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Traffic effects of Automated Vehicle Guidance systems

TNO Inro

A literature survey

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PREFACE

The research described in this document was conducted as part of a study into the development of Automated Vehicle Guidance systems. This project was conducted by the TNO Institute of Infrastructure, Transport and Regional Development (Inro) and financed by the Dutch Ministry of Transport, Public Works, and Water Management. The literature search was conducted based upon previously published TNO reports, relevant conference proceedings, consultation of several experts of which special thanks to A.P. De Vos from TNO-TM and D. Godbole and M.A. Kourjanski from the PATH program (ITS Berkeley), and a CD-ROM search at the library of the Delft Technical University, The Netherlands.

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SUMMARY

Automated Vehicle Guidance (AVG) systems are systems in which driving tasks are supported or taken over partly or entirely by an automated system. The reported benefits of AVG systems involve improvements of road traffic performance, safety, and comfort. The research described in this report has the following objective:

To describe the existing state of knowledge with respect to the interaction between automated, AVG supported vehicles and manually driven vehicles. The description focuses on the traffic effects of the interaction between automated and manually driven vehicles, and more precisely on the effect of this interaction on the maximum achievable capacity.

This research objective was triggered by other studies on AVG systems. These studies mention that the interaction between automated, AVG supported vehicles and manually driven vehicles could obscure the reported improvements of the throughput by the use of AVG systems.

In order to structure the research and the presentation of results and to provide the reader with an overview, we defined three stages for the development for AVG systems. These three stages can be considered as a global chronological development path for AVG systems. It should be noted that many other (orderings of) developments stages can be thought of. The identified stages are:

Stage 1: Early AVG in Mixed Traffic. This stage consists of the introduction and use of systems that are able to support and take over certain driving tasks. These systems will be used in normal traffic condition in which ‘normal’ manually driven cars are present. A possible system is Adaptive Cruise Control (ACC) which maintains a vehicle's speed while keeping a safe distance to a predecessor. In this stage no communication between vehicles and road-side infrastructure is present.

Stage 2: Introduction of AVG lanes. This stage differs from the previous stage by the dedication of certain parts of the infrastructure to AVG equipped vehicles. This infrastructure will mainly involve a lane. Similar to the previous stage, no communication between vehicles and road-side infrastructure is present.

Stage 3: Intelligent AVG infrastructure. This stage differs from the previous stages by the equipment of the infrastructure with intelligent, communicative systems. This equipment allows vehicle-road communication. Another major development within this stage is the expansion of the dedicated lanes to form a network of special AVG roads.

The studies that were found in the literature were assigned to one of these stages. Each study was briefly described. At the end of the discussion of each stage, the results for that stage were summarized into a table. In total 12 relevant references were found on Stage 1. These references use computer simulation, driving simulation and real traffic experiments to analyze the traffic effects of

the interaction of automated and manually driven vehicles. Only 3 relevant studies were found on Stage 2. These three studies all used computer simulation to analyze the traffic effects. Most references were found with respect to Stage 3, namely 28. These studies used optimization, design, analytical modeling, computer simulation, and driving simulation to analyze the traffic effects.

The main conclusions with respect to the stages were:

Stage 1: Introducing ACC systems in mixed traffic conditions is likely to result in a small capacity increase of a few percentages. This capacity increase may, however, turn out to be a capacity decrease if drivers set the target headway too large. As a consequence of this result, ACC is mostly presented as a comfort and safety device.

Stage 2: The capacity gains for introducing a lane exclusively dedicated to AVG vehicles seem to be marginal in comparison with the situation in which both automated and manually driven vehicles are allowed to use the lane. Introducing an AVG lane (without infrastructure intelligence) will probably be based on aspects other then capacity. Firm conclusions could, however, not be derived for this stage, since only a few studies investigate a situation that fits into Stage 2.

Stage 3: The anticipated capacity improvement for this stage are huge. Improvements of 100 to 200% are most frequently mentioned. These capacity estimates are based upon design parameters, and less on actual predictions of traffic behavior. Most future research on this stage will concern studies of the best design of infrastructure and (software) procedures. An important capacity issue is the connection of high capacity AVG lanes with local streets. This connection is necessary for feeding traffic onto an AVG lane and for dispersing traffic off the lane. The consistency of the design parameters is an important issue.

Some suggested future research direction are:

Stage 1: A carefully designed field test of ACC vehicles. This field test is necessary to determine the capacity and other effects for the Dutch traffic situations. Such a test was mentioned by Becker et al. (1994) as a prerequisite to proceed and accompany the market introduction of ACC.

Stage 2: The identification of suitable locations in The Netherlands for introducing a dedicated AVG lane and an analysis of the effect of such a lane on the surrounding road network.

Stage 3: The design of a connection between high capacity AVG lanes and local streets and an exploration of the possibilities of using AVG onto the local streets or within cities. Another interesting research direction is an investigation of the effects of AVG on traffic flows within the road-network .

More general suggestions for future research are the attitude of the public and car manufacturers towards AVG development and the connection between AVG and other (IT) developments in road infrastructure, passenger cars, trucks and public transport.

SAMENVATTING

Automatische Voertuiggeleiding (AVG) heeft betrekking op systemen die bepaalde rijtaken kunnen ondersteunen of die bepaalde rijtaken kunnen overnemen van de bestuurder. De gerapporteerde voordelen van AVG zijn het verbeteren van de verkeersafwikkeling, de veiligheid en het comfort voor de chauffeur en de passagiers. Het onderzoek dat is vastgelegd in dit rapport heeft de volgende doelstelling:

Het beschrijven van de huidige kennis met betrekking tot de interactie van geautomatiseerde, AVG ondersteunde voertuigen en handmatig bestuurde voertuigen. De beschrijving richt zich op verkeerseffecten van deze interactie, en specifiek op het effect op de maximaal bereikbare capaciteit (doorstroming).

Deze doelstelling komt voort uit andere studies naar AVG systemen. Deze studies noemen de interactie van geautomatiseerde, AVG ondersteunde voertuigen en handmatig bestuurde voertuigen als een oorzaak waardoor de gerapporteerde capaciteitswinsten mogelijk niet bereikt kunnen worden.

Om het onderzoek te structureren en de lezer een overzicht te verschaffen, hebben wij drie stadia gedefinieerd voor de ontwikkeling van AVG. Deze drie stadia representeren een globaal, chronologisch ontwikkelingspad voor AVG. Opgemerkt dient te worden, dat vele andere (volgorden) van stadia als plausibel kunnen worden beschouwd. De onderscheiden stadia zijn:

Stadium 1: AVG in gemengd verkeer. Dit stadium betreft het introduceren en gebruiken van AVG systemen die ondersteuning bieden en/of bepaalde taken van de bestuurder kunnen overnemen. Deze systemen kunnen worden gebruikt in normale verkeerssituaties waarin ook handmatig bestuurde voertuigen aanwezig zijn. Een van de systemen die in dit stadium kunnen worden gebruikt is Adaptive Cruise Control (ACC). ACC handhaaft de snelheid van de auto, waarbij het systeem voldoende afstand bewaart tot de voorganger. In dit stadium is er geen communicatie tussen voertuigen en de weg-infrastructuur aanwezig.

Stadium 2: Het introduceren van AVG stroken. Dit stadium onderscheid zich van het vorige stadium doordat bepaalde gedeelten van de infrastructuur exclusief aan AVG ondersteunde voertuigen wordt toegekend. Deze gedeelten betreffen primair een rijstrook. Identiek aan het vorige stadium, is er geen communicatie tussen voertuigen en de weg-infrastructuur.

Stadium 3: Intelligente AVG infrastructuur. Dit stadium onderscheid zich van de vorige twee stadia doordat de weg-infrastructuur is uitgerust met intelligente, communicatieve systemen. Deze systemen maken communicatie mogelijk tussen voertuigen en de wegkant. Een andere belangrijke ontwikkeling in dit stadium is de uitbreiding van de AVG stroken tot een netwerk van AVG wegen.

De in de literatuur gevonden studies zijn toegewezen aan een van deze drie stadia. Elke studie is kort beschreven. Aan het einde van de discussie van elk stadium, zijn de gevonden resultaten van dat stadium samengebracht in een tabel. In totaal zijn er 12 relevante studies gevonden met betrekking tot Stadium 1. Deze referenties gebruiken computer simulatie, rij simulator experimenten en experimenten in echte verkeerssituatie om de verkeerseffecten van de interactie van geautomatiseerde en handmatig bestuurde voertuigen te analyseren. Slecht 3 relevante referenties zijn er gevonden met betrekking tot Stadium 2. Deze drie studies maken allemaal gebruik van computer simulatie. De meeste relevante referenties zijn er gevonden met betrekking tot Stadium 3, te weten 28. Deze referenties maakten gebruik van optimalisatie, ontwerp, analytische modellering, computer simulatie en rij simulator experimenten om de verkeerseffecten te analyseren.

De belangrijkste conclusies met betrekking tot de stadia zijn:

Stadium 1: Het introduceren van ACC systemen in gemend verkeer heeft als meest waarschijnlijke resultaat een verhoging van de maximaal bereikbare capaciteit van enkele procenten. De verhoging van de capaciteit kan evenwel omslaan in een verkleining van de capaciteit in het geval dat bestuurder van een voertuig de volgtijd t.o.v. de voorganger te groot instelt. Als een gevolg van dit resultaat, presenteren de meeste auteurs van de gevonden studies ACC als een systeem dat het comfort en de veiligheid verhoogt.

Stadium 2: De capaciteitswinsten bij het exclusief toewijzen van stroken aan AVG ondersteunde voertuigen zijn waarschijnlijk marginaal in vergelijking met de situatie waarin zowel geautomatiseerde als handmatig bestuurde voertuigen gebruik kunnen maken van de strook. Het introduceren van AVG stroken (zonder infrastructurele intelligentie) zal dus vermoedelijk gebaseerd zijn op andere aspecten dan de capaciteit. Harde conclusies konden evenwel niet worden getrokken met betrekking tot dit stadium aangezien slechts 3 studies een situatie onderzoeken die past in Stadium 2.

Stadium 3: De geprognosticeerde capaciteitswinsten voor dit stadium zijn enorm. Verbeteringen van 100 tot 200% worden het meest frequent genoemd. De schattingen van de capaciteit zijn gebaseerd op ontwerp-parameters en niet zozeer op werkelijke voorspellingen van het verkeersbeeld. De meeste studies onderzoeken het beste ontwerp van de infrastructuur en (software) procedures. Een belangrijke capaciteitsaspect is de verbinding tussen de AVG stroken met de hoge capaciteit en de lokale wegen. Een goede verbinding is noodzakelijk om de strook te voeden met voldoende verkeer om het verkeer weer af te voeren van de strook. De consistentie van de ontwerp-parameters is een belangrijk onderwerp.

Enkele suggesties voor toekomstig onderzoek zijn:

Stadium 1: Een zorgvuldig ontworpen gebruikerstest van ACC voertuigen in echte verkeerssituaties gedurende enkele weken. Een gebruikerstest is noodzakelijk om een schatting te kunnen maken van de capaciteitsinvloeden en andere effecten met betrekking tot de Nederlandse verkeerssituatie.

Stadium 2: Het identificeren van geschikte locaties voor het introduceren van exclusief aan AVG toegewezen stroken in Nederland en het analyseren van het effect van een dergelijke strook.op het omliggende verkeersnetwerk.

Stadium 3: Het ontwerpen van geschikte verbindingen van de AVG stroken met een hoge capaciteit met het lokale wegennet en het identificeren van toepassingen van AVG voor gebruik op locale wegen en binnen stedelijke gebieden. Een ander interessante onderzoeksrichting is het analyseren van de invloed van AVG op de verkeersstromen op netwerkniveau.

Meer algemene toekomstige onderzoeksrichtingen zijn de houding van het publiek en fabrikanten ten opzichte van AVG ontwikkelingen en het analyseren van de relatie tussen AVG en andere (IT) ontwikkelingen op het gebied van weg-infrastructuur, personenauto's, vrachtvervoer en -auto's en het openbaar vervoer.

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1 INTRODUCTION

Automated Vehicle Guidance (AVG) systems are systems in which driving tasks of a driver are taken over partly or entirely by an automated system. Many different configurations of AVG systems have been proposed in the literature. The proposed configurations range from Adaptive Cruise Control (ACC) systems which maintain a vehicle's speed while keeping a safe distance to a predecessor, to fully automated car-driving systems (hands, feet, and brain off) which are able to communicate with other vehicles as well as the road-side systems.

The reported benefits of AVG systems involve improvements of the road traffic performance, safety enhancements and increased driver and passenger comfort. The road traffic performance improvements mainly follow from the possible shorter distance in time and space between two vehicles with AVG capabilities. A promising concept of organizing AVG vehicles is platooning. A platoon is a group of vehicles which can safely drive with (very) short intra-platoon distances and with (very) large inter-platoon distances at high speed. The safety is enhanced by the homogeneous automated systems which are able to coordinate movements much better than human drivers and from the small intra-platoon distances and the large inter-platoon distance. The small intra-platoon distance ensures that collision of vehicles within a platoon will occur with small relative speed differences. The large inter-platoon distance ensures that the platoons will come to a stop before they collide. See Shladover (1991) for clear discussion of this subject. The increased driver and passenger comfort follows from the reduction of the driving task of the driver and from the possibility of a more stable traffic flow (less accelerating and decelerating of vehicles) due to the increased homogeneity among the vehicles.

Worldwide, the research efforts for AVG systems is considerable. A subdivision of the research efforts can be made in the technical research of the AVG systems themselves and the research efforts which focus on assessing the impact of the AVG systems. The main objective of the latter research direction is the identification and formulation of concepts for AVG systems, the introduction of these systems, and the determination of the likely (dis)benefits of AVG systems.

This report will be devoted to assessing the impact of AVG systems. Especially, the traffic effects of the interaction of automated and manually driven vehicles will attain attention. This aspect was identified in many studies on the impact of AVG systems as a crucial element for the success of AVG systems. The studies mention that this interaction determines whether the increased theoretical capacity can be obtained in reality. Since these studies also report a limited knowledge of this interaction, this study is aimed at the investigation and the collection of the reported knowledge on this subject in the literature. The most important traffic effects of transportation systems with AVG systems are the achievable (lane) capacity and safety.

The characteristics of the interaction of automated and manually driven vehicles strongly depend on the observed AVG systems. For example, in the early stages of the use AVG systems both manually driven vehicles as well as automated vehicles will likely use the same roads. The interaction of automated and manually driven vehicles in this early stage is the actual mixing of both types of vehicles. For other stages of the use of AVG systems the characteristics of the interaction of automated and manually driven vehicles can be quite different.

The characteristics of the interaction will differ if AVG lanes are introduced. AVG lanes are lanes dedicated to vehicles with a sufficient level of automation. The main reason for introducing these lanes are increased capacity and improved safety. The interaction of automated and manually driven vehicles with respect to these AVG lanes occurs at the entrance and egress sections of these 'super lanes'. Thus, the reader should keep in mind that no generally applicable definition of the interaction of automated and manually driven vehicles can be given. The definition strongly depends on the AVG system investigated, and should be clear from the context.

The description of the interaction between automated and manually driven vehicles will be based upon three stages for developing AVG systems. The description of the identified development stages as well as the precise formulation of the research objective and approach is the subject of chapter 2. In chapter 3 the considered studies from the literature are presented with the use of the development stages for AVG systems. Based upon the literature review, the current state of knowledge of the interaction is presented in Section 4. A conclusion and steps to fill in the missing gaps in the knowledge on the interaction between automated and manually driven vehicles will end this report.

2 RESEARCH OBJECTIVE AND DEVELOPMENT STAGES OF AVG SYSTEMS

2.1 Research objective

The main objective of the research reported here is:

To describe the existing state of knowledge with respect to the interaction between automated, AVG supported vehicles and manually driven vehicles. The description focuses on traffic effects of the interaction between the automated and manually driven vehicles, and more precisely on the effect on the maximum achievable capacity.

This research objective was triggered by other studies on the development of AVG systems. In these studies the mentioned interaction was identified as one of the major aspects for the successful introduction of AVG systems, since the inefficiency of the interaction between automated and manually driven vehicles may obscure the reported improvements of the throughput by the use of AVG systems. The authors of many studies conclude also that future research should be directed assessing the impact of the interaction because they lack the knowledge of the (capacity) effects of the interaction.

The characteristics of the interaction between automated and manually driven vehicles depend strongly on the implemented AVG systems. On the one hand early AVG systems, like ACC, will allow mixing of fully manually driven vehicles and vehicles in which the driver is supported by ACC. On the other hand, Automated Highway Systems (AHS) will allow no mixture of automated and manually driven vehicles. Therefore, *interaction* can be interpreted more accurately by *transfer* of manually control to automated control or vice versa and by the entering and exiting of vehicles from the automated lane. AHS has been defined as vehicle-highway systems that support hands-off and feet-off driving on dedicated/protected freeway lanes. The AHS concepts define transition points or segments were the driving task is transferred from the human driver to the AHS hard- and software or vice versa.

As was mentioned earlier, the focus will be on the effects on the traffic of the interaction between the automated and manually driven vehicles. The focus of this report is on the effect on the maximum achievable flow (capacity), which is one of the many possible traffic effects. Traffic effects are in turn one of the main aspects (of the development) of AVG systems, see Van Arem (1996).

To present the current state of knowledge of the traffic effects on the interaction in a comprehensive manner, we introduce the following global development path of AVG systems: Early AVG in Mixed Traffic (Stage 1), Introduction of AVG lanes (Stage 2), and Intelligent AVG infrastructure (Stage 3). This development path stems from the evolutionary approach to AVG. This generally agreed path is best characterized as the concept of introducing incremental functionality’s in the transportation system. The major conditions on each functionally incremental step within this development path are clear benefits and feasibility of each step. The other main development path of AVG systems is the geographical approach, which is mostly connected with the AHS concept. This geographical approach consists of implementing most, if not all, AVG functions basically in one step and expanding the geographical areas of implementation.

The approaches to the development AVG systems has been investigated by many authors, see for example Godthelp & Jansen (1993), Bayouth (1996), Minderhoud (1996), Van Arem (1996) and Van Arem (1997). The stages which are defined next are identical to the stages in Van Arem (1997).

2.2 The three development stages of AVG systems

In this chapter we describe the distinguished evolutionary steps. It should be noted that the subdivision is a global chronological development path of AVG systems. This path is mainly defined for presentational purposes. They should not be interpreted as our view on *the* three steps in the evolution of AVG systems.

2.2.1 Stage 1: Early AVG in Mixed Traffic

This stage consists of the introduction and use of systems that can support or take over certain driving tasks. An example of such system is the previously mentioned ACC. ACC is capable to control speed and headway. In this stage ACC is a system with no communication or intervention from the road-side systems. At this stage, no dedicated roads are assigned to AVG vehicles and these vehicles mix with non-AVG vehicles on existing roads. The driver is responsible for controlling the vehicle. AVG functions are enabled and disabled by the driver. Apart from the longitudinal driving support (i.e. breaking and accelerating), lateral control (i.e. steering) may also be offered by the early AVG systems. Stage 1 within the AVG developments could be reached within a few years. The PROMETHEUS program has demonstrated a wide variety of AVG systems in 1992. The CHAUFFEUR program focuses at automated platooning of initially two trucks with the use of existing techniques and solutions. Another demonstration of the state-of-the-art of AVG systems on standard roads is planned in the summer of 1998 in The Netherlands.

2.2.2 Stage 2: Introduction of AVG lanes

This stage discerns from the previous stage by the dedication of infrastructure to AVG vehicles. This infrastructure will mainly involve a lane for exclusive use by vehicles with a sufficient level of automation. Since the vehicles on these lanes can be regarded as homogenous by the minimum standards on automation, traveling can be assured to be safe, fast and comfortable. For maximum use of the dedicated lanes, the level of automation should be sufficiently large, such that more driving tasks are taken over or supported. The driver may be obliged to switch on the AVG functions while driving on the dedicated lanes due to both safety as well as capacity considerations. The infrastructure is equipped with basic, non-communicative functions. For example, this equipment can consist of special marks for lateral control.

2.2.3 Stage 3: intelligent AVG infrastructure

This stage discerns from the previous stages by the equipment of the infrastructure with intelligent, communicative systems. This equipment allows for vehicle-road communication. Another major development within this step is the expansion of the dedicated lanes to a network of special AVG roads. The control of AVG vehicles is now very advanced. Driving tasks could be taken over completely by the AVG functions. Research corresponding to this stage of AVG development mainly involves the work in the United States by the National Automated Highway Systems Consortium (NAHSC) and in Japan by the Advanced Cruise Assist Highway System Research Association (ASHRA). In Japan working prototypes of the AHS concept were developed and a first demonstration was given in Japan in 1996. The research supervised by the NAHSC should result in the specification of an automated highway in 2002. A demonstration of the technical feasibility of an automated highway in the USA was held in 1997.

3 STUDIES ON THE INTERACTION BETWEEN AUTOMATED AND MANUALLY DRIVEN VEHICLES

In this chapter we give an overview of the reports that have been published on the subject of the road capacity with respect to the interaction of automated and manually driven vehicles or with respect to the transfer of manual control to automated control or vice versa. In Section 3.1 the relevant reports which concern Stage 1 are described. Sections 0 and 0 describe the Stages 2 and 3, respectively.

3.1 Stage 1: Early AVG in Mixed Traffic

The first report on capacity implications of mixing supported and manually driven vehicles is found in Zhang (1991) and Benz (1992). The traffic simulator AS (Autobahn Simulator) was used to investigate the effect of ACC on traffic. The ACC function investigated with the use of simulation was capable to inform/warn the driver instead of to control the vehicle. To determine changes in driver behavior under information/warning conditions, a driving simulator experiment was undertaken in which about 90 test-drivers participated. The model was applied to German highway conditions for 2 and 3 lanes of 5 km length without on- and off-ramps. This resulting driving behavior was captured by the minimal following distance to the preceding vehicle and the perception threshold of relative speed to the preceding vehicle. The simulation results show a considerable improvements in safety aspects as a result of informing/warning for all penetration levels: the percentage of small headway's (less than 1s) was reduced significantly. Direct capacity effects were not discovered, probably due to the low traffic densities which were investigated. Therefore, capacity benefits could be expected from the likely occurrence of less accidents due to the improvements of safety aspects. Since the investigated AVG systems warn/inform the driver, the described functionality could be easily accepted by the driver and may cause few institutional and legal problems.

Similar positive effects on safety were found by Broqua et al. (1991) (cf. Broqua (1991)): less decelerating vehicle movements and greater numbers of constant speed. The ACC function investigated by Broqua et al. (1991) is able to maintain a safe distance to a predecessor. The ACC functions are investigated in which ACC is autonomous and in which ACC established communication between vehicles. ACC target headway's of 1s and 2s were examined. The model was calibrated for Italian highway conditions for a two lane highway stretch of 6 km. At the same traffic volume, lower densities were produced than what would be expected according to the case with 0 % of ACC.

Agre and Clare (1993) investigate the possibility of forming platoons in mixed traffic situations. They report simulation results for spontaneous platooning and deplatooning which depends on speed and inter-vehicle distance. The authors assume inter-vehicle communication but no infrastructural intelligence. The authors use an intra-platoon distance of only 0.6 m. Other design parameters are not specified. An achievable flow of 7200 veh/h is reported, which represented a tripling with respect to mentioned maximum flows on today's freeways of 2400 veh/h. The authors report that most platoons are formed in high density and lower speed situation. They also find greater flow disturbances at exits than at entrances.

Mauro (1993) addresses the basic principles of assessing the efficiency of true autonomous ACC with some first results. Mauro identifies the improved reliability of the traffic flow as the major positive effect. Reliability is defined as the probability of traffic breaking down. The gains in the stationary condition (i.e. maximum achievable flow, density, and speed) strongly depend on assumptions with respect to the headway. He finds that no gain in stationary conditions is found with a headway of 1.5s. A gain of about 7% is found with a headway of 1s and a penetration of 20%. The results are obtained for a two-lane, non-usually congested highway. An assessment of the effects of ACC on a congested highway is considered to relevant by Mauro.

Morello, Benz & Lundmann (1994) summarize the main results of the PRO.GEN group of PROMETHEUS on the analyses of ACC. Mauro (1993) is a previous report of this group. In Morello et al. (1994), ACC is a truly autonomous system, which requires no communication with other vehicles or infrastructure. Like Broqua et al. (1991) and Mauro (1993) much attention is paid to platoon stability. Other notable aspects are no ACC support under 20 km/h. ACC headway investigated between 0.8 and 1.5s (normal traffic assumed to be 1.8s (1/2 * speed (km/h) = distance (m)) according to German Road Traffic Regulation (STVO)). The main results were improved reliability and reduced short headway's and strong deceleration (safety) when conservative assumption were taken for the headway (1.5s) and the ACC penetration (40 %). It was argued that the ACC systems with headway's around 1.2-1.5s are the first candidate for early introduction, since they do not degrade efficiency, while improving traffic reliability, safety and driver comfort.

Rothengatter & Heino (1994) report on the results of a driving simulator experiment with 80 test drivers in which a 4-lane highway was simulated. The systems tested were a Collision Warning System (CWS) and an ACC system. The CWS pushes back the gas pedal if a time-to-collision related criterion falls below a certain threshold. Driving with the CWS, the time-headway increased. Driving with ACC (with autonomous brake) caused a decrease in the time-headway.

Becker et al. (1994) report on real traffic experiments on an ACC system, with a target headway between 1.4 and 1.5s. No autonomous brake was included in the system. Both the subjective evaluation by the test drivers and the analysis of the distance data that ACC demonstrated that ACC generates a much more constant headway. The reported benefits of ACC were comfort enhancement and safety improvement. The safety improvements could be reduced by the distraction of the driver to other things than to the primary driving task.

Sayer et al. (1995) report on real traffic experiments on an ACC system with a target headway of 1.4s. No autonomous brake was included in the system. Experiments were performed on a test route through the Metropolitan Detroit Area. The results were that the average mean velocity decreased in the case of ACC use. Applying the brakes occurred more frequent in the case of ACC use. The participants did express concerns with respect to the use of the ACC system on curves and the instability of the system with respect to track merging traffic.

Van Arem et al. (1995) more or less confirms earlier studies that ACC systems can contribute to a more stable traffic flow without sacrificing capacity. However, for 40% penetration and a target headway of 1.5s a deterioration on the traffic performance was found at the higher level of traffic demand, especially on the left lane. This result identifies the ACC reference headway as a major determinant for ACC systems. In this study several aspects of driver behavior were determined with the use of a driver simulator experiment. This study involves a Dutch highway consisting of 3 lanes and total flow levels of over 7000 veh/h.

Ludmann (1995) investigate an ACC system with the use of the traffic micro-simulation program PELOPS. The investigated ACC system was able to operate both the accelerator as well as the brake. The results are based upon traffic demand on a working day on the A9 between Munich and Ingolstadt. The simulation results of the ACC system with 40% penetration and target headway of 0.8s, 1.2s and 1.8s were compared the present situation with 0% ACC. The results showed that slight capacity improvement were obtain for a headway of 0.8s. The target headway of 1.2s gave identical throughput figures as the reference case. A slight reduction of the obtainable maximum throughput was found for the target headway of 1.8s. The target headway's of 1.2s and 1.8s reduced the number of short headway's. A small increase in the number of short headway's was found for the target headway of 0.8s. All target headway's increased the Time To Collision (TTC) and deceased the number of strong (less than $-1m/s^2$) decelerations. Thus, it was argued that both safety as well as comfort were likely to be improved. The improved TTC was explained by the reduction in speed differences between vehicles.

Broucke & Varaiya (1996) develop a macroscopic traffic flow theory to analyze several AHS or ACC configuration. They apply their theory among others to an ACC design with a penetration level of 50% and a ACC headway of 40m. The manual headway was set to be 65m. The maximum flow for the ACC design was 1935.5 veh/h/lane, which is an 7.5% increase with respect to 0% penetration.
Ludmann, Neunzig, & Weilkes (1996) describe the possible improvements of Autonomous Cruise Control is suburban areas, in particular in the case of traffic lights. The micro-simulation program PELOPS was used to determine the capacity improvements. In the case of ACC an increase in throughput of 44% was considered to be possible. In the case of inter-vehicle communication an increase of 52% was reported. An improvement of fuel consumption and emissions was also noted.

Schulze (1997), see also the PROMOTE-CHAUFFEUR consortium (1996), describes the results of the CHAUFFEUR project in which 2 heavy trucks are electronically coupled. By means of simulation, it was investigated what the effect is on the maximum achievable traffic flow if a certain percentage of heavy trucks in today's German traffic is equipped with the CHAUFFEUR system. The target headway was determined based upon the hard- and software components which will be tested in real traffic in the near future. An 4% increase in maximum traffic volume was found if 20% of the trucks were equipped with the system. Although it became also apparent that under certain situations such as highway bottlenecks CHAUFFEUR could slightly reduce traffic flow. These results were obtained on both a 2 and a 3 lane highway under normal German weekday conditions, which implies a recommended speed of 130 km/h and a percentage of trucks of 21%. The target inter-truck distance was 15m at 85 km/h.

The results of the above described studies are summarized in Table 1. A "-" is used if a certain aspect is not investigated or not mentioned.

Table 1: Summary of obtained results for Stage 1: Early AVG in Mixed Traffic

Study	Research method	penetration of ACC	ACC headway	stability	capacity: c_m = density in veh/km and q_m = flow in veh/h
Zhang (1991) and Benz (1991)	Simulation	0,30,50, 100%	not relevant	decrease short headways	no negative effects
Broqua et al. (1991)	Simulation	20% 40%	1s 2s 1s 2s	less decelerations	c_m: +10%, q_m; + 15% c_m: -3%, q_m: -3% c_m: +13%, q_m: +13% c_m: -6%, q_m: -6%
Agre and Clare (1993)	Simulation	-	0.6m intra-platoon	disruptions at exits	q_m: +200%
Mauro (1993) and Morello et al. (1994)	Simulation	20% 40%	1.0s 0.6s 1.0s 1.5s 2.0s	- - - increase -	c_m: +7%, q_m: +7% c_m: +16%, q_m: +21% c_m: +10%, q_m: +15% c_m: 0%, q_m: +0.5% c_m: -13%, q_m: -9%
Rothengatter & Heino (1994)	Driving simulation	CWS, single vehicle ACC, single vehicle	not relevant 1.5s	- -	Av. headway increase Av. headway decrease
Becker et al (1995)	Real traffic	single ACC vehicle	1.4-1.5s	more constant distance, distraction	no differences
Sayer et al. (1995)	Real traffic	single ACC vehicle	1.4s	concerns on curves and merging	reduced speed

Study	Research method	penetration of ACC	ACC headway	stability	capacity: c_m = density in veh/km and q_m = flow in veh/h
Van Arem et al. (1995)	Simulation	20% 40%	1.0s 1.5s 1.0s 1.5s	less shock-waves and variance decrease!	No negative effects no negative effects no negative effects collapse on left lane
Ludmann (1995)	Simulation	40%	0.8s 1.2s 1.8s	larger TTC, less strong decc., more (0.8s) and less (1.2s, 1.8s) short headway's	positive effect equal negative effect
Broucke and Varaiya (1996)	Analytical	50%	40m	-	q_m: +7.5%
Ludmann et al. (1996)	Simulation	-	-	-	q_m: + 44-52%
Schulze (1997)	Simulation	20% (trucks) 40% (trucks) 80% (trucks)	8.0m + 0.3*speed (m/s)	- - -	q_m: +2-4% q_m: +3.5-4% q_m: +6-9%

3.2 Stage 2: Introduction of AVG lanes

Rao & Varaiya (1993) investigate the maximum attainable flow on a ACC lane in which initially both manual and ACC controlled vehicles are present. An ‘adjacent’ transition lane and several entrance ramps are positioned to enter at a regular metered interval rate. Only ACC equipped vehicles are present at the entrance ramps and the transition lane. The initial portion of ACC equipped vehicles was set to be 40%. Platooning was allowed. The manual driven vehicles were allowed to be a platoon leader. The intra-platoon distance was set to be 8m. Despite the efforts of the authors to design a configuration for which the highest possible capacity is obtained, it was found that the maximum achievable flow of the ACC lane was 5,500 veh/h. No permanent traffic flow could be allowed on the transition lane, since this would disturb the filling of the ACC lane. Thus, the average flow on both lanes is 2,750 veh/h., which is marginal better than the USA highway capacity now. The authors conclude that no significant capacity gains may be expected from ACC. They mention improved comfort as the main benefit.

Ioannou & Chien (1993) compare vehicle following in a single lane between the situation with human driving and the situation in which all vehicles use a proposed, true autonomous ACC system. Automatic vehicle following is compared with three different human driver models proposed in the literature. The comparison indicate a strong potential for ACC to smooth traffic flows and increase traffic flow rates considerably. Several emergency situations were simulated and used to demonstrate that the proposed ACC may lead to much safer driving. The results were obtained by taken the vehicle dynamics very detailed into account. Other aspects were not taken into account in detail. A single lane was simulated with only 20 vehicles present and with no on- or off-ramp specifications.

Van Arem et al. (1997) investigate the effect of introducing ACC vehicles and an ACC lane to increase the capacity of a bottleneck in a highway network. The bottleneck road configuration which was examined consists of a highway where one lane of a four lane section is dropped. ACC penetration was assumed to be in the range of 50-60%. The investigated ACC headways were 1.0s and 0.7s. Scenarios with and without a dedicated ACC lane (the left lane, with right-hand driving) were investigated. The total maximum throughput of 7560 veh/h for the reference situation was improved with 8%. The authors note that the statistical significance of the reported total throughput improvement was not proved. However the maximum obtained flow for the busiest lane increased in all cases and thus statistical significance is much more likely for the busiest lane. The maximum capacity on the busiest lane (in the case of a dedicated ACC lane of course the ACC lane and otherwise the left-most lane) was improved by 8% in the case of no dedicated ACC lane and an ACC headway of 1.0s and with 32% in the case of an ACC lane with a target headway of 0.7s and in total a 60% penetration of ACC vehicles. Other reported benefits of ACC are safety improvements (less shock waves) and a smoother merging process. The authors do explicitly require no road side intelligence. Lane changing was allowed when the gap was large enough. Lane changing maneuvering was modeled in detail. This modeling included driver behavior and vehicle capabilities. The authors state that more extensive experiments are necessary, especially with respect to traffic flow impacts with respect to entries and exits of automated lanes.

The results of the above described studies are summarized in Table 2. A “-” is used if a certain aspect is not investigated or not mentioned.

Table 2: Summary of obtained results for Stage 2: Introduction of AVG lanes

Study	Infra configuration	Research method	penetration of ACC	ACC headway	stability	capacity: c_m=density in veh/km, and q_m=flow in veh/h
Rao and Varaiya (1993)	Transition lane, autonomous.	Simulation	Initial 40%	8m intra-platoon distance	-	No significant gains expected (comfort increase !)
Ioannou and Chien (1993)	A single lane	Simulation	100%	4.5m + 0.4s*speed (m/s)	Improved, 'much safer'	Improved
Van Arem et al. (1997)	Pre-warning of AVG lane ahead, autonomous. Mixed traffic	Simulation Simulation	50-60% 50%	1.0s and 0.7s (at 100 km/h) 1.0s (at 100 km/h)	less and less severe shock-waves, but slight increase in short head-way's	improvement of several percent in all cases

3.3 Stage 3: intelligent AVG infrastructure

Assessing traffic effects of intelligent AVG infrastructure is a very difficult task. Many different aspects of a very complex system have to be taken into account, while the functionality of this system is not yet sufficiently clear. Despite these difficulties many articles have been published on this subject. Many of these articles are initiated by the National Automated Highway Systems Consortium (NAHSC) or its Precursor Systems Analyses (PSA), both in the United States. The NAHSC is working on the development of a fully automatic highway (AHS), or equivalent, intelligent AVG infrastructure.

Karaaslan et al. (1991) describe the concept of platooning vehicles. Based upon an existing speed-density model (Drew (1966)), a freeway capacity increase by a factor of four was estimated for platoons consisting of 20 vehicles. The model of Drew (1966) was used by modeling the platoon leader and following platoon as a single vehicle.

Shladover (1991) investigates the achievable lane capacity with platoon operations. This estimate was obtained with 'simple kinematics analysis'. The capacity reduction as a consequence of lane changing and merging operations was set to be 20%. The author reports a lane capacity with a platoon size of 20 under 'conservative assumptions' of 5000 veh/h.

In Rao et al. (1993) the earliest detailed investigation of intelligent AVG infrastructure is reported. This article describes detailed vehicle maneuver procedures based on on-board sensor information.

The importance of traffic streams near entrances and exits was stressed with respect to access and egress rates, achievable flows and rider comfort. All vehicles are assumed to be automated, such that no interaction between automated and manually controlled vehicles is examined. Three different policies governing entrance and egress are investigated. The policies are:

1. The ‘basic model’ specifies that an entering or exiting vehicle needs the inter-platoon distance between its preceding and following vehicle. This characteristic causes large streams of disruptions (accelerations and decelerations of vehicles). Apart from the reduced vehicle comfort, the theoretical capacity of 9000 veh/h was reduced by 25% in the case of an egress demand rate of only 900 veh/h.
2. The ‘improved merge and lane change model’ allows entering and exiting vehicles to need twice the intra-platoon distance between its preceding and following vehicle. This model showed the same drawback as the ‘basic model’: the obtained results were identical.
3. The ‘sorting by exit positions’ model allows exiting vehicles to pull out with about one meter extra space. The exiting vehicle it guaranteed to be the rearmost vehicle in a platoon. Although this model eases the exiting of vehicles, several fundamental drawbacks arise, such as greater turbulence caused by entering vehicles, lower entrance rates and the need for numerous entrances to the AVG lane.

It was found that no matter what the potential capacity of an automated lane, it is the behavior of the traffic stream near entrances and exits, that will determine access and egress rates, achievable flows, and driver comfort. The main cause of stream disruptions near exits is the platoon-split procedure. Attempts to eliminate these disruptions by introducing the sorting by exit positions, was seen to have several fundamental drawbacks. Despite these difficulties, the maximum sustainable flow was estimated to be 5,500 veh/h. Calculations were performed with the use of the simulation program SmartPath with an inter-platoon distance of 30 meter, an intra-platoon distance of 1 meter, and a maximum platoon size of 20.

Chira-Chavala & Zhang (1993) describe three lateral guidance systems with a corresponding phased implementation in High Occupancy Vehicle (HOV) lanes. The main benefits of the systems was the reduced necessary lane width which could accommodate 3 lanes instead of 2 lanes without extending the right-of-way. Based on indicators from the TRB Highway Capacity Manual they estimated a capacity increase of up to 14%. A reduction of accidents was predicted of up to 8 % for lateral warning, of up to 18 % for automated lane keeping and manual lane changing, and of up to 24 % for fully automated lateral control.

Rao & Varaiya (1994), see also Rao & Varaiya (1994a), investigate the link-layer controller which controls the vehicle stream based on aggregate traffic variables. All vehicles are assumed to be automated. The main decisions taken by the link controller is desired lane changing proportions and desired speed. The case of a four-lane roadway was investigated with several on- and off-ramps. The rightmost lane, lane four, is a transition lane from between the three through going lanes and the on-and off-ramps. Lane changing regulations set a maximum to the number of lane changes in a section, and make sure that the density in the destination section is below a desired level. A traffic simulator was constructed. A doubling of the throughput was reported. Furthermore, the authors stress the point that their concept of adaptive lane routing can reduce the influence of the blocking of one lane of a four lane highway. They report a loss of 25% in capacity in case of the blocking of one lane. The current loss in capacity in the USA due to blocking of a lane for 30 minutes is 42 %, see Lindley (1986).

Godbole, Lygeros, & Sastry (1994) describe a possible control system for intelligent AVG infrastructure based upon five hierarchical layers: the network layer, the link layer, the coordination layer, the regulation layer, and the physical layer. The point is made that simulation is needed to analyze the (safety) performance of the design. The obtainable capacity of the design is not investigated, the focus is on safety.

Bloomfield et al. (1994) report the results of driving simulator experiments to determine the human factors of entering an automated lane. The AHS configuration consists of 3-lane highway with the leftmost lane automated (right-hand driving). Continuous transfer is possible between the center lane and the automated lane. The maximum platoon size was 4 and the intra-platoon headway was set to be 0.0625s. The vehicle accelerates on the automated lane from 88.5 km/h to the design velocity. The transfer of control occurs as soon as all four wheels of the simulator vehicle were on the AHS lane. This partially automated transfer protocol was found to be superior to a manual control protocol (press the 'on'-button when all wheels are on the automated lane). The capacity was estimated for the situation in which the inter-platoon distance would allow an entering vehicle to enter for the design velocities 104.7 km/h, 128.8 km/h, and 153.0 km/h. The theoretical and 'measured' capacity (based upon driver reaction time, lane changing, and acceleration time) was found to be 12097 and 7425 veh/h/lane for 104.7 km/h, 5337 and 3545 veh/h/lane for 128.8 km/h, and 2329 and 1816 veh/h/lane for 153.0 km/h.

Bloomfield et al. (1995) investigate exiting of an automated lane. The configuration was identical to Bloomfield et al. (1994) with addition that the exiting vehicle decelerates on the automated lane to the manual lane speed of 88.5 km/h. The 'measured' capacity with the inter-platoon distance which allows the exiting of a vehicle in between all platoons was 2087 veh/h/lane for 104.7 km/h, 1379.2 veh/h/lane for 128.8 km/h, and 634 veh/h/lane for 153.0 km/h.

Varaiya (1995) investigates entry/exit implementations. The main characteristics of entrance and egress maneuvers are:

1. Both transition lanes as well as separate on- and off-ramps are considered.
2. A check-in and check-out procedure is always required.
3. Accelerating from stop in the acceleration lane from an entrance point.
4. Entering of pre-platoons from the acceleration lane at short distance behind the target platoon.

5. The distance between successive exit gates should be large enough.

Many details are given for various entry/exit configuration. However, no definite choices for parameter values are given in this report. Separate segments for entry and exit are recommended, for which no continuous transition lane is needed. Furthermore, coordination of entry/exit maneuvers of automatic vehicles into or out off the ACC lane is recommended to prevent shock waves. This coordination should be performed by the 'Automated Highway System (AHS) control system', which is distributed between vehicles and roadway infrastructure. The mixing of manual and automated vehicles is considered to be dangerous.

Godbole et al. (1995) present a design for entry and exit maneuvers. They used simulation to test their design. Within the simulation they used the figure of 6000 veh/h/lane for the achievable flow. Youngblood, Leonard, & Parsosson (1995) also investigate alternative entry/exit strategies and configurations. They assume infrastructure intelligence. Their firm conclusion is that the entry and exits of vehicles must be coordinated to prevent shock waves and congestion at access and egress points. Dedicated entries/exits are reported to be the most effective and safe. Furthermore, special acceleration/deceleration lanes are recommended just before an entry point and just after an exit point. A transition lane is considered to be moderately effective. If the transition lane is continuous, then this is the most expensive configuration to construct. Apart from the recommended entry/exit configuration, their main conclusion is that more accurate mathematical models have to be developed. These models are necessary for performing quantitative evaluation of entry and exit configurations and for AVG simulation models.

Stevens et al. (1995) summarize the findings of a series of investigations in the context of the Automated Highway Systems (AHS) Precursor Systems Analyses (PSA) program. With respect to the mixing of manual and mixed traffic, they report particular concerns of how to avoid confusing the driver as he or she moves from a dedicated roadway, where the system is responsible, to a non-dedicated roadway where the driver has the responsibility for ultimate control of the vehicle. With respect to entry/exit aspects, details can be found in the previously describes reports of Godbole et al. (1995) and Youngblood et al. (1995). These PSA findings were intended to provided a substantial and credible baseline of AVG information for the AVG program continued by the NAHSC.

Maciuca & Hedrick (1995) investigate the brake dynamics effect on AVG lane capacity. The authors investigate in detail the brake characteristics and perform an simulation to determine the maximal achievable capacity. Their recommendations are a platoon size of 20 vehicles and a reduction of the total time delay of braking to 40ms. This time delay would allow an intra-platoon distance of 1m and an inter-platoon distance of 80m and following these values an maximum achievable capacity of 5402 veh/h. Interesting is their statement that with presently available technology an total time delay of 160ms is achievable, which would translate to an intra-platoon distance of 4.3m and an inter-platoon distance of 83.5m. The maximum reported capacity with these distances is 4706 veh/h. Since no further details are given of the assumptions of the simulation, the reliability of the reported capacity figures can not be determined.

Hall (1995) presents an highly theoretical analysis of the highway capacity. The analysis is based on queuing theory (for example Little's formula is used). No capacity figures are mentioned in the article. The analysis may be interesting in obtaining insight in the order of magnitude of several aspects. The authors mention that many aspects are not taken into account in the model. The consequences of including these aspects in the model are not discussed in the article and may become known after a thorough analysis.

Smith & Noel (1995) investigated the presence of an ACC lane in four situations: an abstract freeway interchange using the simulation system FRESIM and three existing freeway configurations for the Capital Beltway (I-495), the Boston I-93, and for the New York Thruway. The existing freeway configurations were investigated with the use of the INTEGRATION microscopic traffic simulation model. Investigated traffic demands were such that no conclusions with respect to capacity gains were stated.

In the abstract situation a three-lane freeway section was compared with a similar situation in which the left lane was allocated to AVG traffic (hands and feet off). Separate access and egress points were introduced with corresponding transition lanes of 800m (access) and 500m (egress). Vehicles enter and exit the on- and off-ramps from the left-most lane of the two remaining manual lanes. Vehicles join a platoon while entering the ACC lane. The distance between the last vehicle of a platoon and the entering vehicle was assumed to be somewhat larger than the intra-platoon distance of 2.5m. The maximum platoon size was 10 and the inter-platoon distance was set to be 37m. Since only AVG vehicles are allocated to the AVG lane, clear improvements in traffic performance (measured as average and standard deviation of speed) are reported for AVG percentages of 65% and higher.

The other two situations also introduce AVG lanes to replace former manual lanes. For the capital Beltway one existing freeway lane was transformed into an AVG lane. In the Boston I-93 case, two existing freeway lanes were replaced by AVG lanes. For the New York Thruway one AVG lane was added to the existing freeway. The achievable capacity of the AVG lane was mentioned to be 4500 veh/h, while a total increase of 10-20% of peak hour volume was reported. The consistency between the mentioned AVG capacity of 4500 veh/h (an increase of over 100% in comparison with the capacity of a today's highway lane) on the one hand and the 10-20% increase in peak hour volume can be explained by the traffic demand used. The traffic demand was taken from real-world measurements, and therefore throughput improvements can only be achieved by higher average speed. The reported calculations suggest that much higher throughputs can be obtained in the AVG lane configuration than in the existing lane configuration if traffic demand and AVG penetration levels are (chosen) appropriately. It should be noted that the precise level of infrastructure intelligence is unclear from the paper as well as some aspects of the modeling of traffic, such as the weaving sections. If one compares the results and assumptions of this study with those of other studies in Stage 3, then infrastructure intelligence is likely to be a necessity. The general conclusion was that high percentages of ACC penetration is required to experience traffic operations benefits.

Ramaswamy et al. (1995) study algorithms to optimally assign vehicles to lane. The proposed algorithm makes use of micro-simulation to estimate speed and throughput for an Automated Highway System. Based upon the average inter-vehicle distance of 30m, a vehicle length of 5 m, a typical inter-vehicle distance of 7m, and an average speed of 72 km/h, they argue that the current maximal capacity (2100 veh/h/lane for 30m inter-vehicle distance) is 1/3th of the ideal capacity (6000 veh/h/lane for 7m inter-vehicle distance). This reduction is due to essential and nonessential maneuvers.

Bloomfield et al. (1996) report on another driving simulator experiments to investigate the transfer of control and the entering of an automated lane. Similar to Bloomfield et al. (1994) the maximum platoon size was 4, the intra-platoon headway was set to be 0.0625s and the leftmost lane of a three lane highway was automated. Continuous transfer to and from the lane was allowed. The fully automated transfer protocol (press an 'on-button' on the center lane) was found to be superior to other transfer protocols. The capacity was estimated for the situation in which the inter-platoon distance would allow an entering vehicle to accelerate from the manual speed of 88.5 km/h to design velocities of 104.7 km/h, 128.8 km/h, and 153.0 km/h. The 'measured' capacity in personal car equivalence (based upon driver reaction time, lane changing, and acceleration time) was found to be 8528 veh/h/lane for 104.7 km/h, 4130 veh/h/lane for 128.8 km/h, and 2110 veh/h/lane for 153.0 km/h.

Broucke & Varaiya (1996) develop an abstract model to analyze the traffic flow. They state that capacity and transient behavior are likely to be limited by the entry and exit activities. They undertook a microscopic study of ‘entry’ activity, and show how lack of coordination between entering vehicles and vehicles on the main line disrupts traffic flow and increases travel time, although the capacity was not effected in their model by the disruptions. These disruptions were captured in closed form formulas, which are valid under assumptions of independent and exponentially distributed inter-platoon distances. Finally, the authors use their theory to determine the capacity of an AHS design of platoons of 15 vehicles with 10% of the vehicles entering (exiting) in an entry (exit) section. The maximum flow for the platooning design was found to be 4186 veh/h/lane.

Shladover (1996) summarizes the gained knowledge for the NAHSC. He states among others that dedicated on- and off-ramps reduce impacts on manual traffic, that increased intelligence at merges reduce the required length of ramps, and that merging protocols significantly influence effective throughput (reduction of ‘pipeline capacity’). He states among others that achieving absolute throughput levels which are compatible with rest of the transportation network is an unresolved issue. Three of the five mentioned unresolved issues, i.e. dependent on local circumstances, are access and egress related problems. These three issues are access and egress ramp configurations and locations, provisions for heavy vehicle access, and interactions with local streets and highways.

Reynolds, Elias, & Funke (1996) note that the ramp capacity which are by definition manual capacities must equal the entering capacity from the entry ramp to the freeway or from the freeway to the exit ramp. Therefore appropriate ramp and local street designs are required.

The interaction with local streets and highways is the subject of Ran, Huang, & Leight (1996). They investigate the, probably ever-present, problem of congestion caused by exiting AVG traffic from an ACC lane or an AVG network onto the Central Business District roads. They identify three strategies to alleviate congestion in urban roads. The first strategy is to disperse flow through an AHS network. This strategy would require extensive infrastructure extensions, which, at this time, is not considered a viable option. The second strategy is to diffuse AVG traffic throughout urban areas by creating a circular traffic flow. This flow should be created by more one-way streets, fewer intersections and prioritized street network (grade-separation and canalizing local traffic). The third strategy is to consolidate flow at central locations. This inter-modal solution would require building garage areas before the traffic reaches the congested downtown areas. The second and third strategy are preliminary investigated. The problems addressed in this paper may become crucial for the overall performance of transportation system, once the capacity increase of 100% or more is reached on AVG or ACC lanes. Probably, the feasibility of the proposed strategies will heavily depend on local situations.

Hall & Lotspeich (1996) investigate solution techniques for optimally assigning traffic flow to lanes. This assignment can improve achievable throughput if lane changing is avoided. One of their conclusions was that increasing the number of lanes provides decreasing marginal returns, due to the added overhead for lane changes.

Ho & Ioannou (1996) investigate a traffic controller for optimally prescribing speed to vehicles in each section of the highway. By prescribing speed, the traffic density is controlled such that under the given traffic conditions the optimal traffic flow situation is reached. The discussion is mainly based on applying Artificial Neural Networks.

Stemate, Sanso, & Crainic (1996) investigate the case of introducing AVG lanes on a bridge, namely the Champlain Bridge in Montreal. The operational parameters are such that road-side intelligence is required. A buffer zone is introduced for testing vehicles, forcing vehicles into the appropriate lane and forming platoons. The egress capacity was identified as an important factor for the overall capacity. The egress capacity was estimated with the use of the calculated required inter-platoon distance for disintegrating a platoon. The authors introduce an egress strategy with no significant impact on the capacity of the automated lane. The authors state total capacity improvements of the bridge between 32% and 108%. This work is one of the first attempts to analyze automated systems in dense urban highway areas. The operation feasibility of the given design parameters is difficult to assess.

Ran & Tsao (1996) describe an analytical platoon following model from which they derive a set of macroscopic flow-speed-density relationships under steady-state assumptions, including maximum lane flow. The relationships depend on the platoon size, the inter-platoon distance, and the intra-platoon distance. (Very) High capacities per lanes are reported for many design parameters. These calculations are based upon steady state conditions. The system design is such that infrastructure intelligence is required. Their main contribution lies in the fact that their platoon following model could be implemented in a realistic simulation model. The platoon-following model works on the bases of spacing instead of the much more familiar headway.

Chien, Zhang, & Ioannou (1997) also investigate a traffic controller for optimally prescribe speed to vehicles in each section of the highway. The authors demonstrate that the proposed traffic controller can counteract initial density disturbances such that stability is restored and congestion can be avoided. Another traffic controller, the link layer controller, is described in Li et al. (1997).

Del Castillo, Lovell, & Daganzo (1997) present a macroscopic framework in which some of the characteristics of AHS can be studied, like the capacities, the effect of entering and exiting maneuvers, queue storage capabilities, sensitivity to congestion, and issues related to the interface between the AHS and the local street system. The downward capacity correction with respect to entering and exiting is mentioned to be significant for entry and exit flow ratios between 0.2 and 0.4. The capacity of a single AVG lane can reach up to 6000 veh/h. They show that blocking of an AVG lane with a capacity of 6000 veh/h can cause queues with a length of three times the queue length of a normal three-lane motorway (which also has a capacity of approximately 6000 veh/h). The other problem is the absorption of exiting flow onto local streets. Since exits have to be spaced at a considerable distance (the authors state 5 km) for technical (stability) reasons, the flow per exit ramp is very large, especially if the average trip length is not much bigger than the average distance between two off-ramps. In the case of large flows per exit ramp, the extra costs for infrastructure adjustments are not competitive with the costs of normal roadway design. Especially, since the latter is much more flexible with respect to varying traffic volumes. The characteristics of the most promising candidate locations for implementing AHS systems are systems which:

- serve long trips,
- do not have a single predominant terminus, and
- tend to exhibit fairly balanced flow pattern.

Specific locations mentioned are large loops systems as circumferential ring roads, tunnels, bridges, or other forms of infrastructure which would be very expensive to construct. However, such a limited deployment of AVG systems is unlikely to encourage users to buy cars equipped with AVG capabilities. It should be noted that the mentioned problems mainly stem from the high capacity gains of a single AVG lane. In the case of less capacity gains per lane these problem may not occur.

The results of the above described studies are summarized in Table 3. A "-" is used if a certain aspect is not relevant for or not investigated in the study.

Table 3: Summary of obtained results for Stage 3: intelligent AVG infrastructure

Study	Research method	Macro-/ microscopic	Considered infra configuration	Capacity estimates
Karaaslan et al. (1991)	Analytical	Macro	Single lane	+300%
Shladover (1991)	Analytical	Macro	Single lane	5000 veh/h/lane
Roa et al. (1993)	Simulation	Micro	Lane with access-egress	5500 veh/h/lane
Rao & Varaiya (1994,1994a)	Simulation	Macro	4 lanes with access-egress	4500 veh/h/lane (design value)
Godbole et al. (1994)	Design	-	-	-
Bloomfield et al. (1994)	Driving simulation	Micro	3-lanes with leftmost lane automated (entering)	7425 veh/h/lane at 104.7 km/h 3545 veh/h/lane at 128.8 km/h 1816 veh/h/lane at 153 km/h
Bloomfield et al. (1995)	Driving simulation	Micro	3-lanes with leftmost lane automated (exiting)	2087 veh/h/lane at 104.7 km/h 1379.2 veh/h/lane at 128.8 km/h 643 veh/h/lane at 153 km/h
Varaiya (1995)	Analytical	Macro	lane with access-egress	-
Godbole et al. (1995)	Design	Micro	lane with egress-egress	6000 veh/h/lane (design value)
Youngblood et al. (1995)	Design	-	-	-
Stevens et al. (1995)	Design	-	-	-
Maciuca & Hedrick (1995)	Simulation	Micro	Single lane	5402 veh/h/lane
Hall (1995)	Analytical	Macro	2-5 single lanes	-
Smith & Noel (1995)	Simulation	Micro	3 lanes with access-egress/ network	+10-20% 4500 veh/h/lane (design value)
Ramaswamy et al. (1995)	Optimization	Macro and Micro	Network	-
Bloomfield et al. (1996)	Driving simulation	Micro	3-lanes with leftmost lane automated (entering)	8528 veh/h/lane at 104.7 km/h 4130 veh/h/lane at 128.8 km/h 2110 veh/h/lane at 153 km/h
Broucke & Varaiya (1996)	Analytical	Macro Micro Micro	Network Access-egress Lanes with access-	- - 4186 veh/h/lane

Study	Research method	Macro-/ microscopic	Considered infra configuration	Capacity estimates
			egress	
Shladover (1996)	Summary	-	-	-
Reynolds et al. (1996)	Design	-	-	3500 veh/h/lane (design value for trucks)
Ran et al. (1996)	Design	-	Network and local streets	-
Hall & Lotspeich (1996)	Optimization	Macro	Network	-
Ho & Ioannou (1996)	Optimization	Macro	Network	-
Stemate et al. (1996)	Simulation	Micro	Lane with access-egress	+32-108% (bridge)
Ran & Tsao (1996)	Analytical	Macro	Single lane	+6071-8358 veh/h/lane (design value)
Chien et al. (1997)	Optimization/simulation	Macro	Lane with access-egress	-
Li et al. (1997)	Optimization/simulation	Macro	Lane with access-egress	-
Del Castillo et al. (1997)	Analytical	Macro Macro	Lane with access-egress Network and local streets	6000 veh/h/lane -

4 CURRENT STATE OF KNOWLEDGE

In Section 3 we presented short summaries of articles and reports on the interaction of manually driven and AVG supported vehicles. At the end of each paragraph we presented a table in which the most important results of the articles and reports were summarized. We focused on the traffic effect of this interaction. In this chapter we will discuss the current state of knowledge of the traffic effect for the three stages in AVG development. Section 4.1 describes Stage 1: Early AVG in Mixed Traffic. Stage 2 and 3 are discussed in section 4.2 and section 4.3, respectively.

4.1 Stage 1: Early AVG in Mixed Traffic

The AVG systems which are investigated in this stage can be described as follows:
1. Informative AVG system: the driver is informed about the distance and speed (changes) of its predecessor. The driver performs all driving tasks. A Collision Warning System (CWS) is considered to be an informative AVG system. CWS warns when the headway falls below a certain threshold for a given criterion.
2. Autonomous Cruise Control: ACC is able to control speed and headway. The driver is responsible for lateral control and emergency detection and braking.
3. Cruise Control based on inter-vehicle communication. The functions of the system and the driver are identical to ACC. Cruise Control with inter-vehicle communication is likely to be capable to maintain shorter headway's and maybe be able to support platooning.

The research on AVG systems in this stage is much more homogeneous than the research on the other two stages. This is not surprising, since less aspects can be subject to changes by the introduced AVG systems. Most authors report an improvement of the maximal throughput with several percentages. Several authors also reported a degradation in the maximal throughput if the target headway was set only slightly higher.

The research was in all cases focused on modeling the target headway and on the determination of appropriate acceleration and deceleration rates of the AVG system. Three authors explicitly mention the use of a driver simulator experiment to determine the likely behavior of a driver in an AVG equipped vehicle. Zhang (1991) investigates the changes in driver behavior by the introduction of an information device. Rothengatter & Heino (1994) investigate the influence of CWS and ACC. Van Arem (1996) also investigates the changes in driver behavior by the introduction of ACC. Van Arem (1996) reports among others that a driver in an AVG equipped vehicle reacts later in the situation of approaching a stationary traffic queue than a driver in a vehicle without ACC. This possibility of distraction was confirmed by real traffic experiments by Becker et al. (1994). Two real traffic experiments by Becker et al. (1994) and Sayer et al. (1995) could not reveal indications of clear capacity improvements.

Generally agreed determinants of the capacity effects of these early AVG systems are the target headway and the penetration level of AVG equipped vehicles. Reported capacity gains can be explained by the used target headway and the penetration levels of AVG equipped vehicles. Reported capacity losses can be explained similarly. Although this explanation of the obtained capacity effects seems plausible, a thorough analyses of the explanation of the capacity effects could not be found in the literature. For example, no clear proof was found whether an capacity increase was the result of the reduction of the target headway, the changed lane changing behavior, and/or the result from the improved traffic stability., i.e. less variation in speed.

Safety and stability improvements are reported on almost all experiments. Although this could be accounted to avoiding short headway’s by the system and quicker and more homogenous reactions, the explanation is not as straight forward as the explanation of the capacity effects. The discussion of this subject in the reported articles is not as thorough as the discussion of the capacity effects of the AVG systems. In most articles the safety improvements are presented without an explanation of how these improvements were obtained. The reported improvement of safety was not true in all cases. For example, Van Arem et al. (1995) report safety improvements for three of the four investigated cases and safety reductions for one investigated case. The safety improvements were attributed to a decrease in the number of shock-waves and less variance in speed. However, a (small) increase in the number of short headway's was also found for all investigated cases. Ludmann (1995) also found an increase in short headway's in one out of three investigated cases.

Summarizing, most authors agree upon the fact that ACC in mixed traffic conditions is likely to outperform manual traffic with several percentages with respect to the achievable maximum flow. Since the gains strongly depend on the target headway, this improvement could easily turn out to become a degradation of maximal throughput in reality. Headway's of ACC equipped vehicles will be subject to less variance and be concentrated around the target headway. Less variance in speed is also reported in most studies. Although the results are compatible among the authors, a thorough analyses of the determinants of the safety and capacity effects is in most cases lacking or is in need of extensions. In particular the separate effects of reduced target headway, changing lane keeping behavior and traffic stability on the achievable maximum flow is still an open research question. The consistency of the results between the different methodologies, i.e. computer simulation, driving simulation, and real traffic experiments, strongly support the credibility of the obtained results.

4.2 Stage 2: Introduction of AVG lanes

The number of studies on Stage 2: Introduction of AVG lanes is quite small in comparison with the other two stages. Although three studies are described, only one study investigate an ACC lane with exclusively ACC vehicles present and with explicitly no infrastructure intelligence. A possible explanation for the less attention to this stage could be that most researchers consider it unlikely that an ACC lane is designated to ACC equipped vehicles without the addition of infrastructure intelligence to coordinate traffic. This could be explained as follows. AVG lanes will likely to be introduced if the penetration of ACC vehicles is large enough. However if the penetration of ACC equipped vehicles is large, then the capacity gains in the situation of mixed traffic are also large. Thus, the benefits of allocating a lane to ACC vehicles only are likely to be small or even negative in comparison with the situation of mixed traffic. Negative effects may occur if manual traffic flow exceeds the capacity of the manual lane, while the AVG lane is underutilized. Thus, an AVG lane will only be introduced if the capacity of the AVG lane is enlarged by, for example, the use of infrastructure intelligence.

Unlike the studies on Stage 1, the reports on Stage 2 are very divers. The main difference among the studies is the investigated road configuration.

Rao & Varaiya (1993) investigate an ACC lane on which manually driven vehicles are present. These manual driven vehicles are present on the lane at the point along the highway where ACC equipped vehicles are allowed to switch on their systems. Thus ACC is solely allowed to be active at certain pre-specified locations. Furthermore, a transition lane is allocated adjacent to the AVG lane to exclusively (!) allow ACC equipped vehicles to enter and to allow both manually driven and ACC equipped vehicles to exit.

Ioannou & Chien (1993) compare vehicle following in a single lane between automated and manually driven vehicles. The comparison was based upon a limited number of vehicles, namely 20. Since the vehicle dynamics are taken into account in detail and the other aspects of the ACC lane are not discussed, the single aspect that can be said about road configuration is that no infrastructure intelligence is taken into account.

Van Arem et al. (1995) present the only study on a AVG lane for which no expensive infrastructure expansions are necessary and for which no infrastructure intelligence is required. ACC equipment is allowed to work in all situation, such that no switch-on and switch-off points are necessary. The AVG lane is introduced at a bottle-neck of the freeway to improve throughput. Although the introduction of an AVG lane seems to have a slight positive effect on the capacity, no clear benefits can be concluded in comparison with the case in which no dedicated ACC lane is introduced. This stems from the fact that the introduction of an AVG lane also gave a slight decrease in speed.
Summarizing, the situation of a dedicated AVG lane without infrastructure intelligence is not widely investigated. The situation in which no extra infrastructure extensions are necessary is investigated in one study. This study does not proof clear benefits of the situation in which a dedicated AVG lane is present in comparison with the situation in which mixed traffic is allowed. The other two studies involve many costly infrastructure extensions. These two studies report somewhat higher capacity gains. However, one may argue that if these high costs are made that infrastructure intelligence can best be introduced simultaneously. The identification of situations in which a dedicated AVG lane

can be introduced without high infrastructure costs and with provable substantial benefits over mixed traffic seems to be an interesting and necessary research step.

4.3 Stage 3: Intelligent AVG infrastructure

Due to the research efforts in the United States of America, most studies were found on Stage 3: Intelligent AVG infrastructure. It should be noted that many studies exists on aspects which are crucial to this stage, which are not mentioned in this survey. The reason for this is that they do not address traffic effect of AVG systems. Despite this selection the discussed studies are quite divers, since many traffic aspects are effected by the introduction of AVG infrastructure with its designed high capacity per lane.

Based upon described literature, we can conclude that most authors of the found references agree upon the following aspects for organizing traffic:

- Vehicles grouped into platoons with relative small intra-platoon distances and relatively large inter-platoon distances.
- Separate on- and off-ramps with a corresponding accelerating or decelerating lane for entering and exiting vehicles.
- Coordination of entering and exiting vehicles is recommended to avoid traffic flow disruptions. These traffic flow disruptions cause a decrease in maximum achievable flow, in safety, and in driver comfort.

An important problem, addressed by Reynolds et al. (1996), Ran et al. (1996), and Del Castillo et al. (1997), is the dispersion of exiting traffic off the AVG lanes onto the local streets. In addition or as an alternative to this dispersion, other solutions were suggested to absorb the expected large flow of exiting AVG vehicles, such as the consolidation of the traffic flow at central locations (garages) with intermodal connections to the downtown areas. Del Castillo et al. (1997) also identify the interesting aspect of cost-benefit analysis of AVG systems in comparison with normal roadway design.

Summarizing, the studies on Stage 3 have identified several basic characteristics of the AVG systems to be introduced. The concept of platooning is accepted by all authors and seems not to be a point of discussion. Apart from the previously defined general aspects of organizing traffic, no definite conclusions are drawn yet. Several important problems are already identified, which are captured by the question ‘How to feed the AVG lanes with traffic and what to do with the vehicles exiting the AVG lanes?’. A continued following of the most recent research advantages with respect to the (technological) maturity of Stage 3: Intelligent AVG infrastructure is an prerequisite for every possible future step.

For an overview of other than traffic aspects which concern intelligent AVG infrastructure, we refer to the following papers:

1. An overview of the more technical aspects of lateral and longitudinal control research accomplishments can be found in Shladover (1995).
2. An overview of the systems studies of Automated Highway Systems van be found in Bender (1991).
3. Many social and institutional considerations are investigated by means of an Delphi process in Underwood (1990).
4. An overview of the possible development paths of AVG systems can be found in Van Arem (1996).

5 CONCLUSIONS AND SUGGESTIONS FOR FURTHER RESEARCH

This chapter describes the main conclusions from the reviewed literature on the traffic effects of AVG systems and presents suggestions for further research. As with the other chapters of this report, we discuss each stage of AVG development separately. We end this chapter with general conclusions and suggestions for further research.

5.1 Stage 1: Early AVG in Mixed Traffic

The AVG systems that were investigated in this stage all concerned ACC systems. The main conclusion with respect to the use of AVG in mixed traffic conditions is that a small capacity increase is to be expected. However, the change in capacity can easily turn out to be a small or even a large capacity loss. The net effect of ACC on the capacity will most likely depend on the present traffic situation in a country. Thus, the introduction of identical ACC systems can imply for example a capacity increase for Italy and, at the same time, a capacity loss in The Netherlands. This difference can be explained from the factors which influence the maximum achievable capacity. The following factors will strongly differ between countries:

- The average headway. The assumed, or used, target headway of the ACC system is in most studies comparable with the average headway used in today's traffic. A change in the target headway will translate into a change in the maximum achievable capacity. Field test have shown that test drivers have diverse opinions on whether the driver should be able to influence the target headway, see Becker et al. (1994). It is clear that from an individual safety point of view the target headway should not be too small. However, from a society point of view the target headway should be a good compromise between safety and capacity.
- The lane changing and merging behavior. Lane changing behavior will by the use of ACC possibly change towards a behavior in which people have less inclination to overtake a preceding car, and therefore less lane changes will result. The merging capabilities of the present ACC systems are considered to be somewhat troublesome. Also, the changes in the merging behavior of the driver is not yet sufficiently known. The one thing that is advised by all authors is that coordination of merging vehicles is recommended to avoid disrupting traffic flow.
- The average speed. All studies agree on the fact that the average speed is likely to decrease. This is a consequence of the lane changing behavior and the absence of the ‘urge’ to keep up with other vehicles if traffic volume is heavy.
- The average speed difference. Again, all studies conclude that ACC will reduce the speed differences between vehicles. This is a consequence of the automatically controlled headway, the lane changing behavior and the (average) speed of an individual vehicle. More homogeneous traffic flow will increase the maximum achievable capacity. It is interesting to note the conclusion of Sayer et al. (1994) from a field test of ACC vehicles. They found that although the

driver thought that they applied the brakes less frequently, in fact they applied the brakes more frequently.

In order to obtain insight in the above mentioned factors for the Dutch situation, we advise carrying out a carefully designed field test of ACC vehicles. Such a field test for several weeks was also considered by Becker et al. (1994) as the only way to obtain objective data with respect to driver-vehicle behavior. They also state that such a test has to proceed and accompany the market introduction of ACC systems. We have knowledge of an execution of one test in practice at UMTR in Michigan U.S.A, by P. Fancher. Since many factors heavily depend on the local or national situation, a field test is only valid for the country in which it is performed. Thus, a field test in The Netherlands is necessary.

We should note that capacity improvements from the use of ACC can be obtained. This can be seen from the possible reduction in the number of lane changes, from more homogenous traffic conditions and from a reduction of the target headway. Since any capacity improvement will immediately translate into a reduction of the average headway, we provide the reader with some data on average Dutch traffic conditions. The (average) maximum capacity of a lane in The Netherlands is generally assumed to be 2200 veh/h with a corresponding speed of 85 km/h. Thus, the average headway is 33.6m if the average vehicle length is 5m. This average headway is smaller than the 'brick wall headway' of 42.2m. This brick wall headway is based on the distance traveled until the driver has reacted (7.2m or 0.3s at 85 km/h) and the distance for an emergency stop (36m with an average deceleration to zero of 8 m/s^2 at 85 km/h). To illustrate the possible reduction in the average headway, a reduction of 3.8m of the 'brick wall headway' is obtained by the use of ACC from the faster reaction time of the automated system, namely a reaction time of 0.1s for the ACC system instead of 0.3s for the human driver.

Apart from a field test to measure the traffic effect of ACC systems in The Netherlands, a careful analyses of the determinants of the traffic effects is recommended. As was mentioned above, many aspects can influence the maximum achievable capacity. Although the presented studies on the use of ACC in mixed traffic provided several possible explanations for the obtained capacity effects, no thorough and well-established explanation of the obtained results were derived or published. Therefore, analyzing the already obtained results can provide many useful insights. Understanding the way ACC influences the capacity could be more important than knowing the capacity effect itself. A first logical step for further analyzing the obtained results is to apply statistical techniques to the outcomes of one or more presented simulation studies. Since we have access to the results of the MIXIC studies by Van Arem et al. (1996).

5.2 Stage 2: Introduction of AVG lanes

The main conclusion with respect to the introduction of AVG lanes without infrastructure intelligence is that no significant capacity improvements were found in comparison with the situation of ACC in mixed traffic conditions. From a general point of view, dedicating a lane to AVG vehicles only, reduces the flexibility of the total transportation system. A straightforward conclusion from this reduction in flexibility could be that no dedicated AVG lanes should be introduced. This conclusion may not be valid, due to the fact that AVG lanes can stimulate public to buy AVG/ACC equipped vehicles and stimulate industry to produce/develop AVG/ACC equipped vehicles. Moreover, a combination of AVG lanes with already existing High Occupancy Vehicle (HOV) lanes or lanes for Special Target Groups (STG), like trucks and buses, seems to be a logical step for the introduction of AVG systems. Combining HOV/STG lanes with AVG lanes can also be a relatively cheap way to introduce these lanes. The identification of aspects other than the capacity to introduce AVG lanes can therefore be an interesting research direction. These other aspects may involve the previously mentioned stimulus for market introduction, safety or the environment.

Another conclusion from the literature survey is the minor attention this stage receives in the literature. One explanation could be that researchers focus on either the short term development or on the long term ideal situation. The period in-between the long and short term is, although important, overlooked by them. Stage 2 can thus be considered ‘a missing link’. Another explanation, already mentioned in chapter 4, could be that most researchers do not consider this stage an important intermediate stage. One could argue that if infrastructure investments are made for AVG lanes, that it may be wise to simultaneously introduce infrastructure intelligence. Which of these two explanations will turn out to be the correct one, is difficult to foresee.

An interesting research direction is the identification of suitable locations for introducing an AVG lane in The Netherlands. The identification of the factors which determine the suitability of a certain location can be very useful in practice. Based on capacity consideration, many authors, see for example Del Castillo et al. (1997), state that if high capacity gains are reached, problems will arise with respect to feeding the lane with traffic and dispersing the traffic onto local streets. Thus, traffic which uses an AVG lane should not have a predominant origin or terminus. Suitable locations for AVG lanes are the previously mentioned AVG/STG lanes, bridges, and tunnels. The most likely locations for introducing an AVG lane could be analyzed in connection with the surrounding road network on traffic performance. Both the location as well as the (effects of the) AVG system can be selected with the use of expert opinions, see for example Van Arem & Smits (1997) and Verroen, Van Arem & Smits (1996).

The merging behavior of AVG equipped vehicles is important for AVG lanes. This merging behavior determines whether an AVG lane can be filled with traffic. The investigation of this behavior with the use of a micro-simulation model could lead to the specification of the merging process. A first approach could be the suggestion by many authors that coordination of vehicles is required so as to reduce disruption of the traffic flow.

Finally, a study into the possibility of introducing an AVG lane equipped with traffic lights into a city presents an interesting opportunity to introducing specially dedicated infrastructure for AVG vehicles. The main benefit of this application is better response times for a group of vehicles at a traffic light if these vehicles are able to communicate with each other. Thus, the throughput capacity of traffic lights can be increased. Again, this application of AVG can be analyzed with traffic models.

5.3 Stage 3: Intelligent AVG infrastructure

This stage represents the, at this moment the foreseeable, final stage for AVG systems. As was mentioned in chapter 4, consensus exists on several aspects for organizing traffic. The capacity of a lane is mostly estimated to be increased by 100 to 200%, which corresponds to a lane capacity of 4000 to 6000 veh/h/lane. An important problem that is mentioned in the literature is the feeding of traffic onto the AVG lanes and of dispersion of exiting traffic off the AVG lanes once the high capacity is reached. This problem was also mentioned for Stage 2. A similar research direction to Stage 2 is needed, studying suitable locations for introducing intelligent AVG infrastructure with its corresponding high lane capacity and studying the best possible entry and exit configurations. These locations have to be made suitable for the necessary infrastructure adjustments and must have enough spatial possibilities.

An interesting research direction is the exploration of the future (mobility) developments of AVG in connection with overall transportation systems and social and economic trends in general. A macroscopic investigation of this development was performed by defining and quantifying two possible scenarios for the transportation system and its environment, see Van Arem & Smits (1997). The expected AVG developments were determined in a workshop with experts on AVG systems. An interesting new research direction is to explore the developments of AVG systems at a more detailed level, for example by taking the road network explicitly into account. This study can be based upon the same developments which were determined in the previously mentioned workshop. A possible side-effect of such a more detailed study could be a check of the consistency between design parameters and the other assumptions of the many studies on Stage 3. Of course, a consistent scenario for AVG development will be a result of the proposed study. This scenario can be developed from scratch or can be re-used from the previously mentioned macroscopic scenario study.

Another interesting research direction for this stage, is the identification of intelligent AVG applications within cities, instead of the current focus on (inter-urban) highways. Again similar to Stage 2, a connection with traffic lights is interesting in order to improve the capacity of traffic lights.

Investigating the claim that short intra-platoon distance is safe is also necessary. With the use of a micro-simulation program, this claim can be investigated for several worst-case situations.

Finally, an investigation of the possibilities for introducing infrastructure intelligence within a short term (lets say 5 to 10 years) can also be considered as a logical next step.

5.4 Overall

With respect to the traffic, or more specifically, capacity effects, the following conclusions were derived for each of the identified stages:

Stage 1: Introducing AVG/ACC systems in mixed traffic conditions is likely to result in a small capacity increase of a few percentages. This increase may, however, turn out to be a capacity decrease if the driver sets the target headway too large. As a consequence of this result, most authors present ACC as a comfort and safety device.

Stage 2: The capacity gains for introducing a lane exclusively dedicated to AVG vehicles seems to be marginal in comparison with the situation in which both automated and manually driven vehicles are allowed to use the lane. Introducing an AVG lane (without infrastructure intelligence) will probably be based on aspects other than capacity aspects. Firm conclusions could, however, not be derived for this stage, since only a few studies investigate a situation that fits into Stage 2.

Stage 3: The capacity improvements that are predicted for this stage are huge. Improvements of 100 to 200% are mentioned. These capacity estimates are based upon design parameters, and less on actual predictions of traffic behavior. Most research on this stage will study the best design of infrastructure and (software) procedures. An important capacity issue is the connection of high capacity AVG lanes with local streets. This connection is necessary for feeding traffic onto an AVG lane and for dispersing traffic off the lane. The consistency of the design parameters is an important issue.

Apart from the above mentioned conclusions and research directions with respect to capacity, many other aspects are yet unknown and are interesting for further research. The following research questions represent a short collection of these aspects:

1. What can be said about the future relationship between car ownership (and use) and AVG developments?
2. What is the short term development path for AVG? A useful subdivision of these developments are developments that concern in-car equipment and developments in the context of the overall Dynamic Traffic Management (DTM). Interesting aspects with respect to the in-car developments are the economical and technical lifespan of cars and the (past record of) acceptance of innovations in cars. Interesting aspects with respect to DTM are the connection with present IT developments, like dynamic route information signs for motorists and traffic monitoring systems and Traffic Information Centers (TICs).

3. Which role can car manufacturers play in the developments of AVG and what reasons do they have for a specific role? An interesting aspect is the role the car manufacturers have played in the past with respect to innovations.
4. What are the opportunities and threats of AVG developments in freight transportation that can be identified? Aspects like traffic, business economics and the overall transportation system can be considered.
5. What are the opportunities and threats of AVG developments in public transport that can be identified? Aspects like traffic, profitability and the overall transportation system can be considered.
6. What Incident Management actions are necessary for AVG? This question follows from the observation that incidents will have a larger impact when the capacity of a lane has increased.
7. Continuously monitoring of the state-of-the-art in Automated Guided Vehicles? Since the developments in many countries proceed continuously, it is of the utmost importance to keep up-to-date.

REFERENCES

Agre, J. & L. Clare (1993). Spontaneous platooning: A self-organizing approach to improve flow capacity. The proceedings of the 1993 annual meeting of IVHS America. Washington, D.C., pp. 504-512.

Arem, B. van (1996). The development of Automated Vehicle Guidance Systems, a literature survey. TNO-Report INRO-VVG 1996/NV/194.

Arem, B. van (1997). Traffic flow impacts of Automated Vehicle Guidance Systems using microscopic simulation, Proceedings of the workshop on Intelligent Cars and Automated Highway Systems, IROS 97, Grenoble, France, pp.41-46.

Arem, B. van, J.H. Hogema, M.J.W.A. Vanderschuren & C.H. Verheul (1995). An assessment of the impact of Autonomous Intelligent Cruise Control, TNO-Report INRO-VVG1995-17a, Delft the Netherlands.

Arem, B. van & C.A. Smits (1997). An exploration of the development of Automated Vehicle Guidance Systems, TNO-Report INRO-VVG 97/NV/040.

Arem, B. van, A.P. de Vos & M.J.W.A. Vanderschuren (1997). The effect of a special lane for intelligent vehicles on traffic flows; an exploratory study using the microscopic traffic simulation model MIXIC, TNO Inro, Report INRO-VVG 1997-02a, Delft, the Netherlands (to appear in abbreviated form in Proc. 4th World Conference on Intelligent Transport Systems, Berlin, 1997).

Becker, S., M. Bork, H.T. Dorissen, G. Geduld, O. Hofmann, K. Naab, G. Nöcker, P. Rieth & J. Sonntag (1994). Summary of experiences with Autonomous Intelligent Cruise Control (AICC). Part 1: Study objectives and methods & Part 2: Results and conclusions, Proceedings of the first World Congress on Applications of transport Telematics and Intelligent Vehicle-Highway Systems, volume 4, Paris, pp. 1828-35 (Part 1) & 1836-43 (Part 2).

Bender, J.G. (1991). An overview of Systems Studies of Automated Highway Systems. IEEE Transactions on Vehicle Technology, Vol. 40, No. 1, pp. 82-99.

Benz, T. (1991). The Microscopic Traffic Simulator AS (Autobahn Simulator). In: PROMOTHEUS Workshop on Traffic Related Simulation, Proceedings, Stuttgart, pp. 156-170.

Bloomfield, J.R., J.R. Buck, S.A. Carroll, M.S. Booth, R.A. Romano, D.V. McGehee & R.A. North (1995). Human factor aspects of the transfer of control from the Automated Highway System to the driver, Report No. FHWA-RD-94-114.

Bloomfield, J.R., J.R. Buck, J.M. Christensen & A. Yenamandra (1994). Human factors aspects of the transfer of control from the driver to the automated highway system. Report No. FHWA-RD-94-173.

Bloomfield, J.R., J.M. Christensen, A.D. Peterson, J.M. Kjaer & A. Gault (1996). Human factors aspects of transferring control from the driver to the Automated Highway System with varying degrees of automation. Report No. FHWA-RD-95-108.

Broqua, F. (1991). Impact of automatic and semi-automatic vehicle longitudinal control on motorway traffic.

Broqua, F., G. Lerner, V. Mauro & E. Morello (1991). Cooperative driving: basic concepts and a first assessment of 'Intelligent Cruise Control' strategies. In: Advanced Telematics in Road Transport. Proceedings of the DRIVE conferences, Brussels, vol. 2. Amsterdam: Elsevier Science Publishers B.V., 908-929.

Broucke, M. & P. Varaiya (1996). A theory of traffic flow in Automated Highway Systems. Transportation Research Board 75th Annual Meeting, Washington, D.C., USA

Chira-Chavala, T. & W.-B. Zhang (1993). Phased implementation of lateral guidance systems in High Occupancy Vehicle lanes, Transportation Research Record 1408, pp. 56-65.

Chien, C.-C., Y. Zhang & P.A. Ioannou (1997). Traffic density control for Automated Highway Systems. Automatica, Vol. 33, No. 7, pp. 1273-1285.

Del Castillo, J.M., D.J. Lovell & C.F. Daganzo (1997). The technical and economical viability of Automated Highway Systems: a preliminary analysis. Transportation Research Board 76th Annual Meeting, Washington, D.C., USA.

Godbole, D.N., J. Lygeros & S. Sastry (1994). Hierarchical Hybrid Control: a case study. IEEE Conference on Decision and Control, pp. 1592-1597.

Godbole, D.N., F. Eskafi, E. Singh & P Varaiya (1995). Design of entry and exit maneuvers for IVHS, Proceedings of the American Control Conference Seattle, Washington D.C., USA, pp. 3576-3580.

Hall, R.W. (1995). Longitudinal and Lateral Throughput on an Idealized Highway. Transportation Science, Vol. 29, No. 2.

Hall, R.W. & D. Lotspeich (1996). Optimized lane assignment on an automated highway. Transportation Research C, Vol. 4, No. 4, pp. 211-229.

Ho, F.-S. & P. Ioannou (1996). Traffic flow modeling and control using Artificial Neural Networks. IEEE Control Systems magazine, Vol. 16, No. 5, pp.16-26, October.

Ioannou, P.A. & C.C. Chien (1993). Autonomous Intelligent Cruise Control. IEEE transactions on Vehicle technology, Vol. 42, No. 4, pp657-672.

Karaaslan, U., P. Varaiya & J. Walrand (1991). Two proposals to improve freeway traffic flow. Proceedings of the American Control Conference, pp. 2539-2544.

Li, P.Y., R Horowitz, L. Alvarez, J. Frankel & A.M. Robertson (1997). An Automated Highway System link layer controller for traffic flow stabilization. Transportation Research-C, Vol. 5, No. 1, pp. 11-37.

Lindley, J.A. (1986). Quantification of urban freeway congestion and analysis of remedial measures. Technical Report RD-87/052, Federal Highway Administration.

Ludmann, J. (1995). Der ‘Intelligente Tempomat’- eine Analyse mit dem Simulationsprogramm PELOPS. 5. Aachener Kolloquium Fahrzeug- und Motorentechnik, 4.-6. October TH Aachen, (in German).

Ludmann, J., D. Neunzig & M. Weilkes (1996). Traffic simulation with consideration of driver models, theory and examples. Telematik/Vehicle and Environment, Institut für Kraftfahrwesen der RWTH Aachen.

Maciuca, D.B. & J.K. Hedrick (1995). Brake dynamics effect on AHS lane capacity: Systems and issues in ITS, SAE Special Publications, number 1106, SAE, Warrendale, PA, USA, pp. 81-86 951929.

Mauro, V. (1993). Effectiveness of AICC: outline of an assessment. AICC Workshop-Dudenhofen.

Morello, E., Th. Benz & J. Ludmann (1994). AICC Assessment. Proc. 1st World Congress on Intelligent Transport Systems, Paris, pp. 1900-1907.

PROMOTE-CHAUFFEUR consortium, the (1996). Deliverable D03.1.1 Version 2.0; User, safety, and operational requirements, August.

Ramaswamy D., J.V. Medanic, R. Benekohal & W.R. Perkins (1995). Combining lane assignment with route guidance on Corridor systems, Proceedings of the 34th Conference on Decision & Control, New Orleans, USA, pp. 4065-4070.

Ran, B. & H.-S. J. Tsao (1996). Traffic Flow analysis for an Automated Highway System. Transportation Research Board 75th Annual Meeting, Washington D.C., Paper No. 960232.

Ran, B., W. Huang & S. Leight (1996). Solving the bottleneck problem at automated highway exits. The 3rd ITS World Congress, Orlando, USA. pp. 3550-3556. (see also: Some solution strategies for automated highway exit bottleneck problems. Transportation Research-C, Vol. 4, No. 3, pp. 167-179, 1996).

Rao, B.S.Y. & P. Varaiya (1994). Potential benefits of Roadside intelligence for Flow Control in an IVHS. Transportation Research Board 73rd Annual Meeting, Washington D.C., Paper No. 940085 (also published in Proceedings of the American Control Conference, Baltimore, USA, pp. 418-422. 1994).

Rao, B.S.Y. & P. Varaiya (1994a). Roadside intelligence for flow control in an Intelligent Vehicle and Highway System. Transportation Research-C, Vol. 2, No. 1, pp. 49-72.

Rao, B.S.Y. & P. Varaiya (1993). Flow Benefits of Autonomous Intelligent Cruise Control in Mixed Manual and Automated Traffic. Transportation Research Record 1408, pp. 36-43.

Rao, B.S.Y., P. Varaiya & F. Eskafi (1993). Investigations into achievable capacities and stream stability with coordinated intelligent vehicles. Transportation Research Record 1408, pp. 27-35.

Reynolds, P.A., J.A. Elias & D.J. Funke (1996). AHS Design for real world implementation: how do we get from here. The 3rd ITS World Congress, Orlando, USA. pp. 928-936.

Rothengatter, J.A. & A. Heino (1994). Safety evaluation of Collision Avoidance Systems, Proceedings of the first World Congress on Applications of Transport Telematics and Intelligent Vehicle-Highway Systems, volume 4, Paris, pp. 2047-2054.

Sayer, J.R., P.S. Fancher, Z. Bareket & G.E. Johnson (1995). Automatic target Acquisition Autonomous Intelligent Cruise Control (AICC): Driver comfort, acceptance, and performance in highway traffic, Human Factors in Vehicle Design. Lighting, Seating, and Advanced Electronics (SAE Techn. Paper 950970) pp. 185-1990.

Schulze, M. (1997). CHAUFFEUR - Electronic coupling of heavy trucks on European motorways; the project and its actual status. Proceedings of the workshop on Intelligent Cars and Automated Highway Systems, IROS 97, Grenoble France, pp.15-19.

Shladover, S.E. (1991). Potential freeway capacity effects of Advanced Vehicle Control Systems. Proceedings of the 2nd International Conference on Applications of Advanced Technologies in Transportation Engineering. Minneapolis, Minnesota, pp. 213-217.

Shladover, S.E. (1995). Review of the state of development of Advanced Vehicle Control Systems (AVCS). Vehicle Systems Dynamics, 24, pp. 551-595.

Shladover, S.E. (1996). Summary of Current Knowledge of AHS Concept Issues. NAHSC/-ses@ws3knowl.9/96.

Smith, E.R. & E.C. Noel (1995). Assessment of the impact of an automated lane in freeway operations. Institute of Transportation Engineers 65th Annual Meeting, 1995, pp. 41-48.

Stemate, L., B. Sanso & T.G. Crainic (1996). Estimating possible impact on total delay of Automation scenarios for a bottleneck sub-network. The 3rd ITS World Congress, Orlando, USA. pp. 666-674.

Stevens, W., J. Harding, R. Lay & G. McHale (1995). Summary and assessment of findings from the Precursor Analyses of Automated Highway Systems. MITRE corporation.

Tsao, H.-S. J., R.W. Hall & I. Chatterjee (1997). Analytical models for Vehicle/Gap distribution on Automated Highway Systems. Transportation Science, Vol 31, No 1, pp. 18-33.

Underwood, S.E. (1990). Social and institutional considerations in Intelligent Vehicle Highway Systems. SAE Transactions, Vol. 99 No. 6, pp. 1361-1378.

Varaiya, P. (1995). Precursor Systems Analyses of Automated Highway Systems, Activity Area J - Entry/Exit Implementation Final Report. FHWA-RD-95-044.

Verroen, E.J., B. van Arem & C.A. Smits (1996). Lange termijn perspectieven voor Dynamisch VerkeersManagement (Eng: Long term perspectives for Dynamic Traffic Management), TNO-report INRO-VVG 1996-27a. In Dutch with an English summary.

Youngblood, W.R., J.D. Leonard & P.S. Parsosson (1995). Precursor Systems Analyses of Automated Highway Systems, Entry/Exit implementation strategy, Report FHWA-RD-95-098.

Zhang, X. (1991). Intelligent Driving - Promotheus Approaches to Longitudinal Traffic Flow Control, VNIS ’91, pp. 999-1010.