator is used. If followers’ time-to-collision value to the leader wanting a lane-change is below the threshold value (about 8 seconds) a lane change is not started.

The requirements 3. and 4. are safety considerations and mainly prevent vehicles from making lane changes at large speed differences with both leader and follower on an adjacent target lane.

5. For a positive gap acceptance decision, there must be a sufficient distance margin between the front of the vehicle and its (new) leader, and between the rear of the vehicle and its (new) follower. If these minimum margin sizes (approximately 2 metres) are not available, a lane change manoeuvre is not started.

For a discretionary lane change manoeuvre to the right, the rear margin is substantially larger and proportional to the speed (about 1 seconds headway). This is required to prevent the follower from needlessly decelerating for a suddenly appearing new leader.

6. The gap size expressed in metres must be large enough. Especially at speeds below 50 km/h, the gap distance is often not large enough, while the gap expressed in time headway may be sufficient. The minimum gap distance is determined by the minimum margins and the physical vehicle length. If the actual distance is too small, a lane change will not be started.

The conditions given above hold for situations with both follower and leader on the adjacent lane, which however, can easily be adapted when only a follower or leader is present. In that case, the driver’s visible range (about 400 m under normal weather...
conditions) determines the location of a ‘dummy’ follower or leader. The mathematical equations for the six conditions mentioned, can easily be drawn up based on figure 7.15. In the model, reference point for determining rear vehicle and front vehicle on the target lane is the rear bumper of the subject vehicle.

After positive evaluation of the gap acceptance conditions, the state of the vehicle (being vehicle positioning) turns to execute lane change (see figure 7.9) During the lane change execution, the car-following routine is applied. A lane change manoeuvre will not be aborted in the model.

In addition to the conditions described above, the gap selection procedure for a vehicle needing a mandatory lane change has some extra features. Since these lane changes must be made to reach a destination, they are performed with an increased risk acceptance compared to a discretionary lane change. At first, the same conditions are applied for evaluating the gap acceptance. However, when there is no direct success, the conditions are changed by adapting the parameters indicated in figure 7.16. Table 7.5 shows the different characteristics of gap selection and acceptance behaviour as a function of vehicle position on the shunt zone. The characteristics only affect driver behaviour of subjects who must perform a lane change in order to reach their destination.

<table>
<thead>
<tr>
<th>Position on shunt zone</th>
<th>Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Entire zone</td>
<td>Parameters for gap acceptance are determined based on distance to end</td>
</tr>
<tr>
<td>After 25% of zone length</td>
<td>Subject will adapt speed to target lane speed in order to position to appropriate gaps</td>
</tr>
<tr>
<td>After 70% of zone length</td>
<td>Positioning decelerations smaller than lane change deceleration allowed</td>
</tr>
<tr>
<td>After soft-wall boundary</td>
<td>Decelerations will be applied to vehicle in order to stop before hard-wall</td>
</tr>
<tr>
<td>10 m before end</td>
<td>Lane change is executed, feasibility is not tested</td>
</tr>
</tbody>
</table>

TABLE 7.6 Characteristics of a shunt zone (for vehicles with mandatory lane change request only)

7.4 Simulation model input and output data

The simulation model is designed to analyse traffic flow impacts of a wide variety of driver support system compositions of the vehicle fleet under various roadway configurations and traffic demand conditions. A specific combination of roadway configuration, traffic demand, and system composition is called an experimental scenario. This section describes the input data (parameters) and output data (flow data) of the model.

7.4.1 Input data

A scenario consists of a concise description of the road geometry, user classes and traffic demand. An overview of the required input variables and parameters for the simulation of a scenario is given in this section.

Road geometry
• Length of motorway segments;
Supported Driving: Impacts on Motorway Traffic Flow

- Number of lanes, position of lane drops, on-ramps and off-ramps;
- Dedicated lanes for specific user classes;
- Location and length of road barriers;
- Location and length of shunt zones;
- Location of detectors;

**User class profile**
- Mean and standard deviation desired speed;
- Minimum / maximum acceleration;
- Update time interval;
- Additional delay time, standard deviation;
- Perceptible range;
- Desired gap distance function parameters;
- Congestion factor;
- Car-following strategy and corresponding sensitivity parameters;
- Minimum / maximum lane change acceleration;
- Time-to-collision threshold for left / right side lane change;
- Lane change duration;
- Speed differential threshold for starting left side lane change;
- Minimum margin for gap acceptance;
- Average and minimum time headway for gap acceptance;
- Presence of assistance system;

**Assistance system characteristics in case of user class with assistance system**
- Minimum / maximum speed for system functioning;
- Minimum / maximum acceleration the system can handle;
- System's update time interval or refresh rate;
- System's delay time;
- System's sensor range;
- Reactivation functionality;
- Desired distance function parameters;
- Car-following strategy and corresponding sensitivity parameters;

**Traffic demand**
- Traffic flow level at origins as function of time;
- Proportion of user classes at origins;
- Origin-destination relations;

**Simulation parameters**
- Simulation duration;
- Simulation time scan;
- Aggregation time interval detector data.

7.4.2 **Output data**

A microscopic simulation model can in principle deliver all microscopic data (vehicle $i$ is at position $x$ at time $t$) the user wants. Some data is aggregated directly during the simulation,
since mesoscopic and macroscopic data is in several cases more useful than detailed microscopic data. The outcome of a simulation is a mixture of microscopic and macroscopic data collected at specified detectors. For the macroscopic data, an aggregating time interval must be specified between one and sixty minutes. During the simulation, graphs of the data (lane use, speed-flow diagrams, phase plane diagram, trajectories) can be viewed. The model gives the following outcomes:

**Macroscopic data**
Average speed per lane per interval;
Flow rate per lane per interval;
User class distribution per lane per interval;

**Mesoscopic data**
Headway distribution per lane;
Gap distance distribution per lane;
Acceleration level distribution per lane;
Time-to-collision frequency distribution per lane;

**Microscopic data**
Vehicle trajectories per lane (can be viewed during simulation).

### 7.5 Summary

This chapter gave an overview of the microscopic driver theory adopted in the microscopic simulation model SIMONE. Special attention has been given to driver decisions in common motorway situations, and the role of AICC in these processes. Theory and model assumptions are described. The modelling approach for the speed adaptation models and lane change decision and gap acceptance are discussed.

The model is capable of representing AICC-equipped vehicles with different support functionalities in mixed traffic composition and can simulate motorway stretches as well as bottlenecks in existing motorway networks.

The applied car-following model distinguishes different car-following situations in which different parameters are applied for an individual driver. The desired gap distance is furthermore dependent of the perceived traffic state by the driver. The use of a time scan of 0.1 s and stochastic elements of the user class variables - such as desired speed and delay - make a realistic representation of today’s motorway traffic possible. Calibration results (Appendix A) show a good resemblance with practice, including a distinction between pre-queue and queue discharge flow rates. The lane distribution is also according to empirical observations.

The following chapter describes the application of the model to a number of common bottleneck cases, and presents results for the traffic flow impact analysis of AICC systems.
CHAPTER 8

TRAFFIC FLOW IMPACTS OF AUTONOMOUS INTELLIGENT CRUISE CONTROL CONCEPTS

This chapter presents results of the traffic flow analyses performed for the Autonomous Intelligent Cruise Control concepts as described in the experimental setup (Chapter 6). These analyses consider capacity and safety referring to three selected motorway bottleneck types. After summarizing the concepts studied in the introduction, the on-ramp bottleneck scenarios are discussed. A two-lane motorway (section 8.2) and a three-lane motorway (section 8.3) with on-ramp are analysed. Section 8.4 presents the analysis of a weaving section bottleneck. The chapter closes with an assessment of the findings on capacity and safety of motorways (section 8.5) and their potential implications for transportation planning (section 8.6).

8.1 Traffic flow investigations conducted

In this chapter, results of the traffic flow analyses of ten AICC concepts are presented, analysed, and clarified. The experimental setup, including the selected concepts, has been developed in Chapter 6 and will briefly be summarized here. Figure 8.1 depicts the elements of the experimental setup we will present in this section.

The AICC concepts

The future AICC systems are divided into five groups. In increasing order of technological demands, we distinguish the following AICC designs (see table 6.1):

- **Normal AICC**: the first foreseen system to be deployed on cars, with a deceleration authority of -0.3g and a minimum supported speed of 30 km/h.
- **Extended AICC**: similar to the Normal AICC but featuring an automatic reactivation function instead of a manual reactivation requirement.
- **Queue AICC**: similar to the Extended AICC, however, the system only assists the driver in the 0 to 60 km/h speed range.
- **All speed AICC**: similar to the Extended AICC, but having an enlarged speed range covering speeds between 0 and 150 km/h.
- **Complete AICC**: assists the driver over the full speed range with the maximum available deceleration, while having an automatic reactivation function as well.
Several headway settings (in the range from 0.8 to 1.4 s) of the AICC designs have been investigated. Based on assumptions on how drivers will use these devices (which has been described in section 7.2.3), traffic flow impacts of these different AICC concepts are studied for a number of roadway and traffic settings.

**The network bottleneck cases**

Based on findings in the literature (Chapter 5) and theoretical considerations of roadway capacity (Chapter 4) it was decided that our traffic flow analyses should adopt motorway network oriented indicators of traffic flow quality instead of capacity values of uniform motorway stretches. Consequently, the investigation focusses on three different motorway bottlenecks which constitute the elements in motorway networks determining the network quality. The following respective bottleneck types are studied:

- two-lane motorway segment with on-ramp;
- three-lane motorway segment with on-ramp;
- symmetric weaving section;

**The traffic flow conditions**

Main subject of research is the capacity estimation and assessment of the selected bottlenecks, as a function of AICC design and equipment penetration rates. The simulation scenarios are prepared in such a way that road capacity is reached and is sustained for about an hour. Congestion at the upstream detector is a requirement for a valid capacity determination at the downstream detector. In addition, to facilitate explanation of some of the observed changes in capacity, the lane utilisation has been investigated.
The traffic flow impacts

An assessment of AICC-induced capacity changes relative to a reference is our primary objective. A well-defined, interpretable capacity estimation method is needed. The average queue discharge flow rate is used as capacity value estimate (see section 4.3.3). We verified that a single simulation run consisting of ten consecutive five-minute intervals of maximum flow levels is sufficient to determine a significant difference of means between an AICC scenario and a reference case without AICC-equipped vehicles (see Appendix D for an elaborated explanation of the statistical analysis). Assuming equal maximum flow distributions and standard deviations, a critical two-sided relative difference of about 1% with the reference scenarios' capacity is found. Considering the practical relevance of estimated capacity changes, together with safety and convenience considerations, we accept the accuracy percentage of 1%.

The speed at capacity, and the calculated critical density are secondary traffic flow indicators used in the assessment, among others to explain some of the findings. Another measure of performance used in the traffic flow impact assessment in this chapter is the total number of vehicles that passed the downstream detector in a simulation run.

Furthermore, the safety implications are studied by means of newly developed time-to-collision indicators (described in section 6.6.3). The driver intervention frequency is studied as an indicator of driver comfort.

The structure of sections 8.2, 8.3 and 8.4 is similar, each describing the simulation results of a bottleneck case. Capacity, safety and comfort analyses are given in the subsections. The emphasis is on the capacity analysis where we make a clear distinction between Normal AICC systems, AICC systems with headway setting of 1.2 s, and the remaining tested AICC systems, respectively. Speed, headway, and lane distribution data is used to explain some of the findings on capacity and safety. Figure 8.2 illustrates the issues which will be dealt with in the description and analyses of the simulation outcomes in sections 8.2, 8.3 and 8.4.

![Diagram](image)

FIGURE 8.2 Factors affecting the main line capacity

Figure 8.2 presents schematically the interaction between input factors (AICC penetration, AICC use), intermediate factors (car-following behaviour), and microscopic and macroscopic output data per lane (gap distances, density, speed, and lane capacities),
eventually contributing to the main line capacity (the capacity over all lanes in one driving direction).

![Road geometry of two-lane main line with on-ramp](image)

**FIGURE 8.3** Road geometry of two-lane main line with on-ramp

### 8.2 On-ramp to a two-lane motorway

Our analysis starts with a two-lane motorway with on-ramp, as described in section 6.5. The simulated motorway link is five kilometres long, with the on-ramp acceleration lane located at about halfway the link (as depicted in figure 8.3). The adopted traffic flow demand pattern is given in Appendix B. The capacity analysis is based on the flow counted at the downstream detector, using the queue discharge capacity notion.

#### 8.2.1 Capacity analysis

Car-following behaviour of drivers affect the *gap distances* maintained by the drivers, which has been indicated in figure 8.2. The deployment of AICC systems with a specific car-following algorithm, including a safe distance model, is expected to have an impact on the gap distances drivers maintain. One of the expectations mentioned in section 4.2 is the decrease of the average gap distance when AICC systems are introduced with a target headway setting equal to that of the average headway of human, non-supported, drivers. Another expectation is the more uniform behaviour with AICC, leading in less differences between the headways maintained by supported drivers.

Thus, the minimum average gap distance per lane between the situation with 0% AICC-equipped vehicles and 100% penetration of AICC vehicles is expected to change. We analysed the changes with a comparison of the reference situation without AICC and full penetration of the Normal AICC. The distributions in figures 8.4 and 8.5 represent the reference scenario headway distribution and the headway distribution of the Normal AICC at 1.2 s headway setting at full penetration, respectively. The distributions have been established using microscopic data collected at the downstream detector of the two-lane main line and cover 2.5 hours of simulation.

A comparison of figures 8.4 and 8.5 shows the differences in the headway distributions (in the range from zero to three seconds). A reduction of variation is not found when we compare the coefficient of variation of the distributions. But when we compare the headway distributions, it is clearly that full penetration of the Normal AICC leads to a more uniform
and safer car-following behaviour, with on the left lane about 90% of the headways between 1.0 and 1.25 seconds, and only a negligible proportion of drivers with headways below 1.0 s. In the reference case, the proportion of headways below 1.0 s is 22%.

The average gap distance is nearly the same in both scenario’s, about 1.2 s.

![Figure 8.4 Headway distribution at downstream detector (reference case)](image)

![Figure 8.5 Headway distribution at downstream detector (100% Normal AICC at 1.2 s headway)](image)

Table 8.1 shows for a sample of AICC systems a selection of findings from the simulation experiments for the situation with fifty percent AICC penetration.

The main line capacity $Q_v$ in column (1) is differentiated per lane in columns (2) and (4). The lane utilisation is calculated as percentage of the capacity flow in columns (3) and (5). The sixth column gives the speed at queue discharge capacity $U_v$, while the lane speeds are given in columns (7) and (8). The critical density of the main line is shown in column (9). The critical density for the motorway is calculated from $k_c = Q_v / U_v$, thus column (1) divided by column (6). The critical densities estimated for the different AICC scenarios are
compared to the critical density in the reference case and shown in column (10). The last column (11) shows the average headway at capacity. This value includes the vehicle length, which is about 0.2 s headway for passenger cars at capacity speeds.

<table>
<thead>
<tr>
<th></th>
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<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
</tr>
<tr>
<td>Reference</td>
<td>4285</td>
<td>2290</td>
<td>53.4</td>
<td>1995</td>
<td>46.6</td>
<td>85.5</td>
<td>85.5</td>
</tr>
<tr>
<td>Normal 1.0</td>
<td>4458</td>
<td>2563</td>
<td>57.4</td>
<td>1895</td>
<td>42.6</td>
<td>86.7</td>
<td>87</td>
</tr>
<tr>
<td>Normal 1.2</td>
<td>4350</td>
<td>2413</td>
<td>55.5</td>
<td>1937</td>
<td>44.5</td>
<td>87.8</td>
<td>88.1</td>
</tr>
<tr>
<td>Extended 0.8</td>
<td>4428</td>
<td>2668</td>
<td>60.3</td>
<td>1760</td>
<td>39.7</td>
<td>90.5</td>
<td>91.6</td>
</tr>
<tr>
<td>Extended 1.0</td>
<td>4467</td>
<td>2588</td>
<td>57.9</td>
<td>1879</td>
<td>42.1</td>
<td>88.2</td>
<td>88.8</td>
</tr>
<tr>
<td>Complete 0.8</td>
<td>4703</td>
<td>2788</td>
<td>59.3</td>
<td>1915</td>
<td>40.7</td>
<td>89.8</td>
<td>90.1</td>
</tr>
<tr>
<td>Complete 1.2</td>
<td>4377</td>
<td>2426</td>
<td>55.4</td>
<td>1951</td>
<td>44.6</td>
<td>85.9</td>
<td>85.9</td>
</tr>
</tbody>
</table>

TABLE 8.1 Motorway capacity, capacities per lane, speed at capacity, and critical density estimated for scenarios with two-lane motorway with an on-ramp bottleneck (50% AICC penetration)

From table 8.1, it can be seen that the utilisation of the left lane increases significantly when AICC equipped vehicles replace today’s vehicle fleet. In all AICC scenarios, the left lane capacity increases. With 50% penetration of the Complete AICC at 0.8 s, the left lane capacity growth is 21% (from 2290 to 2788 veh/h, column 2), whereas the overall capacity change is estimated at 9% relative to the reference case (from 4285 to 4703 veh/h, column 1). Also noticeable in table 8.1 is the trend that the right lane is used in both absolute and relative terms by less drivers. The right lane capacity value decreases with AICC. Nevertheless, the overall capacity increases for the shown AICC scenarios.

![Graph showing queue discharge speeds at two-lane motorway for sample of AICC systems](image-url)

FIGURE 8.6 Queue discharge speeds at two-lane motorway for sample of AICC systems
Chapter 8 - Traffic Flow Impacts of Autonomous Intelligent Cruise Control Concepts

With respect to speed changes, we conclude that AICC introduction increases the speed at capacity. The speed at capacity (or more correctly: the average queue discharge speed), measured downstream the bottleneck, appears to increase substantially (between 3 and 10%) when AICC’s are introduced, see figure 8.6. The largest speed change (about 10%) is found with the Extended AICC at 0.8 s. Such a speed increase is observed for all AICC concepts, except the Normal AICC at 1.4 s headway setting. The increase is expected due to smaller headways and efficient car-following behaviour as hypothesised in section 4.2. Although not shown, it should also be remarked that the queue discharge speed is somewhat lower than the speed at pre-queue capacity.

In conclusion, the overall capacity increase with the AICC systems can be explained by two factors:
- left and right lane speeds increase;
- an increase of the critical density on the left lane.

This last aspect needs a further elaboration. Compared to the reference critical density, there are two scenarios in which the critical density decreases (Normal 1.2 s and Extended 0.8 s). Further inspection shows that the critical density of the left lane increases, but that the critical density of the right lane decreases. This characteristic is observed for the other scenarios as well, but the overall critical density of the two lanes increased compared to the reference case. We presume that the density increase of the left lane is caused by AICC functional characteristics (e.g., small headway settings, small time delays, quick acceleration responses) which induce higher capacity speeds and herewith contributes to the overall motorway capacity enlargements downstream the on-ramp (see fig. 8.2).

The lower maximum flow rates at the right lane, which are observed with AICC systems, are explained by:
- an overall lane speed increase;
- rise of speed differences between left and right lane, leading to an increased attractiveness of the left lane.

The latter factor appears to be essential in the two-lane motorway case, because at the right lane of a three-lane motorway a decrease of maximum flow rates has not been observed. However, an increase is not observed either (see section 8.3.1).

It appears that the overall motorway capacity raises predominantly due to the increased capacity speed and to a lesser extent due to a higher critical density on the left lane. The impact of the decreased critical density on the right lane (caused by speed differences between the lanes which augment left lane attractiveness) is compensated fully by the left lane density increase. The estimated capacity values for the AICC scenarios, and the relation with the penetration rate are described in the sequel of this subsection. First, the lane utilisation by user classes is described and analysed, in order to explain possible differences in lane density caused by specific user classes.

The user class distribution over the lanes (at capacity flows) is shown in figures 8.7 and 8.8 for the Normal AICC at 1.0 s headway and the Complete AICC at 0.8 s headway, respectively. Both cases are analysed at fifty percent AICC-penetration rate, whereas the user class proportions are determined over the queue discharge period at the downstream detector. The graphs are similar with respect to the division of user classes per lane. On the left lane, nearly fifty percent of the vehicles is equipped. On the right lane this percentage
is approximately 42% for both passenger car user classes. The truck percentage on the right lane is about 18%, while on the left lane only 2% trucks are observed.

From these findings, we may conclude that there is no difference in lane utilisation by a specific user class. Apparently, the deployment of AICC does not lead to a larger proportion of these vehicles on the left lane in the queue discharge state of the motorway.

![Figure 8.7 User class distribution at queue discharge capacity (50% penetration of Normal AICC 1.0 s)](image)

![Figure 8.8 User class distribution at queue discharge capacity on two-lane motorway (50% penetration rate of Complete AICC 0.8 s)](image)

To illustrate the changes in the lane utilisation as function of time we show some time series. Figures 8.9 and 8.10 depict the left lane utilisation (as percentage of the total flow) for the Normal AICC at 1.0 s headway and Complete AICC at 0.8 s headway respectively. In the figures, the left-lane utilisation is shown as function of the simulation time. For convenience, the utilisation in the reference case is also shown. Notice the change in lane distribution as traffic breaks down at about 75 minutes after the simulation started. The left lane utilisation drops from 60% to 53% on average (see table 8.1). Thus, queue discharge flows are quite balanced over the two lanes. This is caused by the increase in headways drivers maintain in congested flow conditions, which has been modelled for non-supported driving (see section 7.3.2). This behavioural adaptation to the actual traffic condition reduces the maximum flows, especially on the left lane of a motorway, additionally, it limits the attainable lane
speeds compared to the pre-queue flow state.

FIGURE 8.9 Left lane utilisation in two-lane case (Normal AICC 1.0 s)

In contrast, it appears that the Normal AICC makes the lane distribution less balanced after traffic breaks down (approximately at t=75 min). Thus, there seems no difference in pre-queue and queue discharge lane distribution. This can be explained by AICC driving behaviour which does not include an increased desired gap distance in congested conditions. At 50% AICC equipment penetration in the vehicle fleet, the impact is already observable and at full penetration it is clearly that the left lane is used by about 60% of all vehicles.

FIGURE 8.10 Left lane utilisation in two-lane case (Complete AICC 0.8)

For the case of the Complete AICC at 0.8 s headway, similar behaviour is observed. Figure 8.10 shows that the left lane is used by more than 60% of the vehicles before and after traffic breaks down in the scenario with full penetration of the Complete AICC at 0.8 s. We found an overall capacity gain with the deployment of this AICC (see table 8.1) and recall our
conclusion that the left lane contributes to a large extent to the observed gains. These findings indicate that the introduction of AICC on two-lane motorways with bottlenecks gives a less balanced distribution of maximum flows comparable to the pre-queue flow state with non-supported traffic participants. The capacity drop phenomenon is not found in the AICC scenarios at full penetration. The left lane will be used more intensively, while the utilisation of the right lane decreases. This shift is explainable by the increased speed at capacity, while drivers' motivations to change lanes to the right lane diminish as the left lane speed increases. Trucks on the right lane have a maximum speed of about 85 km/h, whereas the AICC scenarios show capacity speeds considerably above this value (see figure 8.6 and table 8.1).

We will now summarize the results of the capacity impact assessment of the two-lane motorway with on-ramp for the different AICC scenarios.

**Normal AICC with different headway settings**
The Normal AICC is the expected system design as it will be introduced around the year 2000. It has limited braking capabilities, a limited speed range (30 - 150 km/h), while it must be reactivated manually after manual intervention. Results of the capacity estimation are presented in figure 8.11 in absolute values. Figure 8.12 gives the capacity changes relative to the reference situation, in which no equipped vehicles are present.

![FIGURE 8.11 Capacity values estimated for Normal AICC with different headway settings](image)

Clearly, at 10% AICC-equipment rate, the tested concepts do not offer significant capacity improvements nor deteriorations. At this vehicle fleet composition, capacity values for the tested concepts differ less than 0.5% from the reference capacity of 4,285 veh/h. This may be explained by hypothesizing that driver behaviour of only the fraction of equipped vehicles is changed while this fraction does not affect the driver behaviour of the other vehicles in the flow. If this is true (i.e., there is no interaction between equipped and non-equipped vehicles), then the observable changes in capacity will only be marginal at small equipment penetration rates, regardless of the AICC system specifications.
Focussing on the Normal AICC at 1.0 s headway, an increasing road capacity is observed as the penetration rate in the vehicle fleet grows. However, there is no further growth beyond 50% penetration in the vehicle fleet. The same is observed for the Normal AICC at 1.2 s headway. The on-ramp traffic flow, responsible for the traffic breakdown, apparently limits the throughput of the two-lane main line traffic such that at large AICC penetration rates no additional capacity gains are possible. One could state that the longitudinal capacity is restricted by the merging processes. The maximum positive impact on capacity is about 4% with the 1.0 s headway setting.

The insignificant capacity changes of the Normal AICC at 1.2 s can be explained by the fact that current driver behaviour is already characterised by an average headway of approximately 1.2 s in capacity conditions. Although an AICC operates differently from a human driver, and these characteristics also may affect the traffic flow, the average maintained headway is to a large extent responsible for the achieved capacity level, see section 4.3.2. In addition, the model simplifications with respect to human driver behaviour (such as omitting errors in drivers’ driving task execution) contribute to underestimation of the advantages of AICC. Especially the positive impact of more uniform behaviour is restrictively taken into account; the behaviour of non-supported drivers is already more or less uniform.

The Normal AICC concept with a headway setting at 1.4 s seems to deteriorate road capacity a little, but only after a large proportion of the vehicle fleet is equipped with the device (figure 8.4). We expect a small capacity loss due to the relatively large headway setting in this concept. Our hypothesis seems to be true according to our simulation results, although only at full penetration in the vehicle fleet a small significant capacity decrease of -1.5% is found.

Comparison of our results with findings reported in the literature is not possible since combinations of such a bottleneck with the tested AICC systems are not studied in the past. Let us recall some values found for uniform stretches. BROQUA et al. (1991) mention a capacity gain of 13% with an AICC system at 1.0 s headway at 40% penetration. REITER
(1994) estimated a capacity gain of 15% with the 1.0 s AICC system at full penetration. With our maximum gain of about 4%, we have a much lower estimate, likely due to the application of a bottleneck instead of a uniform section in our simulation study.

Furthermore, Reiter (1994) predicted a capacity loss of 11% with a 1.5 s AICC system. According to our analyses no important capacity decrease is expected with the comparable Normal AICC at a headway setting of 1.4 s. Capacity values estimated for a uniform section are apparently quite different compared to a bottleneck section. Other explanations for the observed differences in capacity values are the differences in AICC operation, and the appropriateness of the capacity estimation procedures. For example, in the reported studies it is unclear if drivers can intervene in the applied AICC concepts as is in the case in our AICC concepts.

**AICC systems with equal headway setting at 1.2 s**

In order to study differences of capacity impacts between AICC designs, five AICC system specifications are compared on the basis of the 1.2 s headway setting. The headway at 1.2 s has been selected since it is the average preferred headway of drivers on motorways as can be concluded from several empirical studies (see e.g., Fancher et al., 1996 and Dijkers, 1997a). Figure 8.13 shows the estimated absolute capacity values, while figure 8.14 depicts the capacity changes relative to the reference.

The resulting capacity changes, from 0% to full penetration in the vehicle fleet, indicate only small changes in roadway capacity. Most of the values do not significantly differ from the reference value. Except the Complete AICC at 50% penetration level, which indicates a capacity gain of 2%. However, at the 100% penetration level, the gain is not observed anymore. Furthermore, it seems that the Queue AICC has a negative impact on road capacity. At full penetration, the capacity decreases nearly 2%.

![Figure 8.13 Capacity values estimated for AICC systems at 1.2 s headway](image)

In conclusion, AICC designs with a net time headway setting at 1.2 will hardly affect roadway capacity, most likely because the selected headway equals the average headway.
that drivers prefer under capacity conditions. This is in line with our expectations, since the alert and responsive behaviour of AICC devices should increase capacity theoretically (section 4.2). The simplifications made in human driver modelling is the explaining factor for the small differences found between supported and non-supported driving with the same average target headway.

To support the capacity analyses, we established speed-flow relationships for a sample of AICC scenarios, shown in Appendix C. The speed-flow relationships are determined at the downstream detector, so no congested branches are observable. We found that the speed-flow diagrams show no clear distinction between pre-queue and queue discharge capacities at full penetration rate. However, at 20% AICC penetration clear differences are observable, comparable with the reference case. Maximum flow rates and speeds in the pre-queue state are higher than in the queue-discharge state (capacity drop).

In the literature no capacity values for AICC designs at 1.2 s headway have been reported. The disappearance of the capacity drop with AICC introduction on a large scale has not been found in other studies either.

![Graph showing speed-flow relationships for AICC scenarios](image)

**FIGURE 8.14** Capacity changes relative to the reference case estimated for AICC systems at 1.2 s headway

**Remaining AICC systems**

In order to complete the overview of the simulation, the results for another sample of tested AICC concepts is shown in figure 8.15. Special attention should be given to the trends of the Complete AICC and Extended AICC at 0.8 s headway. It appears that a steady growing road capacity is expected when the Complete and Extended AICC systems are replacing the current vehicle fleet. Eventually, a capacity gain of approximately 7% is possible with the ‘Extended’ and even a change of 12% with the sophisticated ‘Complete AICC’. Furthermore, this AICC design shows even at intermediate penetration rates significant capacity gains.

Evidently, the small headway setting at 0.8 s contributes to the observed capacity gains. However, the differences between the gains of the ‘Complete’ and ‘Extended’ must be explained by the other design parameters of the assistance systems. Since the Extended
AICC does not support all speeds, it is necessary for drivers to take over control when they encounter low speeds, i.e., congested conditions (see also section 8.2.3 where the intervention actions are reported). In our scenario, the drivers will meet congested conditions upstream the on-ramp, and should control the car manually. This will reduce the throughput compared with the Complete AICC with full speed support (and full deceleration support).

![Graph showing capacity changes relative to the reference case estimated for remaining AICC systems.](image)

**FIGURE 8.15** Capacity changes relative to the reference case estimated for remaining AICC systems

The capacity decrease for two systems (Complete AICC 1.2 s and Extended AICC 1.0 s), and the reduced capacity growth for the other AICC systems (see figure 8.15), after the penetration exceeds 50% is difficult to explain. We refer to table 8.1 in which the lane distribution is shown for the same sample of AICC systems. It appears that the left lane maximum flow increases while the right lane utilisation decreases. We hypothesise that the increasing capacity speed with larger penetration rates is responsible for this shift. At first, the overall motorway capacity gains from this development. However, the speed increase resulting from large scale AICC deployment eventually leads to a cut back in the capacity growth as the attractiveness of using the right lane decreases.

The impact of the AICC-deceleration authority could not be analysed satisfactorily with the followed experimental setup. Further research should include an AICC version that combines the Complete AICC full deceleration support and the Extended AICC partial speed support in order to investigate the impact of the deceleration variable on capacity.

Table 8.2 displays the total number of vehicles that passed the downstream detector of the considered motorway segment given identical demand upstream. The numbers can be used as a measure of performance. The higher the values, the higher the throughput. Disadvantage of this performance indicator compared to the queue discharge capacity value, is the dependency of the indicator values of the simulation time, roadway length and traffic demand input. For example, if a simulation time of 2 hours is specified instead of 2.5 hours, while the other conditions are equal, lower indicator values will be found. The values in table 8.2 can therefore preferably be applied for a relative comparison of the different scenarios.
<table>
<thead>
<tr>
<th>Penetration %</th>
<th>10</th>
<th>20</th>
<th>50</th>
<th>100</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference</td>
<td>9667</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Normal 1.0</td>
<td>9633</td>
<td>9766</td>
<td>10067</td>
<td>9970</td>
</tr>
<tr>
<td>Normal 1.2</td>
<td>9636</td>
<td>9691</td>
<td>9798</td>
<td>9757</td>
</tr>
<tr>
<td>Normal 1.4</td>
<td>9513</td>
<td>9693</td>
<td>9669</td>
<td>9639</td>
</tr>
<tr>
<td>Extended 0.8</td>
<td>9807</td>
<td>9857</td>
<td>10006</td>
<td>10141</td>
</tr>
<tr>
<td>Extended 1.0</td>
<td>9752</td>
<td>9780</td>
<td>9937</td>
<td>9838</td>
</tr>
<tr>
<td>Extended 1.2</td>
<td>9738</td>
<td>9799</td>
<td>9789</td>
<td>9815</td>
</tr>
<tr>
<td>Queue 1.2</td>
<td>9712</td>
<td>9735</td>
<td>9617</td>
<td>9642</td>
</tr>
<tr>
<td>All speed 1.2</td>
<td>9675</td>
<td>9799</td>
<td>9780</td>
<td>9690</td>
</tr>
<tr>
<td>Complete 0.8</td>
<td>9812</td>
<td>9989</td>
<td>10320</td>
<td>10433</td>
</tr>
<tr>
<td>Complete 1.2</td>
<td>9770</td>
<td>9701</td>
<td>9949</td>
<td>9725</td>
</tr>
</tbody>
</table>

TABLE 8.2 Number of vehicles that passed the downstream detector in scenarios with two-lane motorway with an on-ramp bottleneck. Simulation period is 2.5 hours.

From table 8.2, it is possible to calculate the relative changes compared to the reference case. The highest throughput is realized at full penetration of the Complete AICC at 0.8 s headway: an increase of 8% is found. This percentage is smaller than the estimated 12% capacity improvement for the same scenario (see fig. 8.15), what can be explained by the different observation period considered. The capacity analysis focusses on the last fifty minutes of a simulation run in which the queue discharge flow is present. On the contrary, the flow levels in table 8.2 are determined over the full simulation period, including the periods with low traffic demand at the start. We view the capacity indicator as more useful, and limit the analysis of the total vehicle numbers to a quick scan.

After having focussed the analysis on the throughput of a cross-section of the motorway we will now pay attention to the safety aspects.

8.2.2 Safety analysis

The safety assessment in the study is based on the approach described in section 4.5.3 and applied in section 6.6.3 for the reference situation. Limitation of microscopic simulation tools to assess safety aspects should be taken into consideration when one examines the safety indicator values on their meaning. Microscopic traffic simulation models simplify the traffic processes and driver behaviour compared to reality, while unsafe situations result from exceptional driver behaviour (such as reduced alertness, inadequate braking performance, state estimation errors, etc.). Our approach also suffers from this weakness, however, appears to be a better safety assessment method than inspecting headway or time-to-collision distributions collected at an imaginary cross-section of a road.

A set of safety indicators is applied expressing drivers' exposition to dangerous approaches to a lead vehicle. Dangerous approaches have been defined by a time-to-collision threshold value $TTC^*$ of 3 seconds. This $TTC$ value means that a driver has only 3 seconds to prevent a collision with his front vehicle, if speed difference and collision course remain unchanged (eq. 4.15). Lower $TTC$ values are more dangerous than higher $TTC$ values. The same holds for the safety indicator values in the safety assessment.
The summation of exposed duration to unsafe TTC values - over all vehicles - equal the aggregate safety indicator $TET^*$ (in s). A second related indicator $TET^'$ expresses the average exposition time per vehicle, making the indicator independent of the number of vehicles in a simulation (see section 6.6.3). A third related safety indicator applied in our study eliminates the dependency of the simulation time. This indicator $TETP^*$ gives the probability (in %) that a random driver encounters an unsafe time-to-collision value (in the range 0 to 3 s) during the simulation time in the simulated motorway segment.

In calculating the safety indicator $TET^*$, the total numbers of vehicles in each simulation run are used (table 8.2). In each scenario a different number of vehicles is generated in a simulation, depending on the bottleneck capacity of the scenario. This is the total number of vehicles counted at the downstream detector supplemented by the estimated number of vehicles that have not yet passed the detector after the simulation time elapsed. For the two-lane motorway case, the number of vehicles present before the downstream detector is about 300, assuming a density of 50 veh/km/lane over three kilometres length. The simulation time, used in the calculation of the third safety indicator, is 9,000 s for all scenarios. Table 8.3 shows the estimated outcomes for the three safety indicators.

<table>
<thead>
<tr>
<th>Penetration %</th>
<th>$TET^*$ [s]</th>
<th>$TET^*$ [$10^{-3}$/veh]</th>
<th>$TETP^*$ [$10^{-4}$%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference</td>
<td>19.4</td>
<td>1.9</td>
<td>2.1</td>
</tr>
<tr>
<td>Normal 1.0</td>
<td>15.4</td>
<td>27.4</td>
<td>18.2</td>
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<tr>
<td>Normal 1.2</td>
<td>23.7</td>
<td>25.6</td>
<td>21.9</td>
</tr>
<tr>
<td>Normal 1.4</td>
<td>22.5</td>
<td>25.2</td>
<td>27.1</td>
</tr>
<tr>
<td>Extended 0.8</td>
<td>17.9</td>
<td>27.9</td>
<td>31.1</td>
</tr>
<tr>
<td>Extended 1.0</td>
<td>19.3</td>
<td>19.3</td>
<td>24.5</td>
</tr>
<tr>
<td>Extended 1.2</td>
<td>21.5</td>
<td>20.8</td>
<td>27.8</td>
</tr>
<tr>
<td>Queue 1.2</td>
<td>25.5</td>
<td>23.1</td>
<td>31.2</td>
</tr>
<tr>
<td>All speed 1.2</td>
<td>20.3</td>
<td>23.1</td>
<td>23.9</td>
</tr>
<tr>
<td>Complete 0.8</td>
<td>24.2</td>
<td>22.6</td>
<td>44.2</td>
</tr>
<tr>
<td>Complete 1.2</td>
<td>20.8</td>
<td>32.2</td>
<td>27.6</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Penetration %</th>
<th>$TET^*$ [s]</th>
<th>$TET^*$ [$10^{-3}$/veh]</th>
<th>$TETP^*$ [$10^{-4}$%]</th>
</tr>
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<tr>
<td>10</td>
<td>19.4</td>
<td>1.9</td>
<td>2.1</td>
</tr>
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<td>23.7</td>
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<tr>
<td>100</td>
<td>25.5</td>
<td>23.1</td>
<td>31.2</td>
</tr>
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<td>20.3</td>
<td>23.1</td>
<td>23.9</td>
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<tr>
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<td>24.2</td>
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<td>44.2</td>
</tr>
<tr>
<td>50</td>
<td>20.8</td>
<td>32.2</td>
<td>27.6</td>
</tr>
</tbody>
</table>

TABLE 8.3 Safety indicator values of AICC systems for two-lane motorway with an on-ramp

It can be observed that for the two-lane with on-ramp configuration the $TET^*$ indicator values are comparable for most of the scenarios. For the majority of the tested system designs and penetration rates aggregate indicator values between 20 and 40 s are measured. Due to the stochastic nature of traffic flow, the indicator values are distributed with a mean and standard deviation. For the reference case, the standard deviation of the aggregate safety indicator is estimated at 4.5 s, based on five simulation runs of 2.5 hour. This implies a coefficient of variation of 23% which is quite high. One should be careful in comparing indicator values between scenarios due to the sample size of one (a single simulation run) and the large coefficient of variation.

The impact of the penetration rate on the $TET^*$ indicator is investigated by taking the average indicator value of all systems. We found an average value of 21.1, 24.4, 27.5 and
35.7 s respectively for 10%, 20%, 50%, and 100% AICC penetration (the extreme value of the Extended AICC at 100% is omitted in this calculation). Clearly, a higher penetration rate deteriorates the traffic safety if measured with our safety indicator. This is to be expected since the AICC systems show higher densities which implies smaller headways compared to the reference case. While theoretically systems operating at relatively small headways will encounter smaller time-to-collision values more often than systems operating at larger headways (assuming equal speed differences) see equation (6.1). The impact of the headway setting is obvious when we study the indicator values of the systems with 0.8 s headway setting. These values are generally higher than the values encountered with the other (higher) headway settings. Small headways have therefore a negative impact on traffic safety. The impact of other design characteristics on traffic safety are difficult to assess with the limited number of data. More simulation runs and experiments with additional AICC types are necessary to perform such an analysis.

A relatively high indicator value (74.6 s) is found for the Complete AICC (headway 0.8 s) at 100% penetration rate. However, since the Complete AICC is able to avoid rear-end collisions to a large extent due to its design (full deceleration support, full speed support) the impacts on traffic safety need not to be negative. One might state that the acceptable safety indicator threshold value of such an advanced AICC (at full penetration) may be smaller than the acceptable indicator values at intermediate penetration rates and for cases with restricted functionality systems. Instead of a threshold value of 3 seconds it would be more realistic to adopt smaller values, e.g. 2 seconds or even less. Further research is needed to determine adequate threshold values for AICC-equipped vehicles. We illustrate this with an example, assuming that we might use a $TTC^*$ threshold value of 2 seconds instead of the applied 3 seconds. For the Complete AICC at 0.8 s headway this changes the safety indicator value to 29.6 s, which is considerable smaller than the 74.6 s we calculated with the three second time-to-collision threshold value.

The most surprising finding is the $TET^*$ value for the Extended AICC at 0.8 s headway and 100% penetration rate which deviates dramatically from the other values. With a safety indicator value of 727 s the scenario seems to perform unsatisfactorily with respect to safety considerations. A more detailed analysis shows that 87% of this indicator value is found on the left lane, and 13% at the right lane. This is shown in figure 6.14 (Chapter 6).

The poor safety performance of the Extended AICC at 0.8 s can be explained by the needed driver intervention as speeds drop below the minimum supported speed of 30 km/h. When the drivers intervene they will manually adapt their desired gap distance which is larger than the 0.8 s headway setting. This expansion of car-following headways, simultaneously performed by a number of drivers, resulted in dangerous shockwaves with small time-to-collision values. We will find this behaviour especially on the heavily utilised left lane, however, the right lane shows an unsafe safety indicator value also. One may conclude from these findings that a headway setting at 0.8 s for some types of assistance systems will result in critical safety indicator values. Traffic safety and stability of strings of vehicles is not ensured within an acceptable range. This phenomenon was already concluded with testing the Normal AICC at 0.8 s headway which resulted in rear-end collisions during a simulation. Therefore, this scenario has not been incorporated in the experimental setup and impact assessment.

It must also be remarked that we found a speed increase with application of most AICC systems (see fig. 8.6), as well as an increase in speed differences between lanes (see table 8.1), changes which may deteriorate traffic safety.
In summary, if expressing the longitudinal safety using classical indicators (TTC threshold value of 3 seconds) the introduction of AICC exhibits a deterioration of safety. However, a fair comparison of improved safety indicators is necessary that take into account the special facilities of the AICC-equipped vehicles.

8.2.3 Comfort analysis

During a simulation run of a scenario the number of assistance system driver interactions - voluntary overrule actions and required interventions - has been registered and categorised by their reason. Since driver intervention can be seen as comfort indicator, we will give some attention to this aspect. We will not go into depth in this subject since it is not our main objective, but give some illustrative examples and comments.

Figure 8.16 shows for the Normal AICC at 100% penetration rate the average number of interventions per vehicle, classified by reasons for driver intervention. The average values are based on a simulation time of 2.5 hours.

The total number of interventions per vehicle is 5.1. Taking into account the length of the motorway segment (which is 5 km), the average number of interventions per vehicle per kilometre is about 1. Main reason for taking over control is the lower speed boundary. In the simulation, this lower speed is reached by all vehicles during congestion at the bottleneck, so the AICC must be deactivated here. The other reasons for overruling the system, such as reaching the deceleration or acceleration limits are less frequently observed.

Second important reason why driver make interventions is because they adapt their speed to the left lane speed. This is a legislation aspect combined with drivers' considerations for safe driving under heavy traffic conditions. The SIMONE model uses the speed adaptation to create larger gap distances on the right lanes of a motorway. We assumed that all drivers will reactivate their system if the traffic situation met the defined conditions. In the simulation model, drivers are not able to switch their system off.

For smaller penetration rates the total number of interventions are smaller, but the interventions per vehicle are similar to those in figure 8.16. We should remark that for
automatic reactivation AICC systems the results are not comparable due to the system layout, since the 'overrule' system interaction is counted each time the driver controls the vehicle manually, leading to unusable large interaction values. We also analysed the dependency with the headway setting. It is found that both a smaller headway setting (1.0 s) and a larger headway setting (1.4 s) of the Normal AICC design increases the number of interventions slightly. Apparently, the 1.2 s headway setting is most likely to be accepted by the public. This conclusion follows partly from the modelled human driver with a preferred headway of 1.2 s on average.

In literature, intervention values are reported focussing on uniform stretches (Benz, 1996) and low traffic densities. These intervention rates cannot be compared with our values. However, the dependency of the intervention frequency on the headway setting appears to be in agreement with our findings. A headway setting of 1.2 s results in the smallest number of interventions.

8.3 On-ramp to a three-lane motorway

We expect different processes at three or more lane motorway junctions. For the three lane case we expect to see larger capacity gains than observed at the two-lane motorway with on-ramp, due to a more balanced speed distribution among and within the lanes and the potential of AICC to increase lane capacity in case of undisturbed flows (see section 4.3.4). It should be reminded that trucks and drivers with low desired speed preferences will be found more frequently on the most right lane. In addition, an important difference between the United States and European traffic regulation is the prohibition to pass vehicles on the right-side lane in free flow conditions. The European regulation is adopted. The capacity analysis follows the same structure as in section 8.2.

![Road geometry of two-lane main line with on-ramp](image)

**FIGURE 8.17** Road geometry of two-lane main line with on-ramp

8.3.1 Capacity analysis

We start our capacity analysis of the three-lane motorway case with an overview of the speed changes. It is found that the critical speeds are more or less equal to the reference case at penetration rates below 50% (see figure 8.18). From the speed-flow diagrams (Appendix C) it is also observed that speeds at the pre-queue state are somewhat higher. This holds especially for scenario’s with low penetration rates. When penetration rates are high, drivers’ car-following behaviours are predominantly determined by the AICC systems which
- contrary to human drivers - do not enlarge gap distances after having met congested conditions (see section 7.3.2). This behaviour of AICC systems explains the disappearing of the capacity drop to a large extent.

![Graph showing speed vs. equipment penetration rate for different AICC systems.](image)

**FIGURE 8.18 Queue discharge speed at three-lane motorway for sample of AICC systems.**

It is also interesting to look at the speeds per lane, as one of the explaining factors for a capacity change. This analysis has been conducted and shown in table 8.4.

Table 8.4 gives an overview of capacity (column 1), capacity per lane (columns 2 to 7), speed at capacity (column 8) and critical density (column 9) for a sample of AICC-concepts at 50% penetration.

<table>
<thead>
<tr>
<th></th>
<th>Capacity [veh/h]</th>
<th>Left lane [veh/h] [%]</th>
<th>Centre lane [veh/h] [%]</th>
<th>Right lane [veh/h] [%]</th>
<th>Speed all (left/centre/right) [km/h]</th>
<th>Critical density [veh/km]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>83.8 (82.7/83.6/86.4)</td>
<td>74 ref</td>
</tr>
<tr>
<td>Reference</td>
<td>6170</td>
<td>2289</td>
<td>37</td>
<td>2141</td>
<td>34.7 1740</td>
<td>28</td>
</tr>
<tr>
<td>Normal 1.0</td>
<td>6596</td>
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<td>34.6 1706</td>
<td>26</td>
</tr>
<tr>
<td></td>
<td>6456</td>
<td>2432</td>
<td>38</td>
<td>2250</td>
<td>34.8 1774</td>
<td>28</td>
</tr>
<tr>
<td>Normal 1.2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>83.1 (82.7/82.6/84.4)</td>
<td>78 6.3%</td>
</tr>
<tr>
<td>Extended 0.8</td>
<td>6870</td>
<td>2816</td>
<td>40</td>
<td>2346</td>
<td>34.1 1708</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>85.1 (83.8/85.3/87.1)</td>
<td>81 9.6%</td>
</tr>
<tr>
<td>Extended 1.0</td>
<td>6702</td>
<td>2617</td>
<td>39</td>
<td>2303</td>
<td>34.4 1782</td>
<td>27</td>
</tr>
<tr>
<td></td>
<td></td>
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<td></td>
<td></td>
<td>85.5 (84.6/85.7/86.4)</td>
<td>78 6.5%</td>
</tr>
<tr>
<td>Complete 0.8</td>
<td>7144</td>
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<td>35.1 1845</td>
<td>26</td>
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<td>82.9 (81.8/82.9/84.6)</td>
<td>86 17.1%</td>
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<td></td>
<td></td>
<td>83.0 (81.3/83.1/85.2)</td>
<td>77 5.2%</td>
</tr>
</tbody>
</table>

**TABLE 8.4 Motorway capacity, capacities per lane, speed at capacity, and critical density estimated for scenarios with three-lane motorway with an on-ramp bottleneck.**

From table 8.4 it appears that the overall speed of the main line increases hardly with AICC-introduction at 50% penetration. With respect to differences in speeds per lane, we found negligible speed differences (with lowest average speed at the left lane in all scenarios in the queue discharge state). The right lane has the highest average speed in all scenarios. These findings are contrary to those found for a two-lane motorway case. We speculate that
left lane changes are performed during short periods with relatively higher left lane speeds (while the average speeds are based on 5-minute intervals). Since a large proportion of the drivers drive at speeds below their desired speed, only a short moment of a higher left lane speed is sufficient to initiate a lane change to a left lane (see also the lane-change conditions described in section 7.3.6). However, for making a right-lane change decision other aspects are taken into account as well (see section 7.3.7 for right lane change conditions). The overall effect of the lane change decisions of the drivers in the queue discharge state are the speed and lane use distribution as observed and shown in table 8.4.

The difference between the two-lane and three-lane case is that drivers at a two-lane motorway are more constrained and use the right lane more intensively (to illustrate this we compare the right lane maximum flow of three-lane reference case, 1740 veh/h, to the maximum flow rate of the two-lane reference case, 1995 veh/h).

In column (9), the critical densities are shown for the three-lane main line. The relative change compared to the reference critical density is shown in column (10), from which it is seen that the critical density increases substantially with AICC scenarios. This means that the average gap distance between the vehicles on the three-lane motorway decreases in the queue discharge state. The density increases are much higher compared to the two-lane case (table 8.1).

It is observed in columns (2) and (3) that the left lane capacity increases dramatically compared to the reference case. A smaller increase is observed for the centre lane. The average maximum flow rate at the right lane is lower than found for the two-lane case, which has been explained above. But it appears that the maximum flow rate of the right lane is not affected by introducing AICC. However, when we look at the lane distribution (column 7) the right lane utilisation decreases with AICC. The overall motorway capacity increases with AICC-introduction at 50% penetration (see column 1), which is predominantly caused by the density increase.

![Figure 8.19 User class distribution over lanes (50% Normal AICC 1.0 s)](image-url)

Figure 8.19 shows the user class distribution of the three-lane motorway, based on the queue discharge measurements downstream the bottleneck. There seems no significant difference between vehicles with and without Normal AICC system with respect to lane utilisation. The truck percentage on the right lane is about 16%, on the centre lane about
5%, and on the left lane less than 1%.

Figure 8.20 gives the user class distribution for the scenario with 50% penetration of the Complete AICC at 0.8 s headway. The results are similar to those of figure 8.19.

Figure 8.21 shows the left-lane utilisation on the three-lane motorway for the Normal AICC 1.0 s headway at 50% and 100% penetration downstream the on-ramp. The reference time series show a distinct drop at about 80 minutes of simulation. About 40% of the traffic uses the left lane in capacity conditions. With the Normal AICC, the drop in the left lane utilisation disappears after a short period of lower flows. Then, the queue discharge lane distribution is similar to the lane distribution before congestion started. At 100% AICC penetration rate, the left lane utilisation is about 45%.

The same characteristics can be seen with the Complete AICC at 0.8 s (figure 8.22). At 100% AICC penetration rate, the left-lane utilisation fluctuates around 45%.
Table 8.5 presents the total number of vehicles that passed the downstream detector in a simulation of a specific scenario of the three-lane case. As can be observed in table 8.5, the highest throughput value is found for the scenario with the highest estimated capacity gain (the Complete AICC at 0.8 s headway) as will be shown in the sequel. The indicator values are in agreement with the estimated capacity values for the scenarios.

<table>
<thead>
<tr>
<th>Penetration %</th>
<th>10</th>
<th>20</th>
<th>50</th>
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<td></td>
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<td>Normal 1.0</td>
<td>15002</td>
<td>15027</td>
<td>15252</td>
<td>15554</td>
</tr>
<tr>
<td>Normal 1.2</td>
<td>14894</td>
<td>14794</td>
<td>15179</td>
<td>15088</td>
</tr>
<tr>
<td>Normal 1.4</td>
<td>14735</td>
<td>14998</td>
<td>14636</td>
<td>14639</td>
</tr>
<tr>
<td>Extended 0.8</td>
<td>15071</td>
<td>15220</td>
<td>15853</td>
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</tr>
<tr>
<td>Extended 1.0</td>
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<td>15513</td>
<td>15712</td>
</tr>
<tr>
<td>Extended 1.2</td>
<td>14901</td>
<td>14874</td>
<td>15084</td>
<td>15250</td>
</tr>
<tr>
<td>Queue 1.2</td>
<td>15006</td>
<td>15012</td>
<td>15038</td>
<td>14998</td>
</tr>
<tr>
<td>All speed 1.2</td>
<td>14762</td>
<td>14838</td>
<td>14997</td>
<td>15254</td>
</tr>
<tr>
<td>Complete 0.8</td>
<td>15210</td>
<td>15402</td>
<td>16000</td>
<td>16899</td>
</tr>
<tr>
<td>Complete 1.2</td>
<td>14872</td>
<td>15050</td>
<td>15097</td>
<td>15435</td>
</tr>
</tbody>
</table>

**TABLE 8.5 Number of vehicles that passed the downstream detector in scenarios with three-lane motorway with an on-ramp bottleneck. Simulation period is 2.5 hours.**

In summary, the expected capacity improvements with AICC at a three-lane motorway are mainly explained by the decreased average gap distance of drivers in capacity conditions. This means larger critical densities. Speeds per lane differ slightly, and remain different after AICC-introduction. The queue discharge speed increases considerably for penetration rates between 50% and full penetration, in particular for AICC systems at headways below 1.2
s. This also contributes to higher capacity values at high AICC-penetration rates for the various AICC scenarios. This is shown in the following overview of the capacity value estimates.

**Normal AICC with different headway settings**

Figure 8.23 shows the relation between capacity and equipment rates found for the Normal AICC with headway settings at 1.0 s, 1.2 s and 1.4 s. Figure 8.24 depicts the estimated relative capacity changes. It can easily be concluded from the figures that for a three-lane motorway with an on-ramp, the capacity impact of the 1.0 s version is considerable. The capacity gain grows from approximately 2% at 10 percent equipment rate towards 7% at full penetration in the vehicle fleet.

![Diagram showing capacity values estimated for Normal AICC with different headway settings](image)

The Normal AICC at 1.2 s headway results also in positive capacity changes, although less than has been observed with the 1.0 s version. The 1.4 s version shows no significant positive or negative changes in road capacity of the bottleneck. The observed capacity gains are larger than found at the two-lane motorway bottleneck. This can be explained by the additional third lane in this scenario. At the two-lane motorway case we found an increased utilisation of the left lane. For the three-lane case we expect that such an improvement will be located at both the left and centre lane (see table 8.4). The right lane is relatively unattractive due to the presence of trucks with a maximum speed of about 85 km/h.
Possibly, a four-lane motorway with a bottleneck will exhibit even larger capacity gains since three lanes can operate without direct influence of the trucks on the right lane.

**AICC systems with equal headway setting at 1.2 s**

A comparison of estimated capacity values at the 1.2 s setting of the five tested AICC designs is depicted in figure 8.25. Relative changes are shown in figure 8.26. In contrast to the findings of the two-lane motorway bottleneck, the different AICC designs do now affect
road capacity at the three-lane bottleneck more clearly.

At 10% and 20% equipment penetration rates, the observed capacity gains are only not, or only slightly significant. All tested designs show an increase in capacity from 20% to full penetration in the vehicle fleet. Introduction of the most expensive design, Complete AICC will result in a capacity improvement of more than 7% when all vehicles are equipped with this system. The other AICC designs lead to a 4% capacity gain at full penetration, except the Queue AICC which will hardly improve road capacity.

In the figure, systems with equal headway settings are compared, and there are some differences in the estimated capacity values. Obviously, other design parameters than the headway setting affect the expected capacity improvement as well. For example, the difference between ‘Manual reactivation’ and ‘Automatic reactivation’ can be seen by comparing the Normal AICC with the Extended AICC. We observe that there is hardly a difference in capacity, but we presume that driver comfort with the ‘Automatic reactivation’ of the Extended AICC is much higher.

![Figure 8.26 Capacity changes relative to the reference case estimated for AICC systems at 1.2 s headway setting](image)

The Queue AICC shows the lowest performance. This is probably caused by the fact that the system does not support the longitudinal control at speeds above 60 km/h. However, the system may have a positive impact on queue length.

The most advanced and expensive design, the Complete AICC, exhibits the best performance, which is caused by the provided full functionality, such as supporting the full speed range (system had not to be overruled at low speeds) and full acceleration range (system had not to be overruled in case of heavy decelerations), in contrast to the other systems. The limited performance of the quite expensive All speed AICC, also supporting the full speed range, is due to the needed driver intervention as traffic breakdowns and manually controlled decelerations are needed to maintain a safe car-following distance.

**Remaining AICC systems**

Figure 8.27 gives an overview of all capacity changes derived for the remaining AICC
concepts tested. The highest capacity gain can be achieved with the Complete AICC applying a 0.8 s headway setting. An improvement up to 25% has been observed in the simulation (with 100% AICC equipment rate). The All speed AICC at the 0.8 s headway setting resulted in a substantial 15% gain at full penetration in the vehicle fleet.

The queue discharge speed at the downstream cross-section is depicted in figure 8.22 for a sample of AICC concepts. Surprisingly, the speed at capacity decreases with the Complete AICC at 1.2 s, whereas for the other systems an increase is observed.

In literature, comparable capacity values for a three-lane motorway with bottleneck have not been found, except the case of a lane drop (Van Arendonk et al., 1997).

![Figure 8.27 Capacity changes relative to reference case estimated for remaining AICC systems](image)

To explain the capacity gains observed, we refer to the analysis made in the introduction of this section.

### 8.3.2 Safety analysis

Table 8.6 gives the \( TET^* \) values, average \( \bar{TET}^* \) values per vehicle, and the probability indicator \( TETP^* \) giving the percentage of time a vehicle experiences TTC-values below the threshold value of 3 seconds. The number of vehicles involved per scenario is given in table 8.5 supplemented by 450 vehicles in order to take account of the vehicles that have not yet reached the downstream detector at the end of a simulation.

It appears that the three-lane motorway with on-ramp is on average safer than the two-lane with on-ramp. This can be observed by comparing the average vehicle indicator values in table 8.6 with the values in table 8.3. For the three-lane case, the values are smaller. The conclusion that three-lane motorways are safer than two-lane motorways corresponds to empirical safety indicator values observed in practice (see table 4.2) and can be explained by a more balanced speed distribution among and in the lanes.
TABLE 8.6 Safety indicator values of AICC systems for three-lane motorway with an on-ramp

Again, some exceptions exist. The Complete AICC at 0.8 s and 100% penetration shows a value of 72 s, which is much larger than the majority of the values. The most extreme value is realized with the Extended AICC at 0.8 s and 100% penetration. A value of 1477 s indicates extreme exposition to safety-critical approach situations whereas the system design seems inappropriate.

The impact of the penetration rate on the motorway unsafety is found for the three-lane motorway also. At higher penetration rates, higher indicator values are calculated on average for all scenarios. This aspect is related with the impact of the headway setting on the unsafety. Small headway settings show the least motorway safety indicator values. With respect to speed changes, the three-lane case showed a substantial average speed increase, which can be interpreted as a higher safety risk. The speed differences between lanes are smaller than observed at the two-lane motorway case.

In our analyses, we did not use smaller TTC threshold values for scenarios of AICC systems with special facilities.

8.3.3 Comfort analysis

Figure 8.28 shows the overrule reasons at the three-lane motorway with on-ramp. The total number of interventions per vehicle is 7.1 during its presence on the motorway. The studied motorway segment length is 5 km, thus the average number of interventions per vehicle per kilometre on the three-lane motorway is 1.4. This is slightly higher than the value of 1 found in section 8.2.3. This is explained by the large number of interventions due to left lane speed adaptations. In addition, since the three-lane motorway has three lanes in each direction, vehicles present on the two right side lanes must take into account this legislation aspect. At a two-lane motorway, only drivers on the right-lane must consider speed adaptations in order to prevent passing on the left side. The frequency of this overrule reason is therefore about twice the frequency observed at the two-lane case.
Reaching the lower speed boundary is the second most important reason for overruling the AICC system. It is apparent that a number of the drivers intervene when they want larger accelerations than their system supports. This is also observed in the two-lane case. See further our comments in section 8.2.3.

8.4 Symmetric weaving section

Another common type of bottleneck in motorway networks are weaving sections. The estimated capacity changes at such locations, assuming introduction of AICC in the vehicle fleet, are assessed in this section. A symmetric weaving section has been chosen for our investigation (two identical two-lane main lines merge and split into two identical two-lane main lines) and applying equal weaving proportions. Figure 8.29 illustrates the bottleneck applied in the simulation. Appendix B describes the simulation input in more detail.

8.4.1 Capacity analysis

We start the analysis with a discussion of changes in speed at capacity. Figure 8.30 shows the speed at capacity. In contrast to the other tested bottleneck cases, the AICC-systems appear to have no impact on the speed at capacity at the downstream detector of the weaving section. Firstly, because the measuring location is at the two downstream main lines (with a total of four lanes), which is about 1750 m downstream from the bottleneck location. Secondly, the capacity of the bottleneck restricts the flow levels that can enter the two
downstream main lines, resulting in quite large average gap distances between vehicles. This facilitates drivers’ accelerations towards their desired speed, and thus higher speeds.

![Queue discharge speed at weaving section for sample of AICC systems](image)

FIGURE 8.30 Queue discharge speed at weaving section for sample of AICC systems

Table 8.7 gives capacity values (column 1), capacity on the left and right lane of the left-side main line (columns 2 to 5), speed at capacity (columns 6 to 8), critical density (columns 9 and 10), and the average headway at capacity per lane (column 11) for a sample of AICC systems. Since the two main lines have equal characteristics, the results of only the centre main line are given.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
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</tr>
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<td>96.4 102.1 92.3</td>
<td>72.6 ref. 2.06</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Normal 1.0</td>
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<td>97.1 102.6 93</td>
<td>73.8 1.6% 2.01</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Normal 1.2</td>
<td>7098 2242 31.6 1500 21.1</td>
<td>95.9 99.6 91.4</td>
<td>74 1.9% 2.03</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Extended 0.8</td>
<td>7663 2489 32.5 1513 19.7</td>
<td>97.5 102.4 93</td>
<td>78.6 8.3% 1.88</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Extended 1.0</td>
<td>7362 2327 31.6 1452 19.7</td>
<td>96.8 101.6 93.4</td>
<td>76.1 4.8% 1.96</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Complete 0.8</td>
<td>7725 2512 32.5 1504 19.5</td>
<td>96.5 101.1 92.7</td>
<td>80.1 10.3% 1.86</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Complete 1.2</td>
<td>7094 2207 31.1 1450 20.4</td>
<td>96.7 101.4 93.1</td>
<td>73.4 1.1% 2.03</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

TABLE 8.7 Motorway capacity, capacities per lane, speed at capacity, and critical density estimated for weaving section scenarios

The speed at capacity is about equal for all scenarios (column 5), whereas the speed difference between left and right lane remains also unchanged (columns 7 and 8). The critical density increases considerable with AICC introduction (column 10). Since the motorway capacity increases with AICC (column 1), we can conclude that the density increase is responsible for the estimated capacity gains in the AICC scenarios. With respect to the
capacity increase, the lane utilisation at capacity is analysed.

We observe that the lane utilisation (see columns 3 and 5) is nearly equal for all scenarios. However, the absolute capacity values per lane differ. Systems with small headway settings have higher capacities. When we compare the reference capacity of the weaving section with the three-lane motorway, we find a considerable difference. The four-lanes downstream the weaving zone can theoretically handle more traffic, but the input is constrained by the weaving processes at the beginning of the weaving zone (beginning of weaving zone at 1750 m, see fig. 8.27). From the speed-flow diagrams (Appendix C) it is concluded that there exist a difference in the speeds just before and after the traffic breakdown for the reference case. A capacity drop is not observed clearly, but we expect that a capacity drop could be found when the detector is located closer to the beginning of the weaving section.

The downstream section of the weaving section comprises four lanes of which we analysed the flow distribution. The lane utilisation for the reference case, measured at the downstream detector and expressed as the percentage of the total flow, is shown in figure 8.31. Both left lanes carry about 30% of the traffic, both right lanes carry about 20% of the traffic flow. The lane utilisation before and after congestion has started show no differences.

![Figure 8.31 Lane utilisation (Reference situation)](image)

We also studied the lane distribution for the Normal AICC at 1.0 s and the Complete AICC at 0.8 s at 50% and 100% equipment penetration, but we found no differences with figure 8.31. The user class distribution did not deviate from the expected distribution. The vehicle fleet composition per lane, thus the proportion of equipped and non-equipped vehicles, are distributed according to the penetration rate of the scenario.

In literature there are no traffic flow impact assessments found focussing on AICC systems in combination with a weaving section bottleneck.

Table 8.8 presents the total number of vehicles that passed the downstream detector in a scenario. The maximum throughput is found with the Complete AICC 0.8 s.
The capacity estimates of the tested AICC-scenarios are presented in the following.

**Normal AICC with different headway settings**
Capacity estimation results are shown in figure 8.32. Figure 8.33 shows the capacity changes relative to the reference case. The Normal AICC at 1.0 s shows an increasing capacity with growing penetration rates. An exception in this trend is found at 20 or 50 percent equipment rate. Possibly because of the complex weaving manoeuvres which can not be supported by an AICC-system very well. At full penetration in the vehicle fleet a capacity increase of 7% has been observed.

```
<table>
<thead>
<tr>
<th>Penetration %</th>
<th>10</th>
<th>20</th>
<th>50</th>
<th>100</th>
</tr>
</thead>
<tbody>
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<td></td>
<td></td>
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<td>16544</td>
<td>16766</td>
</tr>
<tr>
<td>Normal 1.2</td>
<td>16326</td>
<td>16446</td>
<td>16195</td>
<td>16559</td>
</tr>
<tr>
<td>Normal 1.4</td>
<td>16191</td>
<td>16337</td>
<td>16231</td>
<td>16168</td>
</tr>
<tr>
<td>Extended 0.8</td>
<td>16392</td>
<td>16547</td>
<td>16726</td>
<td>17322</td>
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<tr>
<td>Extended 1.0</td>
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<td>16531</td>
<td>16798</td>
<td>17046</td>
</tr>
<tr>
<td>Extended 1.2</td>
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<td>16337</td>
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<td>16317</td>
</tr>
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<td>16317</td>
<td>16317</td>
<td>16363</td>
</tr>
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<td>16411</td>
<td>16361</td>
<td>16260</td>
</tr>
<tr>
<td>Complete 0.8</td>
<td>16434</td>
<td>16615</td>
<td>17047</td>
<td>17483</td>
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<tr>
<td>Complete 1.2</td>
<td>16214</td>
<td>16387</td>
<td>16337</td>
<td>16551</td>
</tr>
</tbody>
</table>
```

**TABLE 8.8 Number of vehicles that passed the downstream detector in scenarios with weaving section. Simulation period is 2.5 hour.**

![Graph](image)

**FIGURE 8.32 Capacity values estimated for Normal AICC with different headway settings**

The 1.2 s headway version shows some small insignificant differences compared to the
reference. The maximum increase is estimated at approximately 3% at full penetration. The 1.4 s version shows mainly insignificant negative capacity changes relative to the reference.

**AICC systems with equal headway setting at 1.2 s**

Figures 8.34 and 8.35 show the capacity values and changes respectively of the AICC systems tested at 1.2 s headway. Most capacity changes relative to the reference are not significant for equipment rates between 0% and 50%. At full AICC penetration in the vehicle fleet, small capacity enlargements between 2 and 3% are observed. Surprisingly, the relatively cheap ‘Normal’ and expensive ‘Complete’ AICC show similar elevated capacity values. Apparently, the differences in system layout do not affect the capacity changes at the 1.2 s setting, at a symmetric weaving section.
The curious decrease at 50% penetration (or reversely, the unusual increase at 10% or 20%) for many AICC systems depicted in figure 8.32, can possibly explained by the weaving process, in which two vehicles are involved. In many cases, both drivers must intervene in the AICC system to perform the lane-change manoeuvre correctly (see section 8.3.3). This requirement may limit the benefits of the quick acceleration response and constant gap maintenance of AICCs at specific penetration rates.
Chapter 8 - Traffic Flow Impacts of Autonomous Intelligent Cruise Control Concepts

**Remaining AICC systems**

Similar to the other bottlenecks, major capacity gains can be expected with the Complete AICC at 0.8 s headway, as can be observed from figure 8.36. An increase of 20% is possible when all vehicles are equipped with this system. The Extended AICC at the same small headway resulted in capacity improvements of 16% at full penetration in the vehicle fleet.

The found large capacity value of the Complete AICC at 0.8 s headway, compared to the Extended AICC, can be explained by the full support functionality of the Complete AICC system design. However, for the Complete AICC at 1.2 s headway no extra capacity benefit is observed compared to the Normal AICC at 1.2 s. Surprisingly, the expensive system performs identically to the less advanced system at this headway.

In summary, we found that at a weaving section bottleneck the capacity impacts are predominantly determined by the increased critical density. Speeds are unaffected with AICC introduction. This is explained by the available road capacity downstream the bottleneck (four lanes), and the measurement location, making easy acceleration possible over a length of about 1750 metre. The capacity increase with AICC-equipped vehicles at a weaving section is comparable to those found for the three-lane bottleneck case.

### 8.4.2 Safety analysis

The safety analysis of the weaving section is based on time-to-collision data collected over the four lanes. Table 8.9 shows the safety indicator values for the scenarios. The total vehicle numbers presented in table 8.8, supplemented by 600 to take into account the vehicles present upstream the downstream detector when the simulation run is completed, are used to calculate the average indicator value $\overline{TET}$ and probability $\overline{TETP}$ for each of the scenarios in table 8.9.

<table>
<thead>
<tr>
<th>Penetration %</th>
<th>$TET^*$ [s]</th>
<th>$\overline{TET}$ [10⁻³ s/veh]</th>
<th>$TETP^*$ [10⁻² %]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference</td>
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<td>1.1</td>
<td>1.2</td>
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<tr>
<td>Normal 1.0</td>
<td>15</td>
<td>12.8</td>
<td>16.3</td>
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<td>Normal 1.2</td>
<td>17</td>
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<td>17.4</td>
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<tr>
<td>Normal 1.4</td>
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<td>14.2</td>
<td>17.4</td>
</tr>
<tr>
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<td>19.7</td>
<td>20.5</td>
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<tr>
<td>Complete 1.2</td>
<td>22</td>
<td>17.4</td>
<td>25.3</td>
</tr>
</tbody>
</table>

**TABLE 8.9 Safety indicator values of AICC systems for a weaving section**
Most of the scenarios show $TET^*$ values between 15 and 30 s, which are values similar to the three-lane with on-ramp configuration. In addition, it was no surprise to discover the extreme values for the same scenarios as found for the other bottleneck analyses. The impact of the penetration rate on the traffic safety is similar to the relationships established for the on-ramp bottlenecks. Higher penetration rates give a decrease in the relative safety indicators. The dependency of the headway setting is also similar. Systems with small headway settings have higher indicator values, thus less safe.

The Complete AICC at 0.8 s and 100% penetration showed a value of 52 s, while the Extended AICC at 0.8 s and 100% penetration resulted in a large value of 430 s. Obviously, the latter value implies a much larger safety concern compared to the reference situation. The exposition of drivers to unsafe longitudinal situations increases with at least a factor ten. It is assumed that smaller threshold values for the Complete AICC may be adopted due to the safety features of this system design.

Furthermore, a speed increase is not expected to occur with AICC introduction.

### 8.4.3 Comfort analysis

![Figure 8.37](image)

**FIGURE 8.37** Frequency of system interventions by full penetration of Normal AICC 1.2 s

The left lane speed adaptation is the main reason for driver intervention. See our comments in section 8.3.4. However, it is obvious that the lower speed boundary is here *not* the second reason for intervention. Due to many weaving manoeuvres which must be performed, drivers must look for appropriate gaps or create gaps for vehicles wanting to make a lane change. Therefore, the *anticipation* on merging vehicles is the second most important reason for system intervention at this bottleneck. Reaching the supported acceleration level is the third reason for driver intervention.

### 8.5 Summary of results

Our traffic flow analyses focussed on queue discharge capacities and on time-to-collision impacts of AICCs in three respective bottleneck cases. The conducted comfort analyses in the previous sections was limited, and only provided for illustrative purposes.
Capacity impacts
A comprehensive overview of the capacity analysis is presented in table 8.10. The table shows the capacity changes found for each of the three studied bottlenecks per tested AICC system as function of the penetration equipment rate. No large capacity decrease has been observed with the tested AICC concepts at the selected headway settings. Only a headway setting at 1.4 s will decrease the capacity slightly.

<table>
<thead>
<tr>
<th>Penetration %</th>
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<td>2</td>
<td>4</td>
</tr>
<tr>
<td>Extended 1.2</td>
<td>.</td>
<td>.</td>
<td>.</td>
</tr>
<tr>
<td>Queue 1.2</td>
<td>.</td>
<td>.</td>
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</tr>
<tr>
<td>All speed 1.2</td>
<td>.</td>
<td>.</td>
<td>.</td>
</tr>
<tr>
<td>Complete 0.8</td>
<td>2</td>
<td>5</td>
<td>9</td>
</tr>
<tr>
<td>Complete 1.2</td>
<td>.</td>
<td>2</td>
<td>.</td>
</tr>
</tbody>
</table>

TABLE 8.10 Overview of estimated percentage capacity changes relative to reference (cells with a dot represent insignificant values)

The bottleneck type affects the achievable capacity improvements. We conclude that the capacity at a two-lane with an on-ramp bottleneck can increase moderately by means of AICC as long as the headway setting is lower than today’s average headway maintained by drivers under capacity conditions. The first generation AICCs will increase the capacity here with a maximum of 4%. Sophisticated, expensive AICCs can contribute up to 12%. The throughput downstream a three-lane main line with on-ramp can rise substantially, about twice the gain observed at the two-lane bottleneck. Also, at a symmetric weaving section major improvement in traffic quality is achievable when a large proportion of the vehicle fleet is equipped with longitudinal driver support systems.

As has been hypothesised in section 6.1, the largest capacity gains are observed with AICC concepts using small time headway settings. Indeed, the assistance systems operating at 0.8 s headway showed the best performance. Systems with headway settings at 1.0, 1.2, and 1.4 s showed less changes in capacity levels.

A sophisticated Complete AICC with full speed support and full deceleration capabilities performs better than an Extended AICC at a desired headway setting of only 0.8 s. Other design parameters than headway setting also affect road capacity levels, such as the deceleration authority and supported speed range. This was also one of our hypotheses made in section 6.1. We summarize the factors that have contributed to the capacity improvements found in the following.
Figure 8.38 gives an overview of the mechanisms that may change the bottleneck capacity in the AICC scenarios. The AICC characteristics (such as headway setting, car-following model and sensitivity parameters, etc.) affect the attainable density and speed changes near the bottleneck and downstream the bottleneck. At this location the maximum queue discharge flow can be observed. The changes in density and speed lead to changes in lane utilisation and attainable lane capacities. The capacities of the lanes, and possibly the changes in lane use, determine the overall capacity of the bottleneck. The changes in the bottleneck capacity will influence the queue length, waiting time, and the total change in travel time. Eventually, changes in travel times determine changes in the attractiveness of the motorway routes.

The general changes noticed in the experiments with AICC are the following. For the two-lane case and three lane case a speed and density increase is observed at queue discharge flow rates. Especially the left lane is used by relatively and absolutely more vehicles. In the two-lane case, a small reduction of the right lane utilisation has been detected, whereas such a decrease was not observed in the three-lane case. This can be explained by the lane-change decisions of the drivers, and the already high flow rate of the right lane in the two-lane case. In the two-lane case, AICC deployment causes speed differences between left and right lane which enlarges the attractiveness of the left lane. For the three-lane case, speed differences between the lanes exist in the reference case, and remain nearly unchanged with AICC deployment. Although the average left lane speed is smaller than the other lanes, the differences are negligible. Lane-changes to the left lane are sometimes beneficial for individual drivers. Lane changes to the right lane, however, are started when other, more restrictive conditions are met. This results in a lane distribution with a relatively large flow rate on the left and centre lane. AICC introduction increases the flow rates on these lanes even more by decreasing the intervehicle gap distance and increasing the average speed.

The critical density at the weaving section bottleneck increased, while the queue discharge speed did not change here. The unaffected speed at capacity is mainly explained by the available motorway capacity downstream the bottleneck (four lanes) while the traffic demand is restricted by the traffic processes on the weaving section. Nevertheless, considerable capacity improvements are found, predominantly due to the critical density increase.

For all cases it is observed that the capacity drop phenomenon disappears as result of introducing AICC. This impact can be observed at large AICC-penetration rates only. It is
expected (and modelled) that supported drivers, while using their AICC device, will not increase their gap distance when they experience congested conditions. The observed difference between the average speed and capacity in the pre-queue and queue discharge state in the do-nothing case also converges to a single value with widespread use of AICC.

These findings are unique so far because of the special approach used. Comparable traffic flow impact assessment studies of AICC at motorway bottlenecks were not found in literature (section 5.2). In addition, studies dealing with uniform motorway sections do not consider differences between pre-queue and queue discharge capacities whereas our experiments included a well-defined capacity estimation method based on this difference.

Safety impacts
The safety indicator values of the scenarios are presented in table 8.11. In the table we present the aggregate indicator values $\text{TET}^+$, describing the summed exposition time of unsafe time-to-collision values in the range 0 to 3 seconds. For the average indicator value per vehicle and the probability indicator values we refer to tables 8.3, 8.6 and 8.9.

The majority of the tested scenarios show values in the range 15 to 30 s. More simulation runs must be conducted to draw more precise, statistical significant conclusions. We found a trend of increasing indicator values as the penetration rate increases.

<table>
<thead>
<tr>
<th>Penetration %</th>
<th>2-lane + on-ramp</th>
<th>3-lane + on-ramp</th>
<th>weaving section</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>10    20  50 100</td>
<td>10    20  50 100</td>
<td>10    20  50 100</td>
</tr>
<tr>
<td>Reference</td>
<td>19.4</td>
<td>22.4</td>
<td>18.6</td>
</tr>
<tr>
<td>Normal 1.0</td>
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<td>18.2</td>
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<td>21.9</td>
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<td>Normal 1.4</td>
<td>22.5</td>
<td>22.5</td>
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<td>21.5</td>
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<td>All speed 1.2</td>
<td>20.3</td>
<td>23.1</td>
<td>23.9</td>
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<tr>
<td>Complete 1.2</td>
<td>20.8</td>
<td>32.2</td>
<td>27.6</td>
</tr>
</tbody>
</table>

**TABLE 8.11** Overview of the aggregate safety indicator $\text{TET}^+$ [s]

Some of the values are examined in more detail. The Extended AICC at 0.8 s headway at 100% penetration rate has extremely high indicator values for each of the bottleneck scenarios: 727, 1477 and 430 s respectively. Although a capacity increase is found with this AICC system, due to safety considerations the Extended AICC at 0.8 s headway setting should be rejected for market introduction. We can explain this characteristic by the following. An Extended AICC has a partially supported speed range, thus drivers must take over control when speeds below 30 km/h are encountered. After intervention, the expansion from the initially automatically maintained 0.8 s headway to the desired manual headway at about 1.2 s led to large shock waves with undesired (unsafe) properties.

One may argue that it is unfair to use the same TTC-threshold value (3 seconds) to
compare technological strongly different vehicles, with different reaction and braking times. For some AICC systems it seems more realistic to use lower time-to-collision thresholds to express the same level of collision risks. For example a threshold of two seconds instead of three seconds. An example of such candidate is the Complete AICC, which can support the driver fully with his longitudinal driving task. The system can decelerate with the full deceleration of the vehicle. Exposition to low TTC-values leads with such system design not to safety hazards. It is subject of further research to develop more refined safety indicators that can adequately deal with the technological differences between user classes in the vehicle fleet. We speculate that at least the difference between human driver’s time delay and AICC time delay may be subtracted from the reference TTC-threshold value, since AICC systems react this time duration quicker.

The time-to-collision indicators as adopted in this study, taking into account all time-to-collision values of each vehicle present in the simulation over a given time horizon, is a new approach to investigate safety on motorways. In literature, TTC measurements at motorways are mostly made at single cross-sections (detectors) and do therefore not take into account vehicles exposed to possibly small TTC values at other positions on the roadway. Our approach improves the safety assessment by considering these TTC-values as well.

8.6 Evaluation and implications

We have seen that introduction of AICC in the car fleet may has a considerable impact on the capacity of motorway bottlenecks, and thus on motorway capacity. From the simulation outcomes a number of interesting changes in traffic flow characteristics appeared: among others, speed at capacity and critical densities increased, an increased left lane use, and a reduction in the headway variation. It is interesting to speculate about wider implications of these findings for the functioning of motorway networks in the future. This final section discusses the implications of the findings in relation to other measures to increase motorway capacity currently available, the relation with the autonomous capacity growth over time, and the implications for network related impacts. The importance of motorway networks for motorized traffic in developed countries has been indicated in section 1.2.3. From this section, it can be concluded that the capacity and safety impacts of AICC introduction can differ between countries. We discuss the general implications in the following.

*Capacity gains in relation to other capacity improving measures*

In motorway traffic management, there exist a number of possibilities to increase motorway capacity to a certain extent. Examples are the following:

- **ramp-metering.** The objective of this dynamic traffic management measure is to restrict the inflow of traffic from on-ramps in order to control the capacity of the main line. It is concluded that ramp-metering can elevate the bottleneck capacity only slightly (see e.g., BANKS, 1991, VAN TOORENBURG, 1996).

- **maximum speed reduction.** This measure can lead to higher capacities according to the mechanism shown in figure 8.39. Especially the harmonizing effect on speeds contributes to an improved throughput. The capacity gains will be limited to a few percent only.

- **passing prohibition for trucks.** The impact of passing prohibitions for trucks on capacity is also limited. Maximum capacity gains of approximately 2% are expected after such a measure, see e.g., SCHUURMAN et al. (1994).
• **dynamic route and queue length information.** This will improve the distribution of flows over the motorway network. Its impact on capacity is quite difficult to compare with motorway link related capacity improvements.

• **dynamic and temporarily use of shoulder lane.** By temporarily using an additional lane (the shoulder lane) the motorway capacity can be increased substantially. Disadvantage is the loss of a lane for emergencies. In the Netherlands, such lanes are already deployed successfully during the peak hours.

• **dynamic change of road geometry.** This dynamic traffic management measure changes the road geometry temporarily by adding an extra lane within the original width. With this measure, a two-lane motorway changes into a three lane motorway with smaller (or possibly equal) lane widths. Investigations into the possibilities for practical implementation are under-way.

• **encouraging changes in driver behaviour.** By stimulating well-defined driver behaviour, for example an improved lane change behaviour near lane-closures (‘zipping’), it is theoretically possible to gain higher bottleneck capacity levels. However, studies examining such measures show that the capacity changes are absent (DUJKER et al., 1997a).

The addressed traffic management measures show only small capacity improvements, with a maximum of about 5% per main line (CIA, 1999). Nonetheless, we emphasise the importance of quite small improvements, among others for the reduction of waiting times and queue lengths. This is illustrated in figure 8.40.

Figure 8.40 shows an example of the demand and capacity profile for a day-period. It can be seen that there are short periods with demand higher than capacity resulting in a waiting queue indicated at the bottom. The varying capacity profile illustrates the stochastic properties of motorway capacity. The demand pattern has also fluctuating properties. With a stochastic queuing model, the congestion probability can be calculated, see e.g., BOTMA (1998). Without further calculations, it can easily be seen that a mean capacity increase (e.g., due to AICC introduction) can lead to more than proportional smaller waiting queues, shorter queue
lengths, and less waiting time losses.

A much more rigorous measure to increase the capacity of motorways is the construction of an additional lane. For example, the expansion of a two-lane motorway to a three-lane motorway will increase the capacity from about 4400 veh/h towards 6200 veh/h, taking queue discharge flows downstream a bottleneck (Minderhoud et al, 1996b). Thus, a capacity increase of 40%. The expansion of a three-lane motorway to a four-lane motorway will elevate the capacity from 6200 veh/h to approximately 8400 veh/h, which is 35% increase. For a fair comparison of AICC deployment and capacity increasing measures, the construction of a new lane is not taken into account here further.

When we compare the capacity gains found in our study with the attainable gains with traffic management measures, it is obvious that the introduction of autonomous longitudinal driver support systems, such as AICC, can increase road capacity further, without infrastructural adaptations or other costs for the motorway authority. Expected capacity increases for the first generation AICC systems lie in the range of 4% to 7% (see table 8.10). The deployment of advanced AICC systems can eventually result in capacity gains between 7% and 25%. Notice that the last figure is in the order of the effect of the expansion of a three-lane motorway to a four-lane motorway.

Again, we emphasise that capacity changes differ by the applied AICC-system design and assumed penetration rate in the vehicle fleet and depend furthermore strongly on the bottleneck type.

Our results show that capacity gains of AICC are larger for motorways with more than two lanes.

**Capacity gains in relation to autonomous capacity growth over time.**

In section 3.1 the impacts of (early) driver support systems, vehicle technology, and improved driving behaviour on motorway capacity have been described. Today’s motorway lane capacity can reach values of 3,000 vehicles per hour (see e.g., Duker, 1997b), whereas the maximum flows in the 1930s were halve of this value. It is generally assumed that the long run average autonomous growth of motorway capacity is about 0.5% to 1% per year.

![FIGURE 8.41 Expected future growth of motorway lane capacity](image)
due to the improved vehicle technology, road technology, and driver behaviour, see e.g. COHEN (1995). We now may ask whether the introduction and expected capacity benefits of AICC-like systems is to be considered part of the 'natural' development that contributes to the yearly growth, or whether it (temporarily) will change the capacity trend growth.

Figure 8.41 illustrates the two different scenarios: (1) a capacity growth with the same pace and magnitude as experienced in the past, or (2) a deviating capacity growth due to the introduction of AICC systems.

Let us calculate the yearly capacity change based on some assumptions. It will normally take about ten to fifteen years to replace the vehicle fleet. However, in the case of a slow development of AICC, we expect that the time to full penetration can even take twenty years.

We expect that the first generation Normal AICC systems with 1.0 s headway setting can then theoretically increase the motorway capacity about 4 to 7%, exact values depending on bottleneck type. Assuming that the maximum gain is applicable for a single lane, this will result in an average lane capacity growth of about 0.4% per year. However, the Complete AICC with 0.8 s headway can increase the lane capacity about 12% to 25% (see table 8.10). This could mean an annual average growth rate of about 0.6 to 1.2%.

Based on these calculations, we expect that the introduction of AICC will give rise to a capacity growth of about 0.5 to 1% per year. We question if this is an extra growth above the observed trend. We view the development of AICC as something that fits in the existing trend of capacity growth due to technological improvements of the car and behavioural improvements of its driver. We expect that after the introduction of AICC, new and more advanced systems will be developed and introduced that will increase the motorway capacity further.

The Dutch transportation authorities also foresee a capacity increase on motorway lanes due to the previously mentioned dynamic traffic management measures (see e.g. ‘Tweede Structuurschema Verkeer en Vervoer, 1989). According to this policy report, a maximum capacity increase of 30% is expected to be possible. Over the period 1990 to 2010, a capacity increase of 15% is envisaged, taking into account the impact of the first generation of automated vehicle guidance systems (such as AICC). We agree with this estimate of 15% in 15 years, but only if all previously mentioned traffic flow control measurements are effectively implemented, while the first generation AICCs are adopted by nearly all drivers.

Capacity gains in relation to motorway network capacity
The study focussed on single bottleneck locations in a motorway network. Our findings indicate substantial capacity increases near such bottlenecks. Consequently, reductions of queue lengths and travel times can be expected, compared to a constant reference situation without traffic demand growth.

Nevertheless, as travel times are reduced due to extra capacity on motorways a number of subsequent developments in trip making can occur (all other factors remaining unchanged).

Firstly, a change may take place for a part of the travellers who shift to locations further from their origin (e.g., increased distance between home and work location). The distance between origin and destination increases for these travellers, but due to the offered travel time benefits and the increased welfare utility these people experience from the new environment, the decision to increase the travel distance results in a higher overall utility for these persons.
Another possibility is a shift from trips made on the underlying road network to using the motorway network. In addition, the total kilometres for such trips may increase, but by using the motorway instead of the underlying road network with its low average speed, door-to-door times will nevertheless reduce. This will lead to more car-kilometres on the motorway, but reduce the car-kilometres travelled on the underlying road network.

A third possibility is that part of the drivers will use the offered capacity and resulting travel time reduction to change their departure time. The impact of such a departure time shift is the creation of a smaller peak period, since more drivers will perform their trip at the same moment. Eventually, this development might increase the congestion during the peak, but this peak is shorter and the reduction of congestion at the shoulders of the peak is larger.

The overall effect of these developments in trip making is an increase in the vehicle-kilometres driven on the motorways. However, a decrease in car-kilometres is expected on the underlying road network (all other things remaining equal). The effects will not take place immediately, but will take some time.

As a consequence, the motorway network performance (for example the vehicle-kilometres per year) will increase. The question if capacity improvement is a good strategy to solve traffic problems or not is a political debate which we will not deliberate here further. In case extra capacity is not desired, one option is to close a motorway lane after successful introduction of a capacity increasing driver assistance system, thus discouraging changes in location choice, attraction of new traffic and maintaining the same travel distances as before the introduction of the longitudinal driver assistance systems.

The potentially significant capacity increases of motorway bottlenecks due to AICC introduction does not imply a comparable capacity increase at the level of the total car network. This because the entrance and exit points to the motorway network - connecting the motorway with the underlying road network - will not benefit from the capacity increase of AICC introduction (MINDERHOUD, 1999b). The complex driving tasks can not be supported here with the first generation AICC systems. Driver control is required, for example to approach standing vehicles before a traffic light. The underlying road network parts may become the new bottlenecks when it can not handle the increased traffic demand to or from the motorway.

Consequences
Our findings indicate that the utilisation of existing motorways can be improved in the near future by the deployment of AICC systems with relatively progressive headway settings. Without expansion of the current road geometry, the attainable capacity can reach the same level as could be achieved with the construction of additional lanes. Conditions for such improvements are the following:
- full penetration of AICC system in the vehicle fleet;
- headway setting below 1.2 s and preferably below 1.0 s;
- headway setting fixed or little adjustable by driver.

Since the capacity gains can be attained without any investments by the road authorities the deployment and implementation of AICC could be stimulated by taking purposeful policy measures. Investments in new infrastructure can possibly be postponed by anticipating oncoming capacity gains. However, since a poor AICC design can decrease the traffic flow throughput considerably (for example, if a car manufacturer introduces an AICC at 2.5 s headway setting) special attention should be given to regulation with respect to the systems.
At this moment, the car and support system manufacturers dominate in the development and selection of operational characteristics of AICC systems. We recommend that the design and characteristics of these AICC systems is bounded within predefined safety and efficiency standards. The regulation and legislation of in-car devices can best be accomplished at the European level.

Policy makers must recognize the impact of motorway capacity improvements on the functioning of the underlying (urban) road network. The number of entrances and exit points of the motorway network must be expanded or the geometry of the facilities adapted in order to handle the potentially increased traffic demand to and from the motorway.

With respect to motorway traffic safety developments, no significant deteriorations nor improvements are found using classical safety indicators (TTC of 3 seconds) for investigating the AICC scenarios. An exception appears to be AICC systems with time headway settings below 1 second which must be intervened if speeds drop below a certain value. The occurrences of rear-end collisions may reduce by the deployment of advanced well-designed assistance systems, assuming small time delays and driver assistance over the full speed range. In addition, only a small part of total traffic unsafety is located on motorways, while AICC systems support the driver on motorways only. The effects on the total number of fatalities and accidents will be quite limited. The introduction of AICC must therefore not be seen as a remedy for traffic unsafety in general. In addition, it appears that average speeds will increase with the majority of tested AICC designs, indicating an unsafety increase.

Apart from this, shifts in traffic demand from lower level roads to motorways will improve safety of the road network as a whole.

The study focussed on three bottleneck types. There are however other types as well noticeable on today’s motorways, such as lane drops. The capacity changes of other discontinuities were not investigated by us or by others, but we could speculate about the possible impacts using our results and knowledge about AICC operation. For example, a three-lane motorway with a lane reduction on the median lane will have about the same maximum flow as the tested two-lane motorway with on-ramp. Nonetheless, some aspects of the traffic flow operation are different and can affect the capacity value. For exact values, simulations of this scenario should be carried out.

With the deployment of the first generation AICC there is no direct need to adapt the geometric road layout of motorways. Possibly, the lane width could be reduced in a later phase with the introduction of new driver support systems such as lane keeping support. Also, with communication between roadside and vehicles new possibilities emerge (IOANNOU, 1997). Special lanes for equipped vehicles may be introduced, increasing the lane capacity a factor two or three. Nonetheless, there are some uncertainties that make the overall capacity gain obtainable with such concepts disputable, see section 5.3. Other options are possible with inter-vehicle and road-side communication, for example, acceleration lanes might be shortened since the path of the merging vehicles can be determined in advance and gaps are created on the main line at the appropriate moment.

Eventually, such a gradual improvement of the functionalities of the Autonomous Intelligent Cruise Control will evolve into the concept of Automated Highway Systems with dedicated lanes where the driver is fully supported and the equipped vehicle will drive automatically. We claim that the future of vehicle and road automation starts with the deployment of Autonomous Intelligent Cruise Control.
CONCLUSIONS AND PERSPECTIVES

This chapter summarizes and discusses the findings from the experiments and conclusions derived in this dissertation. Section 9.1 provides a summary of the research approach and experimental work done, followed in section 9.2 by findings from the theoretical analyses and literature study. The dedicated model specifically developed for this study is outlined in section 9.3, while the results of the simulation study concerning capacity and safety impacts are summarized in section 9.4. Expectations on future developments in motorway capacity are described in section 9.5. Some suggestions for further research on driver support systems are presented in section 9.6. The chapter closes with transportation policy recommendations in section 9.7.

9.1 Summary of research approach and experimental setup

Introduction
One solution for enhancing today's limited road capacity is the development and deployment of functionally improved motorized vehicles replacing parts of the driving task of the driver. Besides capacity gains, driving task automation may also lead to safety improvements. The expected benefits to the individual driver are mainly comfort gains, such as enhanced travel convenience, since less attention is needed to execute the longitudinal driving task. In the past, the impacts of these developments have not been determined unambiguously.

The first generation of driver support systems will become available before the second millennium (e.g. the Distronic system of Mercedes). The early driver assistance systems, referred to as Autonomous Intelligent Cruise Control (AICC), can replace the speed adaptation and distance keeping task of the driver with respect to the vehicle in front on the same lane. Vehicles equipped with such a driver assistance system can drive on the current motorway between non-equipped vehicles.

Objectives and study approach
As described in the first chapter of this dissertation, the objective of our study is to quantify and assess the potential improvements (or deteriorations) of traffic flow quality at bottleneck motorway sections given a number of conditions, such as the proportion of the vehicle fleet equipped with specific longitudinal driver assistance systems, the so-called AICC.

Many questions regarding relationships between design choices and parameter settings
of AICC systems and motorway capacity emerge. Within the scope of the study, the focus is on the following relationships:

- impact of headway setting of AICC on motorway capacity and safety;
- impact of other AICC design parameters such as minimum deceleration level, minimum speed, and manual/automatic reactivation of the system on motorway capacity and safety;
- impact of proportion of the vehicle fleet equipped with AICC.

The study first provided a theoretical analysis of driver behaviour, driver support system operation, and support system categorisation. A literature survey has been conducted into the capacity impacts of driver support and automated vehicle guidance systems. The findings have led to the exact definition of the study objectives and the experimental setup needed. We concluded that a dedicated simulation model is needed to assess the impacts realistically. A new dedicated microscopic simulation model for motorway traffic has been developed and calibrated, since existing models cannot address our research objectives and requirements adequately.

**Experimental setup**

Three bottleneck situations have been selected as test cases for the impact assessment, since we expected that impacts may differ by type of facility. Furthermore, capacity estimation can only be performed reliably at a bottleneck motorway section. The queue discharge flow rates downstream a bottleneck represent motorway capacity quite well, while this state can be sustained for a long period.

The experiments involved five AICC layouts, at headways between 0.8 and 1.4 s. Differences between the layouts are the operational speed range, the reactivation functionality and the supported acceleration range. The Normal AICC represents the characteristics of early assistance systems, with a speed range of 30 to 150 km/h and manual reactivation. The Extended AICC is an extension of the Normal AICC with an automatic reactivation functionality. Both AICC layouts support accelerations in the range of -0.3g to +0.15g. A Queue AICC is proposed to deal with stop-and-go traffic; it supports only speeds ranging from 0 to 60 km/h. The All Speed AICC is equal to the Extended AICC but supports also speeds between 0 and 30 km/h. The Complete AICC is the most expensive one, since it has all characteristics of the All speed AICC but also supports the full acceleration range of the vehicle.

Each of the AICC concepts have been simulated at various levels of penetration in the vehicle fleet (0%, 10%, 20%, 50% and 100%) for the three bottlenecks considered. Traffic flow analysis especially focused on the capacity changes compared to the reference situation without AICC.

For the safety analysis, a number of purposeful aggregated time-to-collision safety indicators have been developed, taking into account the occurrences of all individual TTC values of vehicles at any roadway position during a simulation run. This new approach has the advantage over existing methods in that very small time-to-collision values can be observed with the same probability as large TTC values, which is not the case when time-to-collision values are measured at one or multiple cross-sections. The safety indicator values have been estimated for all the tested systems and bottleneck situations.
Research challenges
In conclusion, the main research issues tackled in this dissertation were:

- Analysis of driver behaviour on motorways and the role of driver support systems in the driving task support.
- Analysis of traffic flow quality assessment in general, and roadway capacity in particular.
- Development of a dedicated microscopic traffic simulation model to simulate motorway traffic with the presence of vehicles equipped with Autonomous Intelligent Cruise Control.
- Assessment of Autonomous Intelligent Cruise Control concepts to improve motorway capacity and safety.

The conclusions of the study are described in the following sections.

9.2 Conclusions from theoretical analysis and literature study

In Chapter 2, driver behaviour has been described using a control theory model. Several driving subtasks have been distinguished and a new purposeful categorisation of tasks has been described. Aspects of the driving task execution, such as observation task, control estimation, control decision, and actuator control performance are considered in the control model. The model assumes that drivers make a decision based on the utility optimisation of their driving objectives and preferences. The decision is executed with a time delay and will deviate from the ideal value due to observation, decision, and actuator control errors.

A categorisation of possible support systems has been determined so as to investigate the range of applications for future driver support systems. The final categorisation has been accomplished by distinguishing four types of support systems: informing, warning, assisting overrulable and assisting non-overrulable. After the description and examination of the functional support system categories, we found that the longitudinal support systems are the most promising systems to be deployed and to be studied in more detail at this moment.

The theoretical benefits of a driver support system have been analysed and compared to the execution of a driving task by a human driver (Chapter 3). We expect that at the current state of technology a driver support system is able to observe stimuli faster and more precisely, can make a control decision faster, and execute the action more accurately than a human driver, leading to more alert driving in general. This is likely to reduce the occurrence of errors in the driving task execution. These advantages may result in an improved driving task execution for part of the driving tasks and therefore eventually improve traffic flow quality and increase driver comfort.

Chapter 4 studied the traffic flow quality indicators (capacity, speed, stability, and safety) and describes potential changes in the indicators as longitudinal driver support systems are deployed in the vehicle fleet. We found that theoretical safe-distance models are not adequate for describing capacity changes, but that empirical capacity estimation methods are needed. The queue discharge flow has been considered the best method for assessing changes in capacity.

An extensive literature study has been performed (Chapter 5) to assess past capacity expectations of AICC introduction. We concluded that many studies did not use an appropriate capacity estimation method or experimental setup. Bottleneck locations are seldom studied. The number and variation of tested AICC systems are limited in almost all
studies. Headway settings that theoretically deteriorate motorway capacity are often selected in test cases. The influence of other design parameters has not examined extensively. In our experimental setup, it is attempted to alleviate the observed shortcomings and to estimate the traffic flow impacts adequately and more reliably.

From our literature review it also emerges that the deployment of the fully automated systems, referred to as Automated Highway System (AHS), is a long term development. The essence of AHS is that a number of consecutive vehicles follow each other at a small constant gap distance (about 1 m) on a special lane, probably along an existing motorway, sometimes referred to as with platoon driving. Several problems for rapid deployment of AHS have been identified. We observe that the theoretical capacity improvements (said to be a factor of two to three compared with the current motorway lane) are only achievable if vehicles are equipped with communication facilities. A mix of non-equipped and equipped vehicles on the special equipped and dedicated AHS lane is not possible. For a valid comparison of capacity improvements, the extra transition lane for egress and exit processes should be taken into account. In addition, the theoretical capacity on the dedicated lane will be diminished by the merging processes of exiting and entering vehicles which has been reported by several researchers. Furthermore, a hard shoulder along the special AHS lane might be necessary to allow for malfunctioning vehicles.

We found that the overall benefits of an AHS on a network level have not been clearly proven and would need substantial investments in order to be implemented.

### 9.3 Improved modelling

In order to establish the impacts quantitatively, simulation experiments have been set up (Chapter 6) and conducted. Therefore, a new dedicated microscopic simulation model that embodies the driver assistance functionalities of the expected first generation support systems has been developed (Chapter 7). The model is characterised by several new elements compared to similar models. The hypothesised increased gap distance of drivers after having experienced congested conditions was implemented and showed great resemblance to empirical data. We applied a desired speed distribution for drivers of a user class based on a mean and a standard deviation. The same holds for the time delay determining the desired gap distance of a vehicle.

Driver behaviour has been modelled according to a control model that assumes simultaneous longitudinal and lateral driving task execution. For the longitudinal driving task, the speed adjustment depends on the observed leader, the speed on the left side lane, and anticipation lane changes from the right adjacent lane. The leader selection procedure is quite sophisticated, taking into account the state of follower and candidate leaders, including vehicles in front on adjacent lanes. A longitudinal car-following model has been specified using four different parameter sets for four different car-following conditions. The lateral task involves evaluation of the lane change desirability conditions and gap acceptance requirements. Speed-dependent conditions for starting lane changes have been determined. A control action is executed after a delay time which depends on the vehicle's user class.

The microscopic traffic simulation model gives microscopic data (position and speed) which can be aggregated into macroscopic data, such as flow rates and speeds, measured at detectors of the motorway segment in the simulated scenario. At the mesoscopic level, headway, acceleration, and time-to-collision distributions are produced.
9.4 Findings from the simulation experiments

Capacity impacts
We hypothesised that the impact of drivers using AICC systems on motorway capacity depends on the type of bottleneck, headway setting, AICC penetration, and AICC-system characteristics. This hypothesis is supported by our findings (Chapter 8). We expect that a major capacity increase can be achieved at three-lane motorways with on-ramp bottlenecks, and at weaving sections. A maximum capacity gain of about 25% is observed with the Complete AICC. The capacity gains are largest at full penetration in the vehicle fleet composition. We found that the left and centre lanes carry relatively and absolutely more vehicles per hour than in the reference case of the three-lane motorway. The speeds at capacity increase only slightly, but the critical density increased considerably for all AICC scenarios.

The capacity increases at two-lane motorways with on-ramp are smaller than at the three-lane motorway scenarios, but still considerable. The most sophisticated Complete AICC leads to gains of about 12%. We found that the higher the penetration rate, the higher the capacity gains. The left lane shows the highest increase, which compensates for the decreased utilisation of the right lane.

The deployment of the Normal AICC concept with a headway at 1.2 s shows no meaningful capacity improvements at any penetration rate. Driver assistance systems with headway settings below 1.2 second lead to noticeable capacity gains, already at intermediate equipment penetration rates. Capacity impacts for assistance systems operating at a 1.2 s headway setting appear to be insignificant.

The reactivation functionality of AICC should preferably be automatic, since it will probably reduce driver’s mistakes (reliance on the system while idle after intervention). Clear capacity effects of this design aspect have not been found. The supported speed range should be large for safety considerations (including stop-and-go speeds and the safe approach of standing queues). There is little evidence of substantial impacts of the deceleration authority and speed range on the capacity; this issue should be studied further using an adapted experimental setup.

Safety impacts
In general, the time-to-collision indicator values did not differ significantly from those of the reference case. We found some evidence for increasing unsafety as the penetration rate grows. The safety analysis showed unsatisfactory time-to-collision indicator values of the Extended AICC at 0.8 s headway, for all bottleneck types. This is probably caused by shock waves. These are started as drivers take over vehicle control when they experience low speeds which are not supported by the AICC. Simulations with the Normal AICC at 0.8 s headway setting showed the occurrence of some rear-end collisions and was therefore not included in our previous capacity impact study.

The Normal AICC at 0.8 s and Extended AICC at 0.8 s are examples of unsafe system designs if they (fully) replace the vehicle fleet. Preferably, these system designs should not be deployed.

Another aspect related to the safety on motorways is the average speed. It has been observed that the average speed increases with AICC introduction at on-ramp bottlenecks. This finding contributes to an increased unsafety on motorways.
Comfort impacts
The frequency of driver interventions was investigated to analyse the differences between intervention reasons among the respective bottlenecks. It was found that at a weaving section the majority of drivers take over vehicle control to anticipate manoeuvres of other traffic participants. The lane-change manoeuvres required by a large proportion of the flow explains these interventions. Upstream the on-ramp bottlenecks, however, after capacity has been reached, drivers are required to take over control as their speed drops below the AICC-supported speed.

9.5 Expectations for future motorway traffic flow

When we compare the capacity increases derived in our study with the attainable gains with dynamic traffic management measures (maximum capacity increase about 5%), it is obvious that the introduction of driver support systems or AICC can increase road capacity further, without infrastructural adaptations or other costs for the road authorities. Expected capacity changes for the first generation AICC systems lie in the range between 4% to 7%. The deployment of advanced AICC systems can result in capacity gains up to 25%. Notice that the last figure is comparable to the effect of the expansion of a three-lane motorway to a four-lane motorway.

We expect that the introduction of AICC fits in the normal capacity trend growth as experienced in the past, due to technological improvements of the car and its driver. The deployment of AICC systems will take some time (a period of 10 to 15 years is minimal required to equip a large proportion of the vehicle fleet), so will the estimated capacity changes. An annual growth rate between 0.5 and 1% is a realistic assumption for the next decade. By the time the majority of the vehicles is equipped with AICC, new assistance systems based on vehicle-to-vehicle and roadside-to-vehicle communication might be available or in development. The impacts of these advanced systems on capacity and safety will probably be larger, since vehicle control decisions can be made centralized, anticipating actual and expected traffic conditions.

A gradual improvement of the functionalities of the first generation assistance systems will eventually evolve into the concept of Automated Highway Systems with dedicated lanes, where the driver is fully supported and the equipped vehicles will drive automatically in platoons.

9.6 Further research

Driver assistance systems and experimental setup
One of the main problems in this study is to select the layout of the AICC systems in the traffic flow analysis. Many combinations and parameter settings are possible, but only a limited amount of time for analysis is available. Therefore, not all combinations of headway and system layout have been investigated. It is recommended that in further research of AICC a differentiation be made between an AICC with a soft, medium and hard deceleration authority. Evidence for impacts on capacity for this aspect could not be determined in the setup followed.

The investigation deals with short term developments in driver support system
deployment. For medium term advancements, the analysis of Intelligent Cruise Control based on intervehicle communication is interesting. Such an approach could further increase the traffic flow quality. It can be seen as a precursor of fully automated vehicle guidance, such as platoon driving on dedicated lanes. But the introduction of these concepts on the public motorway will take a considerable amount.

The study setup followed and time available have limited the capacity analysis to queue-discharge capacity, since insufficient data was available for a reliable pre-queue capacity estimation. Moreover, only an average capacity value has been determined, while a capacity distribution is desirable. These imperfections could be resolved by increasing the number of simulation runs per scenario.

**Driver behaviour theory and modelling issues**
We have assumed that drivers will not adjust or change the AICC-system parameters. The situation where drivers may adapt their preferred headway is interesting, but complex, since it requires a model for headway selection by drivers. Such an adjustable AICC may conceivably have smaller impacts on traffic flow than an AICC with a fixed headway. Further research is needed on this subject.

In our model representation of AICC systems and human driver behaviour, the same longitudinal controller has been applied. The calibration goal was to create an AICC controller that acts like a human driver. Other calibration goals may be followed in developing an AICC longitudinal algorithm, for example comfort objectives.

The simulation model SIMONE incorporates various submodels for longitudinal and lateral behaviour. Although calibration results show a good resemblance between empirical and simulated motorway flow data, more empirical research is needed to prove the validity of the submodels used. For example, the desired minimum gap distance of a single actor is assumed to be constant in the model, but may be specified as a function of trip time or as a function of other factors. It also appears that the model simulates congested conditions at higher speeds than observed in practice. Further model calibration and model adaptations are desired to match the simulation outcomes against empirical data from congested traffic flow conditions.

The safety indicators developed are useful for comparative purposes. An appropriate time-to-collision threshold value is needed for such analyses. Further research is desired into the exact threshold values. Especially the relationship between support system design and safety-critical TTC threshold value has been found to be essential for fair safety comparison.

More knowledge is also needed about the use of AICC systems, thus validating the modelled conditions for driver intervention and reactivation. A field test of instrumented vehicles could make valuable contribution towards expanding the knowledge on this subject. Furthermore, the model could be adapted to incorporate vehicles using communication to support the longitudinal driving task. In addition, other types of driver support are possible and useful expansions of the model.

### 9.7 Recommendations for transportation policy

Capacity of motorway networks is expected to increase due to the use of driver assistance systems in the near future. Other developments, such as an improved driver education and driver behaviour also contribute to the annual growth of road capacity of about 0.5 to 1%
which has been noticed over a long period since the introduction of the motor vehicle. As today a two-lane motorway currently has a capacity value of about 4,400 veh/h, in fifteen years this will be approximately 5,000 veh/h. The capacity of a three-lane motorway will probably increase even more, from about 6,200 veh/h to 7,200 veh/h in fifteen years. Our findings indicate that in traffic demand calculations and prognoses the increase in motorway capacity due to AICC should be adopted for a correct calculation of future situations.

The expected growth in capacity induces some questions with respect to transport policy (other things remaining equal). A capacity increase will reduce travel times, and thereby affect location choice and route choices. More vehicle-kilometres will be driven on motorways, whereas the car-kilometres on the underlying road network will be reduced. Changes in departure time will change the traffic demand pattern. Peak periods will become shorter and more intense, but the congestion and waiting times in the shoulders of the peak will decrease.

One possibility to obtain the possible capacity gains with AICC faster, is a policy that will stimulate the use of such assistance systems, and boost the vehicle fleet equipment penetration rate. This policy requires subsidies or other financial offers to increase the deployment rate of the longitudinal driver assistance systems. The investments must be compared to other possible measures to increase motorway capacity to the same level.

We recommend to the transport policy authorities that the design of AICC systems be regulated. The design of the system dictates the possible capacity gains. For example, an AICC with a headway setting of 2 seconds will decrease the road capacity in the long term. Upper and lower boundaries of essential design parameters should be defined at an early stage in collaboration with the system manufacturers.
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APPENDIX A : CALIBRATION OF SIMONE

Calibration of a microscopic simulation model is a complicated but essential part in the model development. Without an adequate calibration, followed by a validation, the practical value of the model is limited.

The calibration of a microscopic traffic simulation model will generally consist of:
- determination of appropriate vehicle/driver characteristics, as parameters which can generally be set by the user of the model;
- determination of appropriate parameter settings that determine driver behaviour;
- feedback to theory and model algorithms (adaptation or improvement of theory and algorithms to increase resemblance with practice).

The SIMONE model was mainly calibrated with macroscopic traffic data from the A2 Vinkeveen site (available from Tuesday may 26th 1992). The 2x3-lane A2 motorway connects, among others, Amsterdam and Utrecht in the Netherlands, see figure A.1. At this site, the bottleneck cause in the motorway is an overloaded on-ramp to the three lane motorway.

The simulation results can best be depicted as speed-flow relationships, a macroscopic aggregation of individual driver behaviour. During the calibration process, parameter values in the model are changed, results checked on their resemblance with practice, and parameter values adapted to improve the fit with observations or expectations. The goal of this iterative process is to find appropriate user class and model parameters resulting in speed-flow curves very close to those observed in reality.
The calibration process is quite complex, since changing one parameter to fit simulation outcomes better to the empirical data observed at a specific cross-section and lane may contribute to a deterioration of the results for another cross-section and lane.

To be more concrete, the simulation results were judged on the resemblance of the following points.

1. Downstream median lane
   - uncongested branch of speed-flow curve
   - pre-queue capacity and speed
   - queue discharge capacity and speed
2. Downstream centre lane
   - uncongested branch of speed-flow curve
   - pre-queue capacity and speed
   - queue discharge capacity and speed
3. Downstream shoulder lane
   - uncongested branch of speed-flow curve
   - pre-queue capacity and speed
   - queue discharge capacity and speed
4. Upstream median lane
   - uncongested branch of speed-flow curve
   - pre-queue maximum flow rates and speed
   - congested branch of speed-flow curve
5. Upstream middle lane
   - uncongested branch of speed-flow curve
   - pre-queue maximum flow rates and speed
   - congested branch of speed-flow curve
6. Upstream right lane
   - uncongested branch of speed-flow curve
   - pre-queue maximum flow rates and speed
   - congested branch of speed-flow curve
7. Visual inspection of merging process near on-ramp
8. Visual inspection of lane-change behaviour and frequency

Figures A.3 to A.8 show the speed-flow data points (using a 5-minute aggregation interval) generated by SIMONE and measured in practice at an upstream (fig. A.2, no.2) and downstream detector (fig. A.2, no. 5). About 5% trucks were present in the vehicle fleet composition. Table A.1 presents a selection of the calibration results.

<table>
<thead>
<tr>
<th></th>
<th>Pre-queue maximum flow [veh/h]</th>
<th>Speed at pre-queue state [km/h]</th>
<th>Average queue discharge flow [veh/h]</th>
<th>Speed at queue discharge state [km/h]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Median lane</td>
<td>2,900</td>
<td>2,900</td>
<td>90</td>
<td>95</td>
</tr>
<tr>
<td>Center lane</td>
<td>2,500</td>
<td>2,550</td>
<td>83</td>
<td>91</td>
</tr>
<tr>
<td>Shoulder lane</td>
<td>n.a.</td>
<td>1500</td>
<td>n.a.</td>
<td>85</td>
</tr>
</tbody>
</table>

Table A.1 Calibration results at downstream detector data (aggregated per 5-minute) A2 at Vinkeveen site
FIGURE A.3 Upstream median lane A2 at Vinkeveen

FIGURE A.4 Upstream center lane A2 at Vinkeveen
FIGURE A.5 Upstream shoulder lane A2 at Vinkeveen

FIGURE A.6 Downstream median lane A2 at Vinkeveen
Figure A.8 lacks empirical data due to a destroyed data file.

Based on the figures, it can be concluded that the calibration of SIMONE has resulted in quite satisfactory figures. The capacity and congested conditions are represented well by the macroscopic diagrams. One major difference between practice and simulation is the lack of simulated data below 40 km/h, although the congestion branch is quite similar to the empirical data. Further calibration and modelling effort is needed to obtain an improved
resemblance of the outcomes in congested conditions. For capacity analysis (pre-queue and queue-discharge), the model suits very well.

![Vehicle trajectories of traffic simulation at center lane in vicinity of Vinkeveen on-ramp](image)

FIGURE A.9 Vehicle trajectories of traffic simulation at center lane in vicinity of Vinkeveen on-ramp

The validation of the model was based on the two-lane scenario described in chapter 6. We found that the simulation outcomes correspond well with the traffic flow characteristics observed at such motorway locations in the past. A capacity of 4300 veh/h at a speed of 90 km/h is most commonly observed (Dijker et al., 1997a, Schuurman et al., 1993).

Figure A.9 shows an example of the vehicle trajectories from simulation of the centre lane near the on-ramp location Vinkeveen. The figure exhibits the characteristic behaviour of traffic flows.

Figures A.10 to A.13 depict the estimated speed and flow rate as function of simulation time, for the downstream and upstream detectors. A clear intensity drop is observed at the median lane. From this moment, the speed of the lanes are nearly equal. At the upstream detector, speeds below 40 km/h are observed, clearly indicating congested conditions.
FIGURE A.10 Estimated speed at downstream detector as function of time

FIGURE A.11 Estimated flow rate at downstream detector as function of time
FIGURE A.12 Estimated speed at upstream detector as function of time

FIGURE A.13 Estimated flow rate at upstream detector as function of time
APPENDIX B: TRAFFIC DEMAND IN BOTTLENECK SIMULATIONS

Figure B.1 shows the simulation input for the traffic demand, defined for the two-lane main line with bottleneck scenario. The traffic flow increases from 1,000 veh/h to 3,000 veh/h at the end of the simulation for the median lane. The input for the three-lane main line with bottleneck is similar, the added centre lane has the same curve as the median lane.

FIGURE B.1 Traffic demand at two-lane main line with on-ramp

FIGURE B.2 Traffic demand at weaving section
Figure B.2 depicts the traffic demand input for the weaving scenario. The two median and shoulder lanes have the same flow-time relationship.

The origin-destination relationship of the weaving section is shown in figure B.3. On average, the proportion of weaving traffic (i.e., vehicles changing lanes from left to right main line and right to left main line) is about 30%. We assume that a proportion of the traffic already selects the appropriate lane in advance of the actual weaving location to perform a weaving manoeuvre. The proportion of weaving traffic differs therefore per lane.

![Graph showing weaving and through traffic proportions](image)
APPENDIX C: PREDICTED SPEED-FLOW RELATIONS FOR VARIOUS SCENARIO'S

Two-lane motorway with on-ramp
Points in the diagrams represent average speed and average flow over a five-minute time interval (downstream detector). The speed and flow rate are expressed in km/h and veh/h respectively.

![Graph showing speed-flow data for two-lane motorway with on-ramp](image1)

**FIGURE C.1** Speed flow data points of two-lane motorway with on-ramp

![Graph showing speed-flow data for two-lane motorway with on-ramp](image2)

**FIGURE C.2** Speed flow data points of two-lane motorway with on-ramp
FIGURE C.3 Speed flow data points of two-lane motorway with on-ramp

FIGURE C.4 Speed flow data points of two-lane motorway with on-ramp
FIGURE C.5 Speed flow data points of two-lane motorway with on-ramp

FIGURE C.6 Speed flow data points of two-lane motorway with on-ramp
Three-lane motorway with on-ramp

FIGURE C.7 Speed flow data points of three-lane motorway with on-ramp

FIGURE C.8 Speed flow data points of three-lane motorway with on-ramp
FIGURE C.9 Speed flow data points of three-lane motorway with on-ramp

FIGURE C.10 Speed flow data points of three-lane motorway with on-ramp
FIGURE C.11 Speed flow data points of three-lane motorway with on-ramp

FIGURE C.12 Speed flow data points of three-lane motorway with on-ramp
Weaving area

FIGURE C.13 Speed flow data points of weaving section

FIGURE C.14 Speed flow data points of weaving section
FIGURE C.15 Speed flow data points of weaving section

FIGURE C.16 Speed flow data points of weaving section
FIGURE C.17 Speed flow data points of weaving section

FIGURE C.18 Speed flow data points of weaving section
APPENDIX D: STATISTICAL ANALYSIS OF CAPACITY ESTIMATES

In order to compare the estimated capacity values of the distinguished scenarios, statistical tests of the reliability of the differences have been carried out. Figure D.1 illustrates the statistical notions and problem we deal with in our capacity impact estimation study.

The problem can be understood by assuming the position of the null hypothesis. This says, that there is no difference between sample means. In practice, the means of samples (e.g., samples of maximum flows obtained in different observation periods) differ. The distribution of a sample of maximum flows - the distribution of maximum flows - is defined by the mean and standard deviation of the distribution.

We found that the maximum flows are normal distributed for the reference situation (see section 6.6.2), and we assume that this distribution form holds for all AICC-scenarios.

If we repeat this experiment over and over again, we can plot the distribution of the resulting means and obtain a distribution as depicted in the middle of figure D.1. This is called the sampling distribution of the mean. The standard deviation of a sampling distribution is known as the standard error of estimate. The standard error of estimate is \( \sqrt{(s^2/n)} \) where \( s^2 \) is the variance and \( n \) the sample size. We can also write \( s/\sqrt{n} \) as the standard error of estimate, where \( s \) is the standard deviation of the maximum flows.

When we test a hypothesis, it is our objective to see whether a particular difference of means \( d \) falls within, e.g., the most extreme 5% of difference of means which could be expected. For a two-tailed test, that is 2.5% on both sides of the curve (middle figure in figure D.1). With \( t = \frac{d}{(s/\sqrt{n})} \) a t-value can be calculated, giving the number of standard errors our difference mean \( d \) is from zero of the theoretical distribution, assuming equal variances of the two samples (with total sample size is \( n \)). A difference between means is
significant if the $t$-value is larger than the critical value at the (e.g., 2.5%) tail of the distribution.

Several approaches are possible for our statistical analysis of capacity estimates. First approach assumes equal standard deviation for reference and AICC-scenario maximum flow distribution. Second approach assumes an equal coefficient of variation for reference and AICC-scenario maximum flow distribution ($c.o.v. = s / \mu$). A third option is to assume different standard deviations or c.o.v. between reference and scenario. This last approach implies a time-consuming activity, since we consider about 120 scenario’s in our study, so only the first and second approach are considered. The standard deviation in the first approach, and the c.o.v. in the second approach are based on the maximum flow distribution of the reference case. The maximum flow distribution, standard deviation, and coefficient of variation of the three different reference cases (the three bottleneck types with 0% AICC-vehicles) are determined using a sample size of $n=50$, which gives a sufficient accurate value for sample mean and standard deviation. However, we will conduct the experimental scenarios with a fewer sample size in order to limit the simulation effort. We hypothesise that a sample size of $n=10$ is sufficient to compare a scenario mean with the reference mean.

For the reference cases (0% penetration of AICC) of the three bottleneck types, five simulation runs are performed resulting in a sample of independent maximum flows of $n=50$. Table D.1 shows the results. For the queue discharge speed, a mean of 4,285 veh/h was found for the two-lane motorway with on-ramp. A standard deviation of 81.5 veh/h was observed, which means a coefficient of variation of 1.9%.

<table>
<thead>
<tr>
<th></th>
<th>Capacity (n=50) [veh/h]</th>
<th>Standard deviation (n=50) [veh/h]</th>
<th>c.o.v. [%]</th>
<th>Standard error n=50 (n=20) [veh/h]</th>
<th>c.o.v. of mean n=50 (n=20) [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Two-lane with on-ramp</td>
<td>4,285.2</td>
<td>81.5</td>
<td>1.9</td>
<td>11.5 (18.2)</td>
<td>0.27 (0.42)</td>
</tr>
<tr>
<td>Three-lane with on-ramp</td>
<td>6,170.4</td>
<td>99.6</td>
<td>1.6</td>
<td>14.1 (22.3)</td>
<td>0.23 (0.36)</td>
</tr>
<tr>
<td>Weaving section</td>
<td>6,996.1</td>
<td>153.8</td>
<td>2.2</td>
<td>21.8 (34.4)</td>
<td>0.31 (0.49)</td>
</tr>
</tbody>
</table>

**Table D.1** Mean, standard deviation, standard error, and coefficient of variation for the reference cases of the distinguished bottleneck types

Table D.2 presents results of the Student’s $t$-test which has been applied to determine the accuracy level relative to the reference case in each bottleneck type. The calculations are performed assuming ten maximum flow rates per scenario, thus $n_{ref}=10$ and $n_{sc}=10$. The total sample size on which the test is based is thus $n=20$. Equal variances of maximum flows for all scenario’s of a bottleneck type have been assumed. Calculations using an equal c.o.v. will give results that will only slightly differ from the presented outcomes.

The critical value (two-tailed, $p<0.05$) for $t$ is shown in the first column. The second column gives the insignificance margin, expressed in vehicles/hour, that the (mean) capacity of a scenario can deviate from the (mean) capacity of the reference. If the difference is larger than this value, the means are significantly different with 95% level of confidence. The third column shows the critical difference, expressed as a percentage of the reference mean. The last column gives the minimum number of simulations needed to achieve a critical
relative difference (accuracy) of 0.5%.

<table>
<thead>
<tr>
<th>Critical t-value (n=20, p&lt;0.05)</th>
<th>Critical difference [veh/h]</th>
<th>Accuracy</th>
<th>Needed sample n (0.5% accuracy)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Two-lane with on-ramp</td>
<td>2.45</td>
<td>44.6 veh/h</td>
<td>1.0%</td>
</tr>
<tr>
<td>Three-lane with on-ramp</td>
<td>2.45</td>
<td>54.6 veh/h</td>
<td>0.9%</td>
</tr>
<tr>
<td>Weaving section</td>
<td>2.45</td>
<td>84.3 veh/h</td>
<td>1.2%</td>
</tr>
</tbody>
</table>

TABLE D.2 Results of conducted t-test with assumed equal variance of all scenarios of bottleneck type

From the table it follows that an accuracy range between approximately -1% and +1% can be achieved when we use a sample size n=10 per scenario. Thus, an indifference band around the reference mean capacity of ± 1% is applied in our analyses of capacity impacts of AICC introduction. For higher accuracy levels, the needed sample size increases substantially, as will the time-consuming simulation effort.
## LIST OF SYMBOLS

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$x(t)$</td>
<td>vector of the actual state attributes at instant $t$;</td>
</tr>
<tr>
<td>$y(t)$</td>
<td>vector of state observations (e.g. speeds, relative speeds, distances);</td>
</tr>
<tr>
<td>$\hat{x}(t)$</td>
<td>vector of estimated state attributes at instant $t$;</td>
</tr>
<tr>
<td>$u(t)$</td>
<td>vector of feasible control actions;</td>
</tr>
<tr>
<td>$u^*(t)$</td>
<td>vector of selected control actions;</td>
</tr>
<tr>
<td>$\bar{u}^*(t)$</td>
<td>vector of executed control actions;</td>
</tr>
<tr>
<td>$e_{\text{obs}}$</td>
<td>vector of perception errors</td>
</tr>
<tr>
<td>$e_{\text{dec}}$</td>
<td>vector of decision errors</td>
</tr>
<tr>
<td>$e_{\text{act}}$</td>
<td>vector of actuator errors</td>
</tr>
<tr>
<td>$J$</td>
<td>objective function with driver’s objectives;</td>
</tr>
<tr>
<td>$H$</td>
<td>time horizon;</td>
</tr>
<tr>
<td>$\tau$</td>
<td>overall time delay (effect)</td>
</tr>
<tr>
<td>$\tau_{\text{obs}}$</td>
<td>state observation time delay;</td>
</tr>
<tr>
<td>$\tau_{\text{dec}}$</td>
<td>decision time delay (state prediction and control decision);</td>
</tr>
<tr>
<td>$\tau_{\text{act}}$</td>
<td>actuator time delay;</td>
</tr>
<tr>
<td>$\tau_{sc}$</td>
<td>time scan interval (model parameter);</td>
</tr>
<tr>
<td>$\tau_{\text{serv}}$</td>
<td>update time interval (user class dependent model parameter);</td>
</tr>
<tr>
<td>$\tau_{\text{ad}}$</td>
<td>additional time delay (model parameter);</td>
</tr>
<tr>
<td>$i$</td>
<td>index for vehicle;</td>
</tr>
<tr>
<td>$j$</td>
<td>index lane;</td>
</tr>
<tr>
<td>$c$</td>
<td>index capacity state;</td>
</tr>
<tr>
<td>$u$</td>
<td>index user class;</td>
</tr>
<tr>
<td>$x$</td>
<td>longitudinal position of vehicle on roadway;</td>
</tr>
<tr>
<td>$\dot{x}$</td>
<td>local speed of vehicle;</td>
</tr>
<tr>
<td>$\ddot{x}$</td>
<td>local acceleration of vehicle;</td>
</tr>
<tr>
<td>$a, c, l, m$</td>
<td>parameters in the classic car-following model;</td>
</tr>
<tr>
<td>$d$</td>
<td>net gap distance [m];</td>
</tr>
<tr>
<td>$l$</td>
<td>vehicle length [m];</td>
</tr>
<tr>
<td>$s$</td>
<td>gross gap distance [m];</td>
</tr>
<tr>
<td>$h$</td>
<td>gross time headway [s];</td>
</tr>
<tr>
<td>$q$</td>
<td>flow rate [vehicles/hour];</td>
</tr>
<tr>
<td>$n$</td>
<td>sample size [vehicles];</td>
</tr>
<tr>
<td>$r$</td>
<td>reaction time distance [m];</td>
</tr>
<tr>
<td>$b$</td>
<td>braking distance (with assumed constant deceleration) [m];</td>
</tr>
<tr>
<td>$m$</td>
<td>desired safety margin [m];</td>
</tr>
<tr>
<td>$z_1, z_2$</td>
<td>parameters in safe distance function;</td>
</tr>
<tr>
<td>$\mathcal{N}(\mu, \sigma)$</td>
<td>normal distribution with mean and standard deviation;</td>
</tr>
<tr>
<td>$\tau_{sc}$</td>
<td>time scan [s];</td>
</tr>
<tr>
<td>$TTC_i(t)$</td>
<td>time-to-collision value for driver $i$ at moment $t$ [s];</td>
</tr>
</tbody>
</table>
\(TTC^*\) : time-to-collision threshold value [s];
\(TET\) : aggregate safety indicator based on exposition to TTC values [s];
\(TIT\) : aggregate safety indicator based on weighted exposition to TTC values \([s^3]\);
\(\overline{TET}\) : average exposition to unsafe TTC-values per vehicle \([s/\text{vehicle}]\);
\(TETP\) : probability of driver’s exposition to unsafe time-to-collisions below \(TTC^*\);

\(\pi\) : headway margin (model parameter);
\(c_1, c_2\) : parameters in Helly’s car-following model;
\(\eta\) : congestion factor in car-following model;
\(v_{\text{des}}\) : desired speed;
\(\dot{x}_{\text{left}}\) : estimated adjacent left lane \(j-I\) speed (by driver \(i\) on lane \(j\));
\(\Delta v_{\text{thr}}\) : threshold speed differential for starting lane change;
\(TTC_{\text{left}}\) : threshold time-to-collision value for starting left lane-change,
\(T_{u,\text{rel}1}\) : relaxation time to adapt to left adjacent lane speed (user class dependent model parameter);
\(T_{u,\text{rel}2}\) : relaxation time to position along gap on adjacent lane (user class dependent model parameter);
SUMMARY

Supported Driving: Impacts on Motorway Traffic Flow
Michiel M. Minderhoud

Introduction
One solution for enhancing today's limited road capacity is the development and deployment of functionally improved motorized vehicles replacing parts of the driving task of the driver. In addition to capacity gains, driving task automation may also lead to safety improvements. The expected benefits for the individual driver are comfort gains and greater travel convenience since parts of the driving task are carried out automatically. In the past, the impacts of these systems have not unambiguously been determined.

The first generation of driver support systems will become available before the second millennium. These early driver assistance systems, referred to as Autonomous Intelligent Cruise Control (AICC), can replace the speed adjustment and distance keeping task of the driver with respect to the vehicle in front on the same lane. Vehicles equipped with such a driver assistance system can drive on the current motorway among non-equipped vehicles. Infrastructural adaptations are not needed.

Objective and study approach
The objective of our study is to quantify and assess the potential improvements (or deteriorations) of the traffic flow quality at bottleneck motorway sections given a number of conditions, such as the proportion of the vehicle fleet equipped with specific longitudinal driver assistance systems, the so-called AICCs.

Many questions emerge regarding relationships between design choices and parameter settings of AICC systems and motorway capacity. Within the scope of the study, the focus is on the following relationships:

• impact of headway setting of AICC on motorway capacity and safety;
• impact of other AICC design parameters such as minimum deceleration level, minimum speed, and manual/automatic reactivation of the system on motorway capacity and safety;
• impact of proportion of the vehicle fleet equipped with AICC.

A survey of literature has been conducted on the expected capacity impacts of driver support and automated vehicle guidance systems.

Literature study
An extensive literature study has been performed to assess past capacity expectations of AICC introduction. We conclude that many studies did not use an appropriate capacity estimation method or experimental setup. Bottleneck locations are seldom studied. The number and variation of tested AICC systems are limited in almost all studies. Headway settings that theoretically deteriorate motorway capacity are often selected in test cases. The influence of other design parameters is not examined extensively. In our experimental setup, it is attempted to alleviate the shortcomings observed and to estimate the traffic flow impacts more reliably.
From our literature review it also emerges that the deployment of the fully automated systems, referred to as Automated Highway System (AHS), is a long-term development. Several problems relating to rapid AHS deployment are identified. We observed that the theoretical capacity improvements (said to be a factor of two to three compared with the current motorway lane) are only achievable if vehicles are equipped with communication facilities. For a valid comparison of capacity improvements, the additional transition lane for egress and exit processes should be taken into account. In addition, the theoretical capacity on the dedicated lane will be diminished by the necessary merging processes of exiting and entering vehicles.

**Experimental setup**

Three bottleneck situations have been selected as test cases for the impact assessment of AICC systems, since we expected that impacts may differ by location. Furthermore, capacity estimation can only be performed reliably at a bottleneck. The so-called queue-discharge flow capacity can then be determined quite well, since this situation can be sustained for a long period. We use five minute intervals to aggregate the microscopic data generated by the simulation model.

The experiment involved five AICC layouts, with headway settings between 0.8 and 1.4s. Differences between the layouts are the operational speed range, the reactivation functionality and the supported acceleration range. The 'Normal AICC' represents the characteristics of early assistance systems, with a speed range of 30 to 150 km/h and manual reactivation. The 'Extended AICC' is an extension of the 'Normal AICC' with an automatic reactivation functionality. Both AICC layouts support accelerations in the range -0.3g to +0.15g. A 'Queue AICC' is proposed to deal with stop-and-go traffic, it supports only speeds from 0 to 60 km/h. The 'All Speed AICC' is equal to the 'Extended AICC' but supports also the 0 to 30 km/h speeds. The 'Complete AICC' is the most expensive one, since it has all characteristics of the 'All speed AICC' but also supports the full acceleration range of the vehicle.

All AICC-systems have been tested at various levels of penetration in the vehicle fleet (0%, 10%, 20%, 50% and 100%) for each of the three bottlenecks considered. Analyses of traffic flow quality impacts especially focussed on the capacity changes compared to the reference situation of each of the bottleneck cases.

For the safety analysis, a number of purposeful aggregated time-to-collision safety indicators have been developed, taking into account the occurrence of all individual TTC values of vehicles at any roadway position during a simulation run. This new approach has the advantage above existing methods that very small time-to-collision values are observed when they occur, and not just rarely at a cross-section. The safety indicators have been derived for all the tested systems and bottleneck situations.

**The dedicated microscopic simulation model**

In order to establish the impacts quantitatively, simulation experiments have been conducted. A new dedicated microscopic simulation model that embodies the driver assistance functionalities of the expected first generation support systems has been developed. The model is characterised by new elements compared to similar models. The hypothesised increased gap distance of drivers after having experienced congested conditions has been implemented and shows great resemblance to empirical data. The desired speed distribution of vehicles of a user class have been based on a mean and a
standard deviation, and the same holds for the time delay determining the desired gap distance of a vehicle.

Driver behaviour has been modelled according to a control model that assumes simultaneous longitudinal and lateral driving task execution. For the longitudinal driving task, the speed adaptation depends on the observed leader, the speed on the left-side lane, and anticipation of foreseen lane changes from the right adjacent lane. The leader selection procedure is quite sophisticated, taking into account the state of follower and leader, and position on adjacent lanes. A longitudinal car-following model has been specified using four different parameter sets for four different car-following conditions. The lateral task involves evaluation of the lane change desirability conditions and gap acceptance requirements. A large set of speed dependent conditions for starting lane changes have been determined. A control action is executed after a delay time depending on the vehicle’s user class characteristics.

The model reproduces microscopic data (position and speeds) which is aggregated into macroscopic data. Headway, acceleration, and time-to-collision distributions are also determined.

Findings from the simulation study
We found that the capacity impacts near a bottleneck on a three-lane motorway are considerable. Fewer but also significant capacity changes are found at the tested two-lane motorway on-ramp bottleneck.

It appeared that as the penetration rate increases, the capacity gain increases. At full penetration, the capacity gain of the expected early AICC at a two-lane motorway with on-ramp bottleneck is about 4%. The sophisticated Complete AICC achieves even a 12% gain. At the three-lane bottleneck site, the early AICC-systems achieve capacity changes of about 7%. The Complete AICC lead to a capacity increase of 25%. The impacts at a weaving section are comparable with the three-lane motorway bottleneck.

An important factor that explains to a large extent the capacity gains found are the time headway settings of the tested AICC systems. Small settings below 1.2 s increase the critical density and the road capacity. Capacity remains at the same level with systems using a headway setting of 1.2 s. A small capacity decrease has been observed at the 1.4 s headway setting. We observed that the left and centre lanes carry relatively and absolutely more vehicles per hour than in the three-lane scenarios. Analysis of the user class distribution showed that there is no difference between equipped and non-equipped vehicles in using a particular lane.

The speed at capacity increases considerably for the two-lane AICC scenarios. The speed increase for the three-lane scenarios is less, while the weaving section shows no improvement in critical speeds at all.

The Extended AICC with automatic reactivation functionality did not clearly perform better than the Normal AICC with manual reactivation at the tested headway settings.

For the majority of the AICC systems tested the time-to-collision safety indicator values do not significantly differ from the safety indicator value for the reference case. However, the safety analysis shows unsatisfactory time-to-collision indicator values of the Extended AICC at 0.8 s headway. The full penetration of the system in the vehicle fleet can result in dangerous shock waves since drivers must take over control as they experience low speeds not supported by the AICC. Drivers must intervene if the acceleration boundaries have been
reached, or the minimum speed boundary has been reached. In this case, the left lane shows the greatest unsafety.

Another finding is the increased average travel speed in most scenarios, indicating an higher safety risk.

**General conclusions and implications**

The general conclusion is that AICC can have a positive impact on the motorway capacity. Requirements for attaining these gains are headway settings below 1.2 s and the restriction (our assumption) that a driver can not adjust or change this headway setting. The reactivation functionality of an AICC should preferably be automatic, since it will probably reduce driver’s mistakes (reliance on the system while idle after intervention). Clear capacity effects of this design aspect have not been found. The supported speed range should be large for safety considerations (including stop-and-go speeds and the safe approach of standing queues). Hardly evidence has been found of substantial impacts of the deceleration authority and speed range on the capacity. This issue should be studied further in an adapted experimental setup.

The safety of the majority of the tested AICC systems appears acceptable when using the developed safety indicators with a TTC threshold value of 3 seconds. We found that systems at 0.8 s headway and restricted support (speed range or deceleration) are relatively unsafe. At full penetration of these AICC systems, rear-end collisions may occur in extreme situations. The Normal AICC at 0.8 s and Extended AICC at 0.8 s are examples of unsafe system designs which should not be deployed.

If we compare the capacity gains derived in our study with the gains attainable with dynamic traffic management measures (maximum gain about 5%), it is obvious that the introduction of driver support systems or AICC can further increase road capacity. The expected increase can be achieved without infrastructural adaptations or other costs to the motorway operator. However, a considerable number of vehicles should be equipped in order to notice the capacity improvements expected.

We expect that the introduction of AICC fits in with the capacity trend growth due to technological improvements of the car and its driver. A gradual improvement of the functionalities of the first generation assistance systems may eventually evolve into the concept of Automated Highway Systems with dedicated lanes, where the driver is fully supported and the equipped vehicles will be driven automatically in platoons.
SAMENVATTING

Ondersteund rijden: Invloed op de verkeersafwikkeling van autosnelwegen
Michiel M. Minderhoud

Inleiding
Een van de mogelijkheden om de huidige schaarse wegcapaciteit te vergroten is de ontwikkeling en invoering van bestuurdersondersteunende systemen in motorvoertuigen. De verwachting is dat het gebruik van deze systemen gaat leiden tot capaciteitsverhogingen en tevens een positieve bijdrage levert aan de verkeersveiligheid. Het grote voordeel van de bestuurder is de vergroting van het rijcomfort en reisplezier doordat delen van de rijtaak automatisch worden uitgevoerd.

De eerste generatie van deze bestuurdersondersteunende systemen zullen binnenkort op de Europese markt beschikbaar zijn, bijvoorbeeld het Distronic systeem van Mercedes. Deze eerste systemen, ook wel aangeduid met AICC (Autonomous Intelligent Cruise Control), kunnen automatisch de snelheid van het voertuig aanpassen om zodoende een gewenste veilige afstand te kunnen handhaven ten opzichte van de voorligger op dezelfde strook. Voertuigen uitgerust met zo'n systeem kunnen eenvoudig op bestaande autosnelwegen rijden tussen voertuigen die niet met dit systeem zijn voorzien. Het gebruik van AICC vereist geen infrastructure aanpassingen aan autosnelwegen.

Doel en studie opzet
Het doel van de studie is het kwantificeren en vaststellen van de mogelijke effecten van rijtaakondersteunende systemen met betrekking tot de verkeersafwikkeling, gegeven een aantal condities, zoals het aandeel van een bepaald type AICC in de voertuigvloot.

Een groot aantal onderzoeksvragen volgen uit deze vraagstelling, onder meer:
- het verband tussen volgtijdinstelling en wegcapaciteit;
- de relatie tussen de wegcapaciteit en andere ontwerpvariabelen van een AICC, zoals de minimum snelheid en maximum deceleratie ondersteund door het systeem;
- de invloed van de uitrustingsgraad op de wegcapaciteit.

Een literatuurstudie is uitgevoerd om meer inzicht te krijgen in de mogelijke capaciteits-effecten van AICC en andere automatiseringsconcepten. Hierdoor kon de studieopzet verder worden verfijnd.

Literatuurstudie
Een uitvoerige literatuurstudie naar de capaciteits-effecten van AICC-systemen is uitgevoerd, en de bevindingen hieruit bestudeerd. We concluderen dat veel studies geen geschikte capaciteitsschatterings methode gebruiken, of een juiste experimentele opzet volgen. Knelpunt locaties zijn zelden bestudeerd. In de meeste studies is het aantal en de verscheidenheid van de geteste AICC-systemen te beperkt. Volgtijdinstellingen die theoretisch de capaciteit verslechteren worden vaak gekozen als een test-case. De invloed van andere ontwerpvariabelen wordt niet of nauwelijks onderzocht. Onze experimentele opzet tracht de tekortkomingen van de bestudeerde literatuur te verlichten.
Uit de literatuurstudie blijkt tevens dat de invoering van een zogenaamde Automatische Snelweg een lange termijn ontwikkeling is. Verschillende problemen spelen een rol voor een snelle implementatie van een dergelijk systeem. Alhoewel de theoretische capaciteitstoename voor een enkele strook met dit systeemconcept geschat wordt op een factor twee of drie van de huidige strookcapaciteit, dient er rekening te worden gehouden met de negatieve invloed van invoegend en uitvoegend verkeer op de strookcapaciteit. Verder vereist dit concept communicatie tussen voertuigen onderling, en tussen het voertuig en de wegkant. Daarnaast moet rekening worden gehouden met de noodzaak van het toepassen van een additionele rijstrook, voor het faciliteren van de in- en uitvoegprocessen naar de automatische strook.

Experimentele opzet
In het onderzoek zijn drie knelpunt (bottleneck) situaties bestudeerd als cases voor de studie naar de effecten van AICC op de verkeersafwikkeling. De verschillende knelpunt lokaties zijn gekozen omdat we veronderstelden dat de effecten zullen verschillen per locatie. Het gebruik van een microscopisch simulatiemiddel bleek nodig om voldoende realistische verkeerskundige analyses te kunnen maken. Voor het vaststellen van effecten op de wegcapaciteit is een betrouwbare capaciteitsschattingmethode gebruikt. Deze gaat er terrecht van uit dat de wegcapaciteit alleen betrouwbaar kan worden vastgesteld benedenstrooms van een knelpunt. De afrijcapaciteit kan hier goed worden bepaald onder voorwaarde van de aanwezigheid van bovenstroomse congestie.

De uitgevoerde simulatiestudie omvatte vijf verschillende AICC types, met volgtijdinstellingen tussen 0.8 en 1.4 seconde. De verschillen tussen de systemen worden gekarakteriseerd door de operationele snelheidsrange, de acceleratierange en methode van reactivatie. De Normale AICC combineert de eigenschappen van de eerste generatie AICC systemen, met een beperkte snelheidsondersteuning (30-150 km/h), beperkte acceleratierange (-0.3 g tot +0.15 g) en met een handmatige reactivatie voorziening. De Extended AICC is een variant van de Normale AICC met een automatische reactivatie voorziening. Verder is een zogenaamde Queue AICC getest met een ondersteunde snelheidsrange van 0 tot 60 km/h, voornamelijk bedoeld voor het ondersteunen van het file-rijden. De All Speed AICC ondersteunt de bestuurder over de volledige snelheidsrange, maar heeft nog een beperkte acceleratieondersteuning. De meest luxe Complete AICC heeft alle functionaliteiten en kan daarmee de bestuurder het meest ondersteunen met zijn longitudinale rijtaak.

Alle AICC-systemen zijn getest op verschillende uitrustingsgraden in de voertuigvloot (0%, 10%, 20%, 50% en 100%) bij elk van de drie bottleneck locaties. De analyse richtte zich voornamelijk op de effecten op de capaciteit, vergeleken met de referentie cases. Voor de veiligheidsanalyse zijn een aantal nieuwe time-to-collision indicators geïntroduceerd die rekening houden met de individuele TTC waarden van de voertuigen gedurende een simulatie. Hierdoor worden de relatief zeldzame, kleine en als gevaarlijke beoordeelde TTC waarden in voldoende mate meegenomen in de veiligheidsanalyse. De indicatorwaarden zijn bepaald voor alle geteste AICC systemen voor elk van de drie bottleneck scenario’s.

Het microscopische simulatiemodel
Voor het bepalen van de capaciteits- en veiligheidseffecten is een simulatiemodel gebruikt. Het toegepaste model is een nieuw ontwikkeld microscopisch simulatie model (SIMONE), speciaal gericht op het simuleren van voertuigen die zijn uitgerust met bestuurdersondersteunende systemen, AICC, zoals omschreven in de experimentele opzet.
Summary

Het omvat tevens nieuwe benaderingen voor het modeleren van het menselijke rijgedrag. Er is onder meer rekening gehouden met de vergrote volgafstand onder congestieve condities. Daarnaast zijn de wensnoodheid en reactietijd individueel bepaald en afhankelijk van de voertuigklasse.

Het rijgedrag is gemedeleerd volgens het principe dat de longitudinale en laterale rijkten simultaan worden uitgevoerd. Voor de uitvoering van de longitudinale rijktaak worden verschillende submodellen onderscheiden die rekening houden met onderdelen van de longitudinale rijktaak, zoals anticipatie op ander verkeer, wetgeving (niet rechts passeren) en de afstand tot de leider. De leider bepaling is een belangrijk onderdeel van de longitudinale rijktaak waarbij onder meer rekening wordt gehouden met de laterale status van volger en voorliggers op de eigen en aanliggende stroken. Een longitudinaal voertuig-volg model is toegepast met vier verschillende parameter sets voor vier verschillende volgsituaties. De laterale rijktaak omvat de evaluatie van de strookwissel wenselijkheid en mogelijkheid. Een uitgebreide set van condities voor het uitvoeren van een strookwisseling is gespecificeerd. De model-uitkomsten laten een goede overeenkomst zien met praktijkwaarnemingen.

Het model aggregereert de microscopische gegevens in macroscopische verkeersgegevens, zoals intensiteiten en snelheden. Daarnaast worden volgtijden, acceleraties en time-to-collision verdelingen vastgesteld per strook.

Resultaten
Het blijkt dat de capaciteitsverbeteringen op een driestrooms autosnelweg vrij aanzienlijk zijn bij toepassing van AICC. De verbeteringen op een tweeestrooks autosnelweg zijn minder groot. Het blijkt verder dat naarmate de uitrustingsgraad toeneemt, de effecten groter zijn. Op een driestrooms autosnelweg worden bij een volledige penetratie van de Normale AICC capaciteitswinsten gevonden van ongeveer 4%. De geavanceerde Complete AICC met 0.8 s volgtijd laat toenames van maar liefst 25% zien ten opzichte van de referentie cases. Bij een tweeestrooks autosnelweg zijn de toenames ongeveer de helft van de toenames op de driestrooms autosnelweg. De capaciteitsveranderingen op een weefvaks knelpunt blijken vergelijkbaar te zijn met de effecten van de driestrooms autosnelweg met oprit. De Complete AICC 0.8 s geeft hier een capaciteitstoename van 20%.

Bij veel scenario's is de kleine volgtijdstelling, en dus hogere kritische dichtheid, de verklarende factor van de capaciteitsverbeteringen. Ook is de hogere snelheid bij de capaciteit aan te wijzen als verklarende factor voor de gevonden toenamen in de capaciteitswaarden bij de twee- en drie-strooms scenario's. De snelheden bij capaciteit veranderden weinig bij de weefvaks scenario's. Systemen met 1.2 s volgtijd geven geen significante verandering van de capaciteit te zien in vergelijking met elk van de referentie cases.

Over het algemeen zijn de veiligheidsindicatorwaarden van de AICC-scenario's vergelijkbaar met de indicatorwaarden vastgesteld voor de referentie cases. Een lichte stijging van de waarden is opmerkelijk bij toenemende uitrustingsgraad van AICC in de voertuigvloot. De veiligheidsanalyse laat een onbevredigende indicator waarde zien voor de Extended AICC met 0.8 s volgtijd. Bij volledige penetratie van dit systeem worden schokgolven met veel lage TTC waarden gevonden, met name op de linkerstrook. Dit is te verklaren door de noodzakelijk overschakeling van automaat naar de bestuurder wanneer snelheden onder 30 km/h worden bereikt.
Algemene conclusies en implicaties
De algemene conclusie is dat AICC kan bijdragen tot een verhoging van de capaciteit op autosnelwegen vergeleken met de huidige situatie. Hiervoor is het wel vereist dat een volgtijdstelling onder de 1.2 seconde wordt gebruikt, en dat bestuurders deze instelling niet zelf kunnen aanpassen. De reactivatie voorziening van een AICC zou automatisch moeten zijn uit veiligheidsoverwegingen, omdat het de kans op fouten gemaakt door de bestuurder verminderd. De ondersteunde snelheidsrange moet zo breed mogelijk zijn om het aantal verplichte bestuurdersinterventies te minimaliseren. Er is weinig bewijs voor een effect van de ondersteunde deceleratierange op de capaciteit. Dit aspect moet nog nader worden bestudeerd met een aangepaste studieopzet met aangepaste systeem specificaties.

De veiligheid van de meeste AICC-systemen lijkt bevredigend. We blijkt de gemiddelde snelheid omhoog te gaan, wat een veiligheidsrisico met zich mee brengt. De Extended AICC met 0.8 s volgtijd bij 100% uitrustingssgraad laat extreem hoge indicatorwaarden zien die wijzen op een onbevredigend en onveilig functioneren, gelet op de ondersteunende eigenschappen van het systeem. Zulke systemen kunnen beter niet worden ingevoerd.

Wanneer we de gevonden capaciteitswinsten vergelijken met mogelijke winsten bij uitvoering van andere capaciteitsverhogende maatregelen op autosnelwegen, dan valt op dat de invoering van AICC een aanzienlijke bijdrage kan leveren zonder infrastructurale aanpassingen of overige kosten voor de autosnelwegbeheerder. Het is echter wel nodig dat de (Europese) overheid het ontwerp en instelmogelijkheden van AICC-systemen aan regels legt, om zo negatieve effecten op wegcapaciteit of veiligheid te kunnen beheersen.

We verwachten dat de invoering van AICC aansluit bij de jaarlijkse trend van een groeiende wegcapaciteit van ongeveer 0.5 tot 1% per jaar. Er is geen langdurige trendbreuk te verwachten gelet op de gevonden capaciteitswinsten, de verwachte termijn van invoering, en de te verwachten verdere ontwikkelingen van meer geavanceerde systemen die de wegcapaciteit verder kunnen doen vergroten in de toekomst. De geleidelijk invoering, ontwikkeling, en verbetering van de eerste generatie assisterende systemen zal op den duur kunnen leiden tot automatische voertuiggeleiding waarbij de voertuigen elkaar volledig geautomatiseerd en op korte afstand volgen.
ABOUT THE AUTHOR

Michiel Minderhoud was born in 1972 in Bussum, The Netherlands. He obtained his degree in Civil Engineering at the Delft University of Technology in 1995. His master’s thesis focussed on a dynamic parking reservation system. It described the design, development and evaluation of such a new approach to relieve parking problems in city centres. This research was awarded with a prize by the Dutch Department of Transport.

After finishing the study, he joined the Traffic Engineering section of the Department of Infrastructure at the faculty of Civil Engineering as a Ph. D. student. During this research, he has presented various papers in the Netherlands and several international conferences. Michiel has published articles of his work in several scientific and professional journals. As a university staff member he assisted students with projects and practical work, which are part of the Civil Engineering curriculum.

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