Deliverable 1:

Overview and Analysis of Vehicle Automation and Communication Systems from a Motorway Traffic Management Perspective

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Acronyms and Abbreviations

AACC	Autonomous Adaptive Cruise Control
ABS	Anti-lock Braking System
ACAS	Automotive Collision Avoidance System
ACC	Adaptive Cruise Control
ACC/S&G	Adaptive Cruise Control with Stop and Go
ACC-LSF	Adaptive Cruise Control - Low Speed Following
ACC-NMV	Adaptive Cruise Control with Non-Motor-Vehicle detection
ACV	Advanced City Vehicle
ADAS	Advanced Driver Assistance Service or System
AdvBS	Advanced Braking System
AES	Automated Emergency Stop
AEVW	Approaching Emergency Vehicle Warning
AFS	Adaptive Front-lighting System
AGD	Active Green Driving
AHS	Automated Highway Systems
AICC	Autonomous Intelligent Cruise Control
ALDWS	Adaptive Lane Departure Warnings System
APC	Automated Public Car
APIA	Active Passive Integration Approach
AQuA	Automated Queue Assistance
ARC	Automated assistance in Roadworks and Congestion
AW	Animal Warning
BA	Brake Assist
BbW	Brake-by-Wire system
BDWS	Braking Distance Warning System
BLIS	Blind Spot Information System
C&SLI	Curve & Speed Limit Info
CA	Congestion Assistant
CA-BS	Collision Avoidance - Braking and Steering
CACC	Cooperative Adaptive Cruise Control
CAS	Collision Avoidance System
CBLC	Communication-Based Longitudinal Control
CC	Cruise Control
CCW	Cooperative Collision Warning
CF	Cooperative Following
CFM	Cooperative Following and Merging
CGR	Cooperative Glare Reduction
CM	Cooperative Merging
CMA	Cooperative Merging Assistance
CSW	Curve Speed Warning
CTG	Constant Time Gap
CTH	Constant Time Headway
CTLS	Cooperative Traffic Light System
CVSLS	Cooperative Variable Speed Limit System
EC	European Commission
EEBL	Emergency Electronic Brake Lights
EU	European Union
EVSC	External Vehicle Speed Control
FCW	Forward Collision Warning
FDW	Following Distance Warning
FEA	Fuel Efficiency Advisor
FOT	Field Operational Test
FSRA	Full Speed Range Adaptive Cruise Control
FSRA+Foresight	Full Speed Range Adaptive Cruise Control plus Foresight
GDA	Green Driving Assistant
GNSS	Global Navigation Satellite Systems
GPS	Global Positioning System
HC	Heading Control
HLN	Hazardous Location Notification
HMI	Human-Machine Interface
HOV	High-Occupancy Vehicle
HP	Highway Pilot
IA	Intersection Assistant

ICC	Intelligent Cruise Control
IDM	Intelligent Driver Model
IEA	International Energy Agency
IRAC	Integrated Roadway/Adaptive Cruise Control
IRSA	Integrated Full-Speed Range Speed Assistant
ISA	Intelligent Speed Adaptation
ISI	Intelligent Speed Information
ISO	International Organization for Standardization
IW	Impairment Warning
IWF	Information & Warning Functions
LAW	Limited Access Warning
LCA	Lane Change Assistant
LCDAS	Lane Change Decision Aid System
LCS	Lane Change Support
LDW	Lane Departure Warning
LHW	Local Hazard Warning
LOS	Level Of Service
LSACC	Low Speed ACC
LTA	Left Turn Assistant
MTM	Motorway Traffic Management
NAVS	Navigation System
NHTSA	National Highway Traffic Safety Administration
NMV	Non-Motor-Vehicle
NV	Night Vision
OA	Overtake Assistance
OEM	Original Equipment Manufacturing
PAss	Parking Assistant
PCD	Pedestrian and Cyclist Detection
PCW	Post-Crash Warning
PND	Portable Navigation Device
PRT	Personal Rapid Transit
PSS	Pre-crash Safety System
R&D	Research and Development
RCW	Reverse Collision Warning
RSCM	Road Surface Condition Monitoring
S&G	Stop and Go
S&G-ACC	Stop and Go Adaptive Cruise Control
SA	Speed Alert
SALS	Speed Alerting and Limiting System
SAWS	Speed Alert or Warning System
SL	Speed Limiter
SLA	Speed Limit Assistance
SOMS	Side Object Monitoring System
SRS	Speed Regulation System
SSA	Stop Sign Assist
SVW	Slow Vehicle Warning
SWOT	Strengths-Weaknesses-Opportunities-Threats
TAP	Temporary Auto Pilot
TJA	Traffic Jam Assistant
TJAW	Traffic Jam Ahead Warning
TR	Terrain Response
TRAMAN21	TRAffic MANagement for the 21st century
TSA	Traffic Signal Adaptation
UK	United Kingdom
USA	United States of America
V2I	Vehicle to Infrastructure
V2V	Vehicle to Vehicle
V2X	Vehicle to both vehicle and infrastructure
VACS	Vehicle Automation and Communication Systems
VPS	Vehicle Platooning System
VSL	Variable Speed Limit
VTM	Variable Time Headway
VWS	Violation Warning System
WAW	Working Area Warning
WHO	World Health Organisation
WP	Work Package

WWDW	Wrong Way Driving Warning

Executive Summary

Traffic congestion on metropolitan motorways is a serious threat for the economic and social life of modern societies, as well as for the environment, which calls for drastic and radical solutions. Some conventional traffic management measures currently applied, face limitations. During the last decade, there has been an enormous effort to develop a variety of Vehicle Automation and Communication Systems (VACS) that are expected to revolutionise the features and capabilities of individual vehicles within the next decades. VACS are typically developed to benefit the individual vehicle, without a clear view or understanding for the implications, potential advantages and disadvantages they may have for the resulting, accordingly modified traffic characteristics. Thus, the gradual introduction of VACS brings along the (largely ignored) necessity and continuously growing opportunities for accordingly adapted or utterly new traffic management actions and strategies.

It is the main objective of TRAMAN21 (TRAffic MANagement for the 21st century) to develop the foundations and first steps that will pave the way towards a new era of future motorway traffic management (MTM) research and practice, which is indispensable in order to accompany, complement and exploit the evolving VACS deployment. TRAMAN21 will assess the relevance of VACS for improved traffic flow and develop specific options for a sensible upgrade of the traffic conditions, particularly at the network's weak points, i.e. at bottlenecks and incident locations. The TRAMAN21 work comprises the development of new traffic flow modelling and control approaches, on the basis of appropriate methods from many-particle Physics, Automatic Control and Optimisation, to consider and exploit the novel vehicle capabilities at a network-wide level. A field trial is also included, aiming at a preliminary testing and demonstration of the developed concepts.

The present deliverable reports on the first outcomes of TRAMAN21's Work Package (WP) 1. The aim of this WP is to address all existing or envisaged VACS options, assess their relevance for traffic management, and develop, for a most relevant subset of VACS, appropriate exploitation possibilities towards a more efficient motorway traffic flow. To this end, an extensive review took place from March 2013 to January 2014 to identify available and/or evolving VACS. The review focused on systems that undertake different vehicle functions at varying levels of automation, which, enhanced by communication features enabling varying levels of cooperation among vehicles and/or vehicles and the infrastructure, aim at assisting and easing the driving task.

The review has been primarily based on materials from scientific and technical journals. Information has been also gathered through the internet, and in particular through the web pages of relevant Research and Development (R&D) projects, large institutes and organisations, as well as through the web pages of companies involved in the development of VACS.

The aforementioned extensive review resulted in the identification of nearly 90 different systems, which have been classified for the TRAMAN21 purposes as:

- *VACS without traffic flow implications*: This category includes VACS that aim only at the safety and comfort of the driver; while their operation does not modify the common traffic flow patterns.

- *VACS with traffic flow implications*: This category includes VACS, the operation of which modifies the common traffic flow patterns, in addition to any possible safety and comfort features that they may also have. These VACS are further distinguished in:
    - *Urban traffic related VACS*, which include VACS that address urban operations only; and
    - *Motorway traffic related VACS*, which include VACS that address, potentially among others, motorway operations.

The current penetration level of VACS is very limited. Thus, their study is performed either via Field Operational Tests (FOTs), which mainly concern technological aspects, safety effects, changes in driving behaviour, user acceptance, and environmental impacts; or via simulation investigations which are used to reveal their traffic flow implications. The FOT results indicate generally that users tend to prefer less intervening systems and use VACS in a way that resembles their personal driving style. Users' acceptance tends to increase after system's actual usage in real traffic conditions, while safety and environmental considerations seem to be pretty well addressed by available and evolving VACS. Unlike FOTs, simulation results appear often controversial and suggest that:

- the identified effects are not always positive,
- no unified study approach is available,
- effects are still neither fully analysed nor fully understood.

Based on the findings of their detailed review, the motorway traffic related VACS have been further classified, according to the particular functions that they can perform, and may be deployed for MTM purposes; and their level of autonomy, which defines their functional requirements, as well as their deployment potential by a MTM system.

Based on the functions that they can perform and are of concern from a MTM perspective, motorway traffic related VACS have been classified as:

- *Speed control systems*: This category includes systems that allow speed or speed limit control at different levels of automation. These levels vary from speed information and recommendations to the driver to fully intervening systems, i.e. systems that impose the recommended speed levels.
- *Headway (gap) control systems*: This category includes systems that enable a vehicle to keep a specified distance from the vehicle in front of it. The distance, which may be defined in terms of time (time headway) or space (space headway), must preserve safety, under all circumstances.
- *Lane change/merge systems*: This category includes systems that assist the execution of lane change and merge manoeuvres. They range from purely assisting systems, providing advice and recommendations, to fully automated systems, which, should the driver decide upon a particular movement, undertake all the tasks necessary to drive the vehicle from the current to the aimed lane.
- *Platooning systems*: This category includes systems that can be used to form vehicle platoons. They range from systems that enable headway control of individual vehicles, which can be grouped together to form platoons, to systems that have been specifically developed and/or deployed for vehicle platooning purposes.

- *Route guidance systems*: This last category includes systems that enable route guidance. So far, route guidance is only provided in an informative manner, i.e. route recommendations are provided to the vehicle driver who chooses to follow or ignore them.

Based on their level of autonomy, motorway traffic related VACS have been classified as:

- *Autonomous systems*: This category includes VACS that carry on board all technology and logic necessary to perform their functions. They are autonomous in that their behaviour and effectiveness depends entirely upon their embedded sensors and intelligence; without provisions to directly communicate with other vehicles or to receive controls or recommendations by a MTM system.
- *Cooperative systems*: This category includes systems, the behaviour and effectiveness of which depends not only upon their embedded sensors and intelligence, but also on their communication and cooperation with other similar systems and/or the infrastructure. Cooperative systems are further classified in:
  - *Vehicle-to-Vehicle (V2V) systems*: This category includes systems that require communication and cooperation with other similar systems in order to carry out their functions.
  - *Vehicle-to-Infrastructure (V2I) systems*: This category includes systems that require communication and cooperation with the infrastructure in order to carry out their functions. In contrast to the systems of the previous categories, these systems can receive directly, and implement according to their respective level of support (informative or intervening systems), external control decisions and recommendations defined by a MTM system. Dual communication also enables vehicle data to be transmitted from the vehicles to the MTM system, which increases the nature, quality and quantity of centrally available real-time information.
  - *Vehicle-to-Vehicle and Infrastructure (V2X) systems*: This last category includes systems, which feature the characteristics of both the V2V and V2I systems categories.

Beyond the analysis of motorway traffic related VACS as standalone products, SWOT (Strengths-Weaknesses-Opportunities-Threats) analyses have been performed to provide an insight into the strengths and weaknesses of their functions from a MTM perspective, as well as to identify any opportunities offered to enhance their strengths, while limiting or even eliminating the weaknesses and potential threats in achieving the MTM objective of improving motorway traffic flow efficiency.

Considering the VACS functions that are of concern from a MTM perspective, as well as the results of the aforementioned SWOT analyses, it seems that the most promising VACS are:

- The Adaptive Cruise Control (ACC), which offers the potential for headway control;
- The Intelligent Speed Adaptation (ISA), which offers the potential for speed control;
- The Lane Change Decision Aid System (LCDAS), which offers the potential for controlling the lane change and merging functions; and
- The Navigation System (NAVS), which offers the potential for route guidance.

However, the analyses also indicate that benefits may be maximised, should the functions of these VACS be undertaken cooperatively, and under the coordination of a MTM system that will be able to provide relevant advices and recommendations, or even impose if necessary, network-wide beneficial settings for their operation. The conservative and/or selfish and myopic use of VACS may not endanger their safety and comfort features, but may dramatically deteriorate the prevailing traffic flow efficiency and congestion levels

In order to avoid the aforementioned conservative, selfish and myopic use of VACS, MTM should get prepared and adapt quickly to the evolution and penetration of VACS. To this end, modelling and simulation tools and control concepts and techniques that will allow the study, analysis, design and application of more effective MTM strategies exploiting the mix of the current and evolving VACS capabilities are necessary.

Overall, the review, analysis and assessment of motorway related VACS have indicated that their contribution to the improvement of traffic efficiency may be enhanced by

- the use of traffic-adaptive settings,
- the extension of their communication and cooperation capabilities,
- the increase of the market penetration rate, and
- the combination of different functions.

Last, but certainly not least, since the reviewed simulation investigations of motorway traffic related VACS indicate that they can affect traffic flow both positively and negatively, they may lead to a deterioration of the overall traffic conditions, if left unsupervised to serve their individual users' aims in a conservative, myopic and/or selfish way.

VACS may offer significant benefits, if deployed appropriately by traffic management, and if traffic management is allowed and prepared to "intervene" cooperatively at varying levels and different aspects of the driving task to influence the driving behaviour in favour of the global traffic conditions. What is therefore needed is:

- VACS that:
    - provide traffic-adaptive functions; thus responding to the prevailing traffic conditions;
    - enable multiple functions; thus responding to multiple needs;
    - allow for V2V and V2I cooperation; thus achieving goals not achievable by autonomously operated systems.
- MTM systems capable to intervene, if and when necessary. It is in the human nature to dislike receiving orders, but sometimes, it is also necessary to be prevented from acting at the expense of the overall benefit.
- Infrastructures capable to cooperate with VACS and support their operation for network-wide benefits. Individual actions that are coordinated and supported by a system with a wider perspective may lead to positive effects, not only locally, but at a network-wide level.
- Modelling and simulation tools, and control concepts and techniques that will allow the study, analysis, design and application of more effective motorway traffic management strategies exploiting the mix of the current and evolving VACS capabilities.

Both the observed VACS evolution and related R&D endeavours seem to follow this path. This is, however, only a small share of the whole venture, since other, equally significant VACS aspects, that should also be considered and studied thoroughly, include:

- *Pure technical aspects*, which concern communication protocols, data management, security, sensors and control systems of VACS, etc.
- *Societal aspects* of involved costs and general acceptance.
- *Political aspects*, which concern the removal of regulatory barriers to introducing new technologies.
- *Legal aspects*, which concern the liability of manufacturer, owner, driver and public authorities.

Last, but certainly not least, *human-related aspects* concerning the human-machine interface (HMI), as well as the user acceptance and usability, and the degree of driver assistance acceptance and involved costs should be given considerable thought. For the real question is "*How much authority are we really willing and prepared to pay for and give to our automobiles?*" and the answer to this question will finally determine the path for all future developments.

1. Introduction

Traffic congestion on metropolitan motorways is a serious threat for the economic and social life of modern societies, as well as for the environment, which calls for drastic and radical solutions. Some conventional traffic management measures currently applied, face limitations. During the last decade, there has been an enormous effort to develop a variety of Vehicle Automation and Communication Systems (VACS) that are expected to revolutionise the features and capabilities of individual vehicles within the next decades. VACS are typically developed to benefit the individual vehicle, without a clear view or understanding for the implications, potential advantages and disadvantages they may have for the resulting, accordingly modified traffic characteristics. Thus, the gradual introduction of VACS brings along the (largely ignored) necessity and continuously growing opportunities for accordingly adapted or utterly new traffic management actions and strategies.

It is the main objective of TRAMAN21 (TRAffic MANagement for the 21st century) to develop the foundations and first steps that will pave the way towards a new era of future motorway traffic management (MTM) research and practice, which is indispensable in order to accompany, complement and exploit the evolving VACS deployment. TRAMAN21 will assess the relevance of VACS for improved traffic flow and develop specific options for a sensible upgrade of the traffic conditions, particularly at the network's weak points, i.e. at bottlenecks and incident locations. The TRAMAN21 work comprises the development of new traffic flow modelling and control approaches, on the basis of appropriate methods from many-particle Physics, Automatic Control and Optimisation, to consider and exploit the novel vehicle capabilities at a network-wide level. A field trial is also included, aiming at a preliminary testing and demonstration of the developed concepts.

TRAMAN21 comprises five interconnected Work Packages (WP):

- WP1. Overview, Analysis and Exploitation of VACS will address all existing or envisaged VACS options, assess their relevance for traffic management, and develop, for a most relevant subset of VACS, appropriate exploitation possibilities towards a more efficient motorway traffic flow.
- WP2. Traffic Flow Modelling in Presence of VACS will adopt and develop appropriate models and modelling approaches, at the microscopic and macroscopic levels, that will allow for a proper reflection of the evolving vehicle features and capabilities.
- WP3. Motorway Traffic Control will develop a generic hierarchical control structure applicable under all different VACS scenarios, as well as detailed control strategies, to be tested in simulation, for selected VACS scenarios.
- WP4. Local Field Test will design and carry out a field demonstration of a local control system, using conventional means that mimic individual speed commands under VACS.
- WP5. Dissemination will undertake a multitude of actions aiming at promoting the ground-breaking character of TRAMAN21 research.

The present deliverable is the main outcome of the aforementioned WP1. Within this WP, an extensive review took place from March 2013 to January 2014 to identify available and/or evolving VACS. The review focused on systems that undertake different vehicle functions at varying levels of automation, which, enhanced by communication features enabling varying levels of cooperation among vehicles and/or vehicles and the infrastructure, aim at assisting and easing the driving task.

The review was primarily based on materials from scientific and technical journals. Information was also gathered through the internet, and in particular through the web pages of relevant Research and Development (R&D) projects, large institutes and organisations, as well as through the web pages of companies involved in the development of VACS. This extensive review resulted in the identification of nearly 90 different systems, which were then examined to identify those that are relevant to MTM in that their operation has implications for the traffic flow. Those VACS that were found to have such implications were then analysed in detail and assessed to identify specific ways of exploitation of their most promising features towards an efficient MTM.

The deliverable is structured in five (5) more chapters:

- *Chapter 2* discusses the emergence of VACS and the factors that boosted their rapid development and evolution observed in recent years.
- *Chapter 3* presents an overview of the VACS identified in the literature, and provides a first taxonomy from the perspective of their potential implications to motorway traffic flow.
- *Chapter 4* reviews in detail those VACS, which were identified as having implications on motorway traffic flow. The review includes their description and functions, available performance evaluation results, as well as conclusions and recommendations for their further development and deployment from a MTM perspective.
- *Chapter 5* further analyses the VACS reviewed in Chapter 4, in an effort to identify specific ways of exploitation of their most promising features towards an efficient MTM. To this end, VACS are classified according to their functions and cooperation abilities, while a SWOT (Strengths-Weaknesses-Opportunities-Threats) analysis is used to provide insights into the strengths and weaknesses of their functions from a MTM perspective, as well as to identify any opportunities offered to enhance these strengths, while limiting or even eliminating the weaknesses and potential threats for achieving the MTM objective of improving motorway traffic flow efficiency.
- *Chapter 6* summarises the current trends and future perspectives of VACS within a MTM context.

Finally, some 150 references at the end of the deliverable can be used to further deepen in the issues addressed.

2. The emergence of VACS

The modern automobile was born in 1886 when Carl Benz applied for a patent for his "vehicle powered by a gas engine", known today as Benz Patent Motor car (see Figure 2.1). In 1902, the automobiles' mass production was launched by Ransom Olds at Lansing, Michigan, USA, while in 1908 the great developments of the mass production concepts introduced by Henry Ford led to the "Ford Model T" (see Figure 2.2), the first affordable, for many people, automobile. Since then, the automobile has become a symbol of human mobility freedom and a symbol of status. Unfortunately, however, the traffic-related facts and statistics seem relentlessly.

Figure 2.1. The Benz Patent Motor car[1]

Figure 2.2. The Ford Model T[2]

According to the World Health Organisation (WHO)[3], the following 10 facts hold for the global road traffic safety (WHO, 2013):

- Every year, there are 1.24 million road traffic deaths worldwide.

[1] http://www.daimler.com/dccom/0-5-1322446-1-1323352-1-0-0-1322455-0-0-135-0-0-0-0-0-0-0-0.html [accessed 25.02.2014]
[2] http://www.hfmgv.org/exhibits/showroom/1908/model.t.html [accessed 25.02.2014]
[3] http://www.who.int/features/factfiles/roadsafety/en/ [accessed 06.10.2013]

- 92% of road traffic deaths occur in low- and middle-income countries that share only 53% of the world's registered vehicles.
- Vulnerable road users account for half of all road traffic deaths globally.
- Controlling speed reduces road traffic injuries; a 5% cut in average speed can reduce the number of fatal crashes by as much as 30%.
- Drinking alcohol and driving increases the risk of a crash.
- Wearing a good-quality helmet can reduce the risk of death from a road crash by 40%, and the risk of severe injury by over 70%.
- Wearing a seat-belt reduces the risk of death among front-seat passengers by 40–65%, and the deaths among rear-seat car occupants by 25–75%.
- Infant seats, child seats and booster seats can reduce child deaths by 54–80% in the event of a crash.
- Prompt, good-quality pre-hospital care can save the lives of many people injured in road traffic crashes.
- Since 2007, 88 countries have reduced the number of road traffic deaths, in 87 countries the number of road traffic deaths has increased, and at the global level has remained stable.

These facts, which have been assessed through information on road safety from 182 countries, accounting for almost 99% of the world's population, indicate that, worldwide, the total number of road traffic deaths remains unacceptably high, while only a few countries have comprehensive road safety laws on key risk factors such as drinking and driving, speeding, use of motorcycle helmets, etc. (WHO, 2013).

At the same time, according to the International Energy Agency (IEA, 2013):

- Transport is the second largest sector in terms of emissions (see Figure 2.3), releasing 22% of global CO_2 emissions in 2011.
- The fast emissions growth of the transport sector was driven by emissions from the road sector, which increased by 52% since 1990 (see Figure 2.4) accounting for about three quarters of transport emissions in 2011.
- Global transport fuel demand is expected to grow by nearly 40% by 2035.

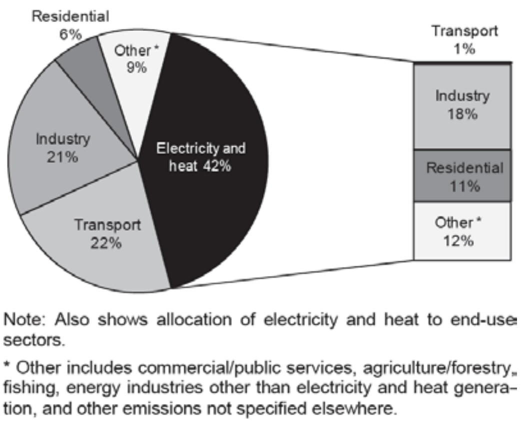

Figure 2.3. Transport sector's share of global emissions (IEA, 2013)

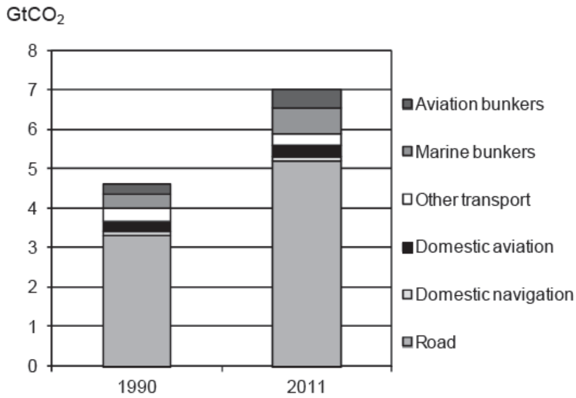

Figure 2.4. CO_2 emissions from transport (IEA, 2013)

Motivated by such facts and statistics, an enormous continuing interdisciplinary effort has been devoted by the automobile industry as well as by numerous research institutions around the world to plan, develop, test and start deploying a variety of systems, called *Vehicle Automation and Communication Systems* (*VACS*). VACS are systems that undertake different vehicle functions at various levels of automation, which, enhanced by communication features enabling varying levels of cooperation among vehicles and/or vehicles and the infrastructure, aim at assisting and easing the driving task. Although safety has been the main motivator behind VACS developments, the reduction of the negative environmental effects of traffic in terms of reduced fuel consumption and related emissions is also among the prime priorities of some VACS or results as a by-product of an improved vehicle operation.

VACS are expected to revolutionise the features and capabilities of individual vehicles within the next decades in favour of the safety and convenience of their users, i.e. the drivers. However, simulation investigations as well as relevant Field Operational Tests (FOTs) indicate that some VACS can also affect, in a positive or negative way, the traffic flow at varying levels. Thus, there is a threat for a deterioration of the overall traffic conditions if VACS are merely serving their individual user’s aims in a myopic and/or selfish way. For example, guiding individual equipped vehicles to time-shorter routes (to avoid congested network parts) may be beneficial under low penetration scenarios. However, as the percentage of vehicles receiving corresponding routing instructions increases, the proposed alternative routes may become congested themselves, and, more generally, the traffic situation at network level may deteriorate.

It is possible therefore for VACS to end up with effects other than those primarily aimed at, contributing to a further deterioration of the already burdened traffic conditions. However, VACS offer potential benefits if deployed appropriately by traffic management, which could “intervene” cooperatively at varying levels and different aspects of the driving task to influence the driving behaviour in favour of the global traffic conditions. To this end, traffic management should adapt to the VACS evolution and gradually deploy the available VACS capabilities in an effort to improve road efficiency and reduce congestion and the resulting negative impacts on environment and quality of life. If traffic management remains stationary at the present state or lags behind the factual VACS evolution, the traffic flow efficiency and congestion levels may under circumstances slightly improve, but may also deteriorate (see grey sector in Figure 2.5).

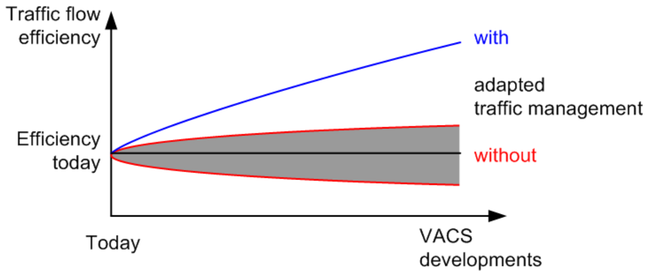

Figure 2.5. The importance of traffic management adapted to the VACS evolution

However, further research is necessary in order to fully exploit the potential in a manner that is safe, understandable and acceptable to the driver and other stakeholders. In this context, it is the principal aim and main objective of TRAMAN21 to develop the foundations and first steps that will pave the way for a new era of future motorway traffic management research and practice. This new research era is indispensable in order to accompany, complement and exploit the evolving VACS deployment, so as to ensure a continuous, lasting and efficient solution to the major societal and environmental problem of motorway congestion.

3. Overview of VACS

3.1. Introduction

Current literature reports on numerous VACS, a part only of which corresponds indeed to different systems. Marketing or differentiation aims lead manufacturers and researchers as well to call, using different names, systems that are practically the same. In addition, several taxonomies have been proposed, serving different purposes and reflecting different VACS aspects.

Bishop (2005), for example, classifies VACS applications in the following four categories that reflect their aimed functionality:

- *Convenience systems*: This category includes driver-support products, which assist the driver in vehicle control to reduce the stress of driving.
- *Safety systems*: This category includes systems, which provide active safety for crash avoidance.
- *Productivity systems*: This category includes systems that apply to commercial vehicles and transit buses, and aim at increasing productivity in terms of operational cost (such as fuel consumption) or time (such as more efficient manoeuvring).
- *Traffic assist systems*: This category includes systems, which combining vehicle communications with advanced vehicle control techniques offer the potential for improving traffic flow in the long term.

The above categorisation is not strict in that it allows the classification of a particular system in more than one category.

Popescu-Zeletin et al (2010) on the other hand, provide a classification that serves better for the study of the VACS communication requirements. To this end, they initially define VACS application domains, in a way slightly different from Bishop (2005), and then, they define communication regimes orthogonal to the application domains, so that VACS are classified both according to their application domains and the communication regimes, necessary to provide their functionalities.

According to the scheme proposed by Popescu-Zeletin et al (2010), three application domains are defined for VACS:

- *Safety*: This domain includes VACS applications aimed at increasing the protection of the vehicles and the vehicles' drivers and passengers.
- *Resource efficiency*: This domain includes VACS applications that aim at improving traffic as well as environmental efficiency.
- *Infotainment and advanced driver assistance services (ADAS)*: This domain includes VACS applications that provide entertainment or information to drivers and passengers.

Furthermore, VACS communication regimes are defined according to both the required technology (transmission scheme) and usage (transmission type). According to the required technology, two communication regimes are defined:

- The *bidirectional regime* that enables connection between two vehicles or vehicle and roadside for bidirectional exchange of information; and
- The *position based regime* whereby information is spread simultaneously to a group of vehicles in a specified geographical area. Information is disseminated one way only by vehicles or roadside units, where roadside units are seen as fixed-position vehicles.

Finally, according to the usage, three communication regimes are defined:

- *In-vehicle regime* refers to communication types that are based on electronic units inside the vehicle;
- *Vehicle-to-vehicle (V2V) regime* refers to communication types allow the exchange of information among vehicles; and
- *Vehicle-to-infrastructure (V2I) regime* refers to communication types that allow the exchange of information between vehicles and the infrastructure.

More recently, van Schijndel-de Nooij et al (2011) proposed a VACS application domain classification considering information/entertainment, warning, lateral driver assistance, longitudinal driver assistance, emergency, eco-driving, traffic management and comfort systems as Figure 3.1 displays.

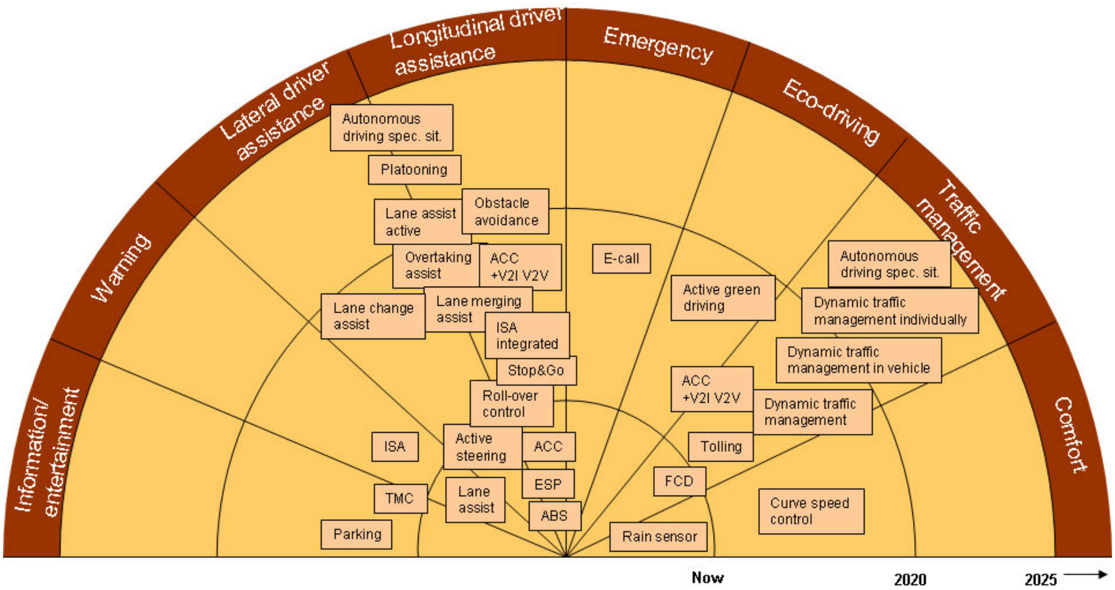

Figure 3.1. The current and possible future applications based on automated driving according to van Schijndel-de Nooij et al (2011)

A completely different aspect of VACS is reflected in the classification adopted by Shladover (2012b), which distinguishes VACS applications according to their level of automation and cooperation. Automation level refers to the degree at which the driving task is automated, while cooperation refers to the potential interactions of the vehicle with other vehicles and/or the infrastructure. The relevant taxonomy along with some examples is illustrated in Figure 3.2.

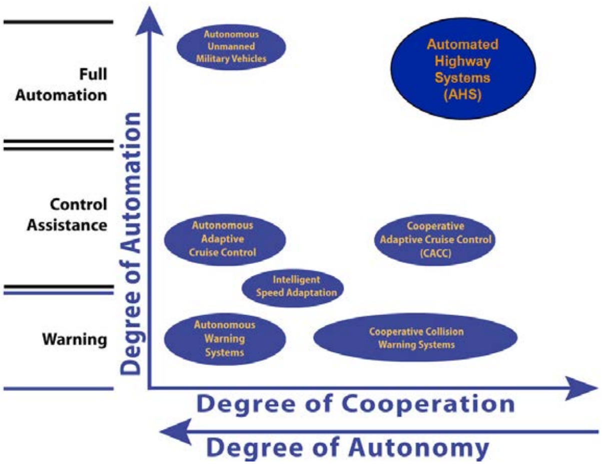

Figure 3.2. Full range of automation and cooperation alternatives according to Shladover (2012b)

A taxonomy based similarly to the Shladover's (2012b) one in VACS automation level, is also provided by the iMobility Forum (2013). Unlike Shladover (2012b), however, iMobility Forum (2013) defines more automation levels, while classifies VACS according to their automation level and application area (urban, rural, highway). Figure 3.3 displays the relevant mapping of the VACS applications.

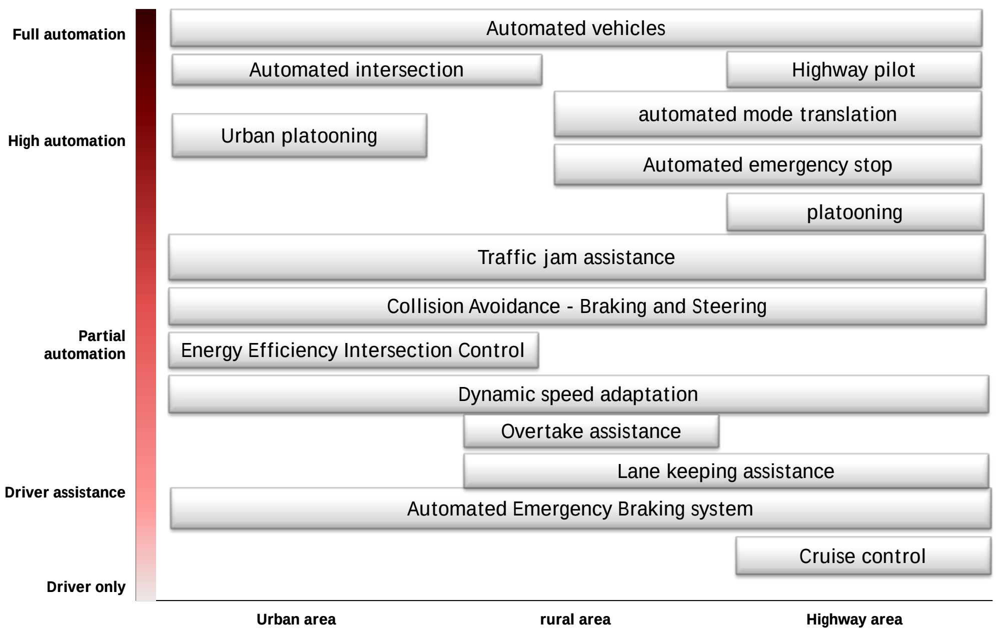

Figure 3.3. Functional mapping of applications according to iMobility Forum (2013)

Especially as far as vehicle automation is concerned, the National Highway Traffic Safety Administration (NHTSA) of USA defines as *automated vehicles* those in which at least some aspects of a safety-critical control function occur without any direct driver input and defines five levels of automation as follows[4]:

- *Level 0 – No-Automation*. The driver is in complete and sole control of the primary vehicle controls (brake, steering, throttle, and motive power) at all times, and is solely responsible for monitoring the roadway and for safe operation of all vehicle controls.
- *Level 1 – Function-specific Automation*: Automation at this level involves one or more specific control functions; if multiple functions are automated, they operate independently from each other. The driver has overall control, and is solely responsible for safe operation.
- *Level 2 - Combined Function Automation*: This level involves automation of at least two primary control functions designed to work in unison to relieve the driver of control of those functions. The driver is still responsible for monitoring the roadway and safe operation and is expected to be available for control at all times as the system can relinquish control with no advance warning.
- *Level 3 - Limited Self-Driving Automation*: Vehicles at this level enable the driver to cede full control of all safety-critical functions under certain traffic or environmental conditions. The vehicle is designed to ensure safe operation during the automated driving mode, while the driver is expected to be available for occasional control, but with sufficiently comfortable transition time.
- *Level 4 - Full Self-Driving Automation*: The vehicle is designed to perform all safety-critical driving functions and monitor roadway conditions for an entire trip. The driver provides destination input, but is not expected to be available for control at any time during the trip; by design, safe operation rests solely on the automated vehicle system.

The above examples indicate that there is no unified or widely acceptable VACS taxonomy. Depending on the intended use, researchers as well as relevant authorities develop classifications that best serve their aims. Following this rationale, to best serve the research and development aims of TRAMAN21 a taxonomy is developed aiming to identify VACS with a potential to be deployed by a MTM system towards improving traffic conditions and efficiency. To this end, the first level of the taxonomy proposed herein differentiates VACS with implications on traffic flow from VACS that serve purely safety and comfort purposes without any, even by side, effects on traffic conditions. Obviously, only VACS of the first category may be useful for exploitation within a traffic management context aiming at improving traffic efficiency via appropriate manipulations of the prevailing traffic flows. This category is then further divided, to differentiate VACS that address motorway operations and they may therefore be useful from a MTM perspective from VACS that address urban operations and, although have implications on traffic flow, cannot be deployed under a MTM concept.

Summarising the above considerations, an initial VACS taxonomy is proposed herein that serves at best the TRAMAN21 research and development aims in that it reflects the relevance

4 http://www.nhtsa.gov/About+NHTSA/Press+Releases/U.S.+Department+of+Transportation+Releases+Policy+on+Automated+Vehicle+Development [accessed 31.01.2014]

of the corresponding systems to the motorway traffic flow efficiency and therefore to the MTM concept. According to this taxonomy, VACS are classified as (see also Figure 3.4):

- *VACS without traffic flow implications*: This category includes VACS that aim only at the safety and comfort of the driver, and their operation does not modify the common traffic flow patterns. Section 3.2 below provides an overview of these systems along with a further functionality-based classification.
- *VACS with traffic flow implications*: This category includes VACS the operation of which modifies the common traffic flow patterns, beyond any other safety and comfort features that they may also have. These VACS are further distinguished in:
    - *Urban traffic related VACS*, which include VACS that address urban operations only; and
    - *Motorway traffic related VACS*, which include VACS that address, potentially among others, motorway operations.

  Section 3.3 below provides an overview of these two VACS classes along with corresponding functionality-based classifications. The motorway traffic related VACS are then reviewed in more detail in Chapter 4, since these are the systems that are of interest from a MTM aspect.

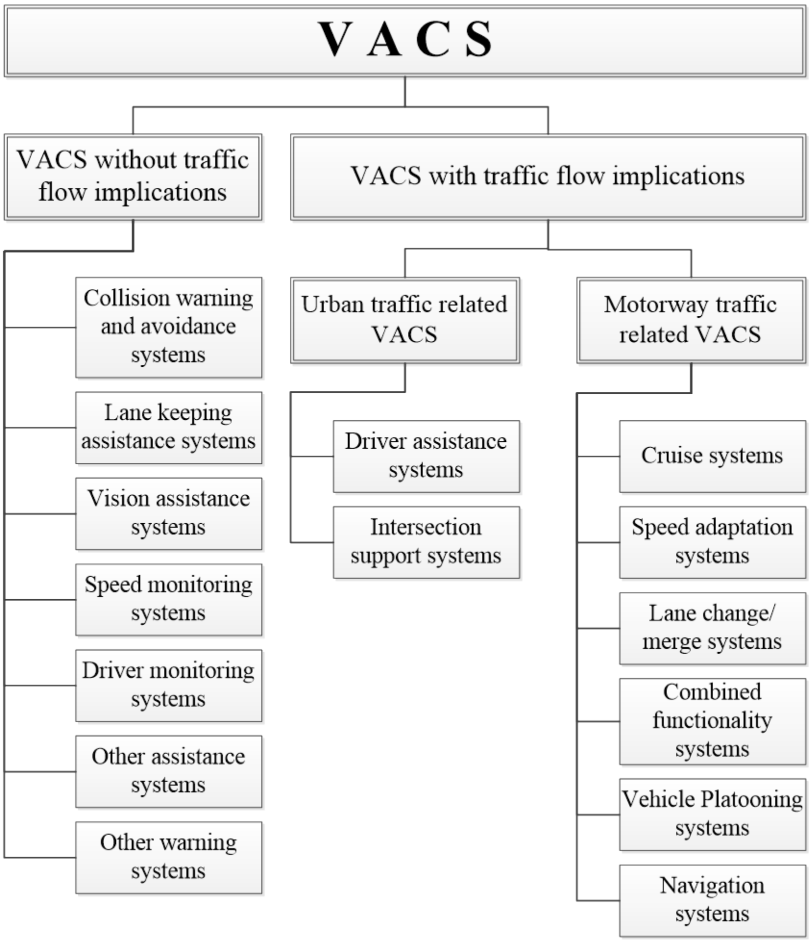

Figure 3.4. VACS taxonomy for TRAMAN21

Before proceeding further in their presentation, it should be noted that all VACS and relevant information reported in the following two sections have been identified through an extensive literature review, which took place from March 2013 to January 2014. In general, literature reports on nearly 90 different VACS most of which belong to the class of VACS with no traffic flow implications. Noticeable also is the fact that even VACS which, according to the detailed review of Chapter 4, have been found to have traffic flow implications were initially conceived as safety and comfort instruments. These facts indicate that there is plenty of room for research and development activities, not only in the area of VACS deployment within traffic management as aimed by TRAMAN21, but also in the development of VACS particularly aiming for such a deployment.

3.2. VACS without traffic flow implications

This class of VACS includes systems aiming only at assisting and improving the safety and comfort aspects of the driving task, without altering the physics of aggregate traffic flow. Of course, if these systems lead to a lower risk of accidents, they will have a corresponding beneficial impact on the average traffic flow performance due to less non-recurrent congestion. The relevant literature reports on numerous such systems, which range from informative to assisting and to even intervening operation and can be further classified based on their aimed functionalities in:

- *Collision warning and avoidance systems*: They aim at reducing the risk of collisions and range from simple visual and/or audio alarms to brakes pre-charge or even braking to minimise impacts. Table 3.1 lists and briefly describes relevant systems. According to a relatively recent FOT (General Motors Corporation, 2005; University of Michigan and General Motors Corporation, 2005a, 2005b), the use of such systems, even in their advisory mode, may lead to increased headways. Such systems, therefore, may have indirect implications on traffic flow, the range and magnitude of which, however, have never been investigated, since they are in principle safety-oriented systems.
- *Lane keeping assistance systems*: They assist the driver to maintain the position of the vehicle in the lane. Table 3.2 lists and briefly describes relevant systems.
- *Vision assistance systems*: They assist the driver under hard visibility conditions (at night and/or at blind spot) to avoid potential hazards. Table 3.3 lists and briefly describes relevant systems.
- *Speed monitoring systems*: They provide warnings for speeding at hazardous locations such as road curves. Table 3.4 lists and briefly describes relevant systems.
- *Driver monitoring systems*: They detect and alert distracted and/or tired drivers; some systems even take control of the vehicle if the driver does not seem to respond to the warnings. Table 3.5 lists and briefly describes relevant systems.
- *Other assistance systems*: This category includes systems aiming at assisting the driver in several tasks and areas not covered by the aforementioned ones, such as overtaking, parking, cyclist and pedestrians detection, etc. Table 3.6 lists and briefly describes relevant systems.
- *Other warnings systems*: This last category includes systems aiming at warning the driver in hazardous situations not covered by the aforementioned ones, including presence of animals, approach of emergency vehicles, approach to non-moving

vehicles/hazardous road surfaces/traffic jams, etc. Table 3.7 lists and briefly describes relevant systems.

Table 3.1. Collision warning and avoidance systems

System	Description	Sources of info
Active Passive Integration Approach (APIA)	Assists the driver if a collision is imminent by reducing the car's braking distance, thereby minimising the risk of a collision; specifically, a Lane Departure Warning (LDW; see Table 3.2 below) system makes sure that the vehicle does not leave the lane, and a Closing Velocity (CV) sensor brakes as soon as the vehicle in front is too close, thus preventing or lessening the seriousness of rear-end collisions	Alkim et al, 2007; http://www.continental-corporation.com/www/pressportal_com_en/Search.html?q=APIA&view=asSearch&filterDoctypes=type_1 [accessed 31.01.2014]
Advanced Braking System (AdvBS)	Combine features of conventional ABS, linked brakes and traction control	http://www.local-transport-projects.co.uk/files/BP5%20004%20Advanced%20Braking%20Systems%20(v1).pdf [accessed 11.03.2013]
Anti-lock Braking System (ABS)	Prevents skidding, reduces stopping distance and allows steering the vehicle around obstacles it would otherwise hit	Burton et al, 2004; Grover et al, 2008
Brake Assist (BA)	Depending on the situation, the system gives the driver an early warning of a potential rear-end collision, determines how much braking power is required to prevent a collision, and automatically initiates an emergency stop if the driver fails to react appropriately	Alkim et al, 2007; http://www.continental-corporation.com/www/pressportal_com_en/Search.html?q=Brake+assist&view=asSearch&filterDoctypes=type_1 [accessed 31.01.2014]
Brake-by-Wire system (BbW)	System that shortens the braking distance based upon Electro Mechanical Brake (EMB) actuation, instead of the currently employed pneumatic actuation; the EMB system is using the principle of self-enforcement for generating brake force, thus leading also to very low energy consumption and more silent braking	Hoeger et al, 2011
Braking Distance Warning System (BDWS)	Generates hazard lights flashes when emergency brake is engaged to warn next car to slow down in speed. Reminds next car to keep proper distance when in use of emergency brake	http://www.taiwantrade.com.tw/argus/products-detail/en_US/555549 [accessed 15.03.2013]
Collision Avoidance - Braking and Steering (CA-BS)	Extension of the Automatic Emergency Braking System that also steers as a means to avoid accidents	iMobility Forum, 2013
Collision Avoidance System (CAS)	Detects an imminent crash and, depending on the particular system's capabilities, may warn the driver, pre-charge the brakes, inflate seats for extra support, move the passenger seat, position head rests to avoid whip lash, tension seat belts and automatically apply partial or full braking to minimise impact	Ehmanns and Spannheimer, 2004; Bishop, 2005; Alkim et al, 2007; Van Driel, 2007; Grover et al, 2008; Benmimoun et al, 2012; Kessler et al, 2012; iMobility Forum, 2013; http://www.eurofot-ip.eu/en/intelligent_vehicle_systems/acc/ [accessed 11.03.2013]; http://ec.europa.eu/transport/road_safety/specialist/knowledge/esave/esafety_measures_unknown_safety_effects/collision_avoidance_systems.htm [accessed 15.03.2013]
Cooperative Collision	Delivers forward collision warning, right-	Sengupta et al, 2007; Popescu-Zeletin et

System	Description	Sources of info
Warning (CCW)	side blind spot or lane change warning, and intersection collision warning capabilities	al, 2010
Emergency Electronic Brake Lights (EEBL)	In case of hard braking, sends a warning to the following vehicles	Popescu-Zeletin et al, 2010
Following Distance Warning (FDW)	Monitors the distance and time headway to a preceding vehicle and provides continuous feedback to the driver without intervening on its own	Bishop, 2005; Regan et al, 2006
Pre-crash Safety System (PSS)	Using information from sensors, detects the risk of a collision with the vehicle in front; if the collision is unavoidable, pre-charges the brakes and retracts the seatbelts to help reduce injuries	Ehmanns and Spannheimer, 2004; Bishop, 2005; Van Driel, 2007; Popescu-Zeletin et al, 2010
Reverse Collision Warning (RCW)	Visual and audible system, which warns drivers about the likelihood of collision with an object behind the vehicle by means of sensors in the rear bumper	Regan et al, 2006; http://ec.europa.eu/transport/road_safety/specialist/knowledge/esave/esafety_measures_unknown_safety_effects/collision_avoidance_systems.htm [accessed 15.03.2013]

Table 3.2. Lane keeping assistance systems

System	Description	Sources of info
Lane Departure Warning (LDW)	Assists the driver to maintain his/her lane position, giving a warning if the vehicle crosses lane markings unintentionally; if no input is given, the system follows the lane automatically	Batavia, 1999; Ehmanns and Spannheimer, 2004; Bishop, 2005; Alkim et al, 2007; Van Driel, 2007; Kessler et al, 2012; iMobility Forum, 2013; http://www.eurofot-ip.eu/en/intelligent_vehicle_systems/acc/ [accessed 11.03.2013]
Adaptive Lane Departure Warnings System (ALDWS)	Same as LDW, but works with a virtual lane boundary instead of the real one	Deram, 2004; Fagerberg, 2004

Table 3.3. Vision assistance systems

System	Description	Sources of info
Adaptive Front-lighting System (AFS)	Illuminates the areas in front and to the sides of the vehicle path to optimise the headlight beam in response to ambient weather and visibility conditions, vehicle speed and road curvature	Bishop, 2005; Van Driel, 2007
Blind Spot Information System (BLIS)	Assists the driver by detecting the presence of vehicles in the driver's blind spot	Ehmanns and Spannheimer, 2004; Van Driel, 2007; Kessler et al, 2012; http://www.eurofot-ip.eu/en/intelligent_vehicle_systems/acc/ [accessed 11.03.2013]
Cooperative Glare Reduction (CGR)	Automated system that, when darkness occurs, switches from high-beams to low-beams and vice versa according to the distance to the surrounding vehicles in forward path area	Popescu-Zeletin et al, 2010
Night Vision (NV)	Helps with detecting objects on or near the road, such as pedestrians and animals, beyond the view of the vehicle's headlights	Ehmanns and Spannheimer, 2004; Bishop, 2005; Van Driel, 2007
Pedestrian and Cyclist Detection (PCD)	Detects and automatically brakes for cyclists swerving out in front of the car	Bishop, 2005; http://traffictechnologytoday.com/news.php?NewsID=47130

System	Description	Sources of info
		[accessed 11.03.2013]

Table 3.4. Speed monitoring systems

System	Description	Sources of info
Cruise Control (CC)	Used to maintain a constant speed set by the user	Benmimoun et al, 2012; Kessler et al, 2012
Curve & Speed Limit Info (C&SLI)	Informs drivers about speed limits and recommended speed in curves	Ehmanns and Spannheimer, 2004
Curve Speed Warning (CSW)	Helps drivers identify potentially dangerous situations if a bend in the road is taken too fast; warns in advance allowing time for proper reactions; warns for potential hazards from speeding and prepares the safety systems in the vehicle, or actively inhibits further acceleration	Bishop, 2005; Hoeger et al, 2011; Benmimoun et al, 2012; Kessler et al, 2012; http://www.eurofot-ip.eu/en/intelligent_vehicle_systems/acc/ [accessed 11.03.2013]

Table 3.5. Driver monitoring systems

System	Description	Sources of info
Automated Emergency Stop (AES)	Also called Driver Monitoring (DM) system, continuously monitors the driver and brings the vehicle at a safe state with a minimum risk manoeuvre (e.g. lane change on emergency lane with subsequent vehicle stop) if he/she drops out	Bishop, 2005; Van Driel, 2007; iMobility Forum, 2013
Impairment Warning (IW)	Alerts tired and distracted drivers; a camera monitors the car's movements between the lane markings and calculates the risk of the driver losing control of the vehicle and a message in the display advises the driver if it is time to take a break	http://www.eurofot-ip.eu/en/intelligent_vehicle_systems/acc/ [accessed 11.03.2013]

Table 3.6. Other assistance systems

System	Description	Sources of info
Heading Control (HC)	Controls the heading of a vehicle under the unpredictable and unstructured surrounding environment	Suppachai et al, 2009
Overtake Assistance (OA)	Assists in overtaking vehicles in rural scenario's by assessing the safe space or location for overtaking, taking into account speed of the vehicles including the vehicle to be overtaken	iMobility Forum, 2013
Parking Assistant (PAss)	Helps drivers in avoiding the minor "dings" that can come with parking manoeuvers	Bishop, 2005
Terrain Response (TR)	Allows a driver to specify the type of surface the vehicle is travelling on and then adjusts the engine, transmission, suspension and traction controls to the relevant surface to ensure optimal performance	Wilmink et al, 2006

Table 3.7. Other warning systems

System	Description	Sources of info
Animal Warning (AW)	Advices drivers by electronic signs for the presence of animals detected by roadside sensors	Bishop, 2005

System	Description	Sources of info
Approaching Emergency Vehicle Warning (AEVW)	Sends warnings to vehicles in the path of an emergency vehicle to move out of the way	Popescu-Zeletin et al, 2010
Hazardous Location Notification (HLN)	Sends warning alerts about possible hazards detected by in-vehicle sensors or infrastructure	Popescu-Zeletin et al, 2010
Information & Warning Functions (IWF)	Transmits signals indicating vehicle breakdowns, detected traffic density and congestions, or road surface conditions, allowing the early warning of approaching vehicles	Maihöfer et al, 2004
Limited Access Warning (LAW)	Sends warning alerts via infrastructure about restricted access	Popescu-Zeletin et al, 2010
Local Hazard Warning (LHW)	Warns for hazards occurring far away in front of the vehicle by the means of communication	Ehmanns and Spannheimer, 2004
Post-Crash Warning (PCW)	Unmoving vehicles (because of an accident or mechanical failure) that disturb or endanger traffic send alert type warning messages to prevent collisions	Popescu-Zeletin et al, 2010
Road Surface Condition Monitoring (RSCM)	Monitors and informs drivers regarding degraded road surface conditions, such as wet or icy pavement	Bishop, 2005
Slow Vehicle Warning (SVW)	Sends warning alerts to surrounding rear vehicles about low speed to prevent collisions	Popescu-Zeletin et al, 2010
Traffic Jam Ahead Warning (TJAW)	Vehicles in a traffic jam send warning alerts about the position of the jam to approaching vehicles in order to avoid possible collisions	Popescu-Zeletin et al, 2010
Working Area Warning (WAW)	Sends warning alerts about road works, blocked lanes announced by infrastructure (roadside units) or distributed by other vehicles	Popescu-Zeletin et al, 2010
Wrong Way Driving Warning (WWDW)	Identifies vehicles driving wrong way and warns drivers of possible collisions	Popescu-Zeletin et al, 2010

3.3. VACS with traffic flow implications

3.3.1. Urban traffic related VACS

This class of VACS includes systems that have direct implications on traffic flow, but address urban traffic operations. They are not thus suitable for deployment under a MTM concept.

The relevant literature reports on several such systems, which, based on their aimed functionalities, may be further classified in:

- *Driver assistance systems*: This category includes VACS that aim at the partial or full automation of the driving task mainly within restricted and/or well defined environments. Table 3.8 lists and briefly describes relevant systems.
- *Intersection support systems*: This category includes VACS aiming at supporting the driving task at the vicinity of intersections. Table 3.9 lists and briefly describes relevant systems.

Table 3.8. Driver assistance systems

System	Description	Sources of info
Adaptive Cruise Control with Non-Motor-Vehicle detection (ACC-NMV)	Adaptive Cruise Control (ACC; see Table 3.11 below) plus Non-Motor-Vehicle (NMV) detection in urban environments	Milanes et al, 2012

System	Description	Sources of info
Advanced City Vehicle (ACV)	Car with driver assistance systems for partial automation and ability to operate automatically under some specialised conditions, such as platooning of empty vehicles without drivers behind a lead vehicle driven by a specially trained person	Shladover, 2012a
Automated Public Car (APC)	Concept combining self-service cars technology (e.g. CyberCars) and Personal Rapid Transit (PRT) technologies	Laugier et al, 2001
CyberCar	Driverless low-speed vehicle operating within restricted environments (examples include Cycab, πCar, BS-car, etc.)	Laugier et al, 2001; Shladover, 2012a
GoogleCar	Driverless car fulfilling human transportation capabilities of a traditional car in an autonomous way	http://en.wikipedia.org/wiki/Google_driverless_car [accessed 11.03.2013]
Personal Rapid Transit (PRT)	Small vehicles operating between stations on special dedicated guideways; concept similar to the Automated Highway Systems but for urban environments.	Laugier et al, 2001; Marsden et al, 2002; Shladover, 2012a

Table 3.9. Intersection support systems

System	Description	Sources of info
Cooperative Traffic Light System (CTLS)	Aims at efficient traffic control, support for individual drivers in hazardous traffic situations and linking of road users by radio	http://www.siemens.com/press/en/presspicture/?press=/en/presspicture/2012/infrastructure-cities/mobility-logistics/soicmol201209/soicmol201209-01.htm [accessed 02.07.2013]
Intersection Assistant (IA)	Aims at preventing accidents at intersections by providing drivers with warnings about potential hazards, including stop sign and red light violation, turning accidents, crossing-path accidents, rear-end collision, collision with pedestrians etc.; some systems also recommend the right speed for a green traffic light wave or when approaching a red traffic light	Ehmanns and Spannheimer, 2004; von Arnim et al, 2008; Le et al, 2009; Roessler and Fuerstenberg, 2009; http://www.volkswagenag.com/content/vwcorp/content/en/innovation/driver_assistance/intersection_assistant.html [accessed 02.07.2013]
Left Turn Assistant (LTA)	Assists drivers in making turning manoeuvers at intersections considering oncoming traffic, pedestrians, and other obstacles	Le et al, 2009; http://www.volkswagenag.com/content/vwcorp/content/en/innovation/driver_assistance/intersection_assistant.html [accessed 02.07.2013]
Stop Sign Assist (SSA)	Using sensors installed at intersections, helps drivers in deciding when they can proceed onto or across a high-speed road after stopping at a rural road stop sign	Le et al, 2009
Traffic Signal Adaptation (TSA)	Detects dangerous situations when vehicles violate red lights and can potentially collide with other vehicles; and triggers a red light in all directions to protect drivers from an imminent danger; when vehicles detect dangerous situations, they can also send warning messages to the infrastructure to trigger an all-red traffic signal stage and prevent a chain reaction of accidents	Le et al, 2009
Violation Warning System (VWS)	Allows the infrastructure to send status information of the traffic lights to approaching vehicles, and provides warnings to the drivers when the estimated risk that their vehicle will violate a traffic light is sufficiently high	Le et al, 2009

3.3.2. Motorway traffic related VACS

This last class of VACS includes systems that have direct implications on traffic flow, and address motorway operations so that they are potentially suitable for deployment under a MTM concept.

The relevant literature reports on several such systems, which, based on their aimed functionalities, may be further classified in:

- *Cruise systems*: This category includes systems that assist equipped vehicles to follow other vehicles in a safe and comfortable manner. Table 3.11 lists and briefly describes relevant systems.
- *Speed regulation systems*: This category includes systems that assist the regulation of speed according to legal or other, such as "green", limits. Table 3.12 lists and briefly describes relevant systems.
- *Lane change/merge assistance systems*: This category includes systems that assist the lane change and merge vehicle manoeuvres. Table 3.13 lists and briefly describes relevant systems.
- *Combined-functionality systems*: This category includes systems, which combine several functionalities and thus, they cannot be classified to only one of the previously three categories. Table 3.13 lists and briefly describes relevant systems.
- *Vehicle Platooning Systems*: This category involves a variety of options for forming closely-spaced vehicle platoons, aiming at more convenient, safe, fuel-efficient and traffic-efficient driving. Table 3.14 describes briefly the options offered by such systems.
- *Navigation systems*: This last category includes systems that are mainly aimed at providing personalised location and route guidance information in order to assist and advice the driver in planning a journey, as well as for en-route decisions. Table 3.15 describes briefly the options offered by such systems.

Table 3.10. Cruise systems

System	Description	Sources of info
Adaptive Cruise Control (ACC)	Automatically adjusts the speed to ensure the vehicle does not get too close to the one in front; activated by setting the desired maximum speed and time gap to the vehicle in front; operates at relatively high speeds	Zwaneveld and van Arem, 1997; Fancher et al, 1998; Swaroop and Rajagopal, 1998; Bose and Ioannou, 1999, 2001, 2003; VanderWerf et al, 2001, 2002; Li and Shrivastava, 2002; Davis, 2004, 2006, 2007; Zhang and Ioannou, 2004; Bishop, 2005; Ioannou and Zhang, 2005; General Motors Corporation, 2005; University of Michigan and General Motors Corporation, 2005a, 2005b; Rajamani et al, 2005; Visser, 2005; Jiang and Wu, 2006; Rajamani, 2006; Yi and Horowitz, 2006; Alkim et al, 2007; Ioannou et al, 2007; Kesting et al, 2007a, 2007b, 2008, 2010; Viti et al, 2008; Yuan et al, 2009; Pueboobpaphan and van Arem, 2010; Xiao and Gao, 2010; Kessler et al, 2012; Tapani, 2012; Benmimoun et al, 2012, 2013; http://www.eurofot-

System	Description	Sources of info
		ip.eu/en/intelligent_vehicle_systems/acc/ [accessed 11.03.2013]
Cooperative Adaptive Cruise Control (CACC)	Adaptive Cruise Control extended so that vehicles are wirelessly connected and can therefore respond in a smoother way to disruptions in traffic flow	VanderWerf et al, 2002, 2001, 2007; Maihöfer et al, 2004; Bishop, 2005; Visser, 2005; Popescu-Zeletin et al, 2010; Shladover et al, 2010, 2011; Arnaout and Bowling, 2011, 2013
Full Speed Range Adaptive Cruise Control (FSRA)	Evolution of the Adaptive Cruise Control, which operates in all speed ranges	Minderhoud, 1999; Ehmanns and Spannheimer, 2004; Bishop, 2005; Alkim et al, 2007; Viti et al, 2008; Hoeger et al, 2011; Shladover, 2012a; iMobility Forum, 2013
Low Speed ACC (LSACC)	Evolution of the Adaptive Cruise Control, which operates in slow, congested traffic to follow the vehicle immediately ahead	Minderhoud, 1999; Benz et al, 2003; SINTEF et al, 2004; Bishop, 2005; van Driel, 2007; van Driel and van Arem, 2008, 2010

Table 3.11. Speed regulation systems

System	Description	Sources of info
Active Green Driving (AGD)	A suitably designed, within the HAVEit EC project, human-machine interface used to coach the driver with the aim to reduce the fuel consumption and pollution	Hoeger et al, 2011
Cooperative Variable Speed Limit System (CVSLS)	Extension of the Variable Speed Limit (VSL) system that employs V2I communication to communicate to vehicles upstream of the existing VSL system location, individual speed limits determined by their current speed and position	Grumert et al, 2013
Fuel Efficiency Advisor (FEA)	Supports in maintaining the engine speed in the "green area" towards optimal usage of the vehicle with respect to fuel efficiency; advices when the engine speed is outside the "green area" longer than a pre-set limit; warns when a certain speed threshold is reached and when the engine is on idle for an extended time	Kessler et al, 2012; http://www.eurofot-ip.eu/en/intelligent_vehicle_systems/fea/ [accessed 11.03.2013]
Intelligent Speed Adaptation (ISA)	Primarily used to maintain speed within the legal (posted) limits; more advanced versions allow for dynamic speed limits that may be adjusted based on factors such as traffic conditions, time of day, and weather conditions	Tampère et al, 1999; Carsten and Tate, 2000, 2005; Varhelyi and Makinen, 2001; Biding and Lind, 2002; Hegeman, 2002; Hogema et al, 2002; Liu and Tate, 2004; Bishop, 2005; van Driel, 2007; Boriboonsomsin et al, 2008; Doecke and Woolley, 2010; Marchau et al, 2010; SWOV, 2010; Hoeger et al, 2011; Vlassenroot et al, 2011a, 2011b; Benmimoun et al, 2012; Blum et al, 2012; Kessler et al, 2012; iMobility Forum, 2013

Table 3.12. Lane change/merge assistance systems

System	Description	Sources of info
Cooperative Merging (CM)	Combines automated longitudinal control with V2V or V2I communication to assist the driver in lane changing manoeuvres by	Tampère et al, 1999; Popescu-Zeletin et al, 2010

System	Description	Sources of info
	creating and maintaining an appropriate gap in the target lane	
Lane Change Decision Aid System (LCDAS)	Supports lane change and merge vehicle manoeuvres to mainly avoid potential collisions	Godbole et al, 1997; Jula et al, 1999, 2000; Smith et al, 2003; Tideman et al, 2007; Visvikis et al, 2008; Popescu-Zeletin et al, 2010; Habenicht et al, 2011; Wan et al, 2011; Bartels et al, 2012; Tomar and Verma, 2012; Knake-Langhorst et al, 2013

Table 3.13. Combined-functionality systems

System	Description	Sources of info
Cooperative Following and Merging (CFM)	Aims at smoothing traffic flow and enhancing traffic safety by avoiding creation of shock waves or limiting their impact, should they appear	Tampère et al, 1999
Highway Pilot (HP)	Vehicle application, which will support the driver on motorways and motorway similar roads with high level of automation in longitudinal and lateral control of the vehicle at speeds between 0 and 130 km/h	iMobility Forum, 2013; Hoeger et al, 2011
Integrated Full-Speed Range Speed Assistant (IRSA)	Informs and helps drivers to maintain a safe speed under a multitude of circumstances such as sharp curves, reduced speed limit zones and traffic jams	Wilmink et al, 2006; van Arem et al, 2007

Table 3.14. Vehicle platooning systems

System	Description	Sources of info
Vehicle Platooning System (VPS)	Involves a variety of options for forming closely-spaced semi or full automated vehicle platoons, aiming at more convenient, safe, fuel-efficient and traffic-efficient driving	PATH, 1997; Michael et al, 1998; Hedrick et al, 2001; Lee and Kim, 2002; Bonnet, 2003; Ehmanns and Spannheimer, 2004; Bishop, 2005; Hallé and Chaib-draa; 2005; van Arem et al, 2006; Alam et al, 2010; Alam, 2011; Tientrakool et al, 2011; Bergenheim et al, 2012a, 2012b; Kavathekar, 2012; Shladover, 2012a; Brännström, 2013; Davila, 2013; iMobility Forum, 2013; Kianfar, 2013; SARTRE, 2013; Tsugawa, 2014;

Table 3.15. Navigation systems

System	Description	Sources of info
Navigation System (NAVS)	Aims at providing personalised location and route guidance information in order to assist and advice the driver in planning or completing a journey	Eby and Kostyniuk, 1999; Pang et al, 2002; McNally et al, 2003; Flinsenberg, 2004; Jahn et al, 2005; May et al, 2005; Kaparias et al, 2007; Ma and Kaber, 2007; Lee et al, 2008; Schultes, 2008; Buscena et al, 2009; Delling and Wagner, 2009; Delling et al, 2009; Kaparias and Bell, 2009, 2010; Lavien et al, 2011; Lee and Yang, 2012; Nagaki, 2012; Skog and Händel, 2012; Belzowski and Ekstrom, 2013

4. Review of motorway traffic related VACS

4.1. Cruise systems

4.1.1. Adaptive Cruise Control (ACC)

4.1.1.1. Description and functions

Also known as:

- Autonomous Intelligent Cruise Control (AICC), or
- Autonomous Adaptive Cruise Control (AACC), or
- Intelligent Cruise Control (ICC),

Adaptive Cruise Control [5] (ACC) is an extension of the conventional driver comfort-oriented Cruise Control (CC).

CC is used to maintain a constant speed without any manual control by the driver; CC is useful and convenient when the driving conditions are appropriate, i.e. when speeds do not vary significantly. The driver sets the speed, which should be above a limit of around 30 km/h, and then the system takes over the throttle control of the vehicle so as to maintain this speed (Benmimoun et al, 2012; Kessler et al, 2012). ACC has been designed so as at to extend the operation of CC to situations where driving at constant speed is not possible.

ACC uses headway sensors to continuously measure the distance to the front vehicle and automatically adjusts the speed to ensure the distance is maintained close to the desired value. However, the driver retains his/her role as a supervisor to monitor the performance of the ACC system, to observe the real traffic situations and to judge whether he/she should take over the control of the vehicle.

According to ISO 15622:2010[6] ACC is "*fundamentally intended to provide longitudinal control of equipped vehicles while travelling on highways (roads where non-motorized vehicles and pedestrians are prohibited) under free-flowing traffic conditions*".

The driver activates ACC by setting the desired maximum speed and then selecting the distance from the vehicle in front (Kessler et al, 2012) in the form of the spacing policy that the design of the ACC system assumes. Over the years, several different spacing policies had been proposed starting with the Pipes' one (Xiao and Gao, 2010), which is called "law of separation", and is the sum of the distance that is proportional to the velocity of the following vehicle and a certain given minimum distance of separation when the vehicles are at rest. Later, five more different kinds of spacing policies were proposed, the constant distance, constant time headway, safety factor, stability and acceptance (Xiao and Gao, 2010). The constant time headway (CTH) (or constant time-gap (CTG)) spacing policy was selected and applied from automakers considering feasibility, stability, safety, capability and reliability (Xiao and Gao, 2010). According to the CTH policy, the speed of the ACC-equipped vehicle is automatically adjusted (via acceleration/deceleration) so as to maintain a desired time gap from the preceding vehicle.

[5] http://www.eurofot-ip.eu/en/intelligent_vehicle_systems/acc/ [accessed 11.03.2013]
[6] http://www.iso.org/iso/home/store/catalogue_tc/catalogue_detail.htm?csnumber=50024 [accessed 12.07.2013]

When the roadway ahead of the equipped vehicle is free, ACC maintains the user-defined free-speed or, in other words, operates in a *speed control mode* just like the conventional CC system. On the other hand, if the ACC sensors detect a vehicle ahead in the same lane within a certain distance, ACC adjusts the speed of the equipped vehicle so as to maintain the user-selected desired distance or, in other words, operates in a *space control mode* (Visser, 2005; Rajamani, 2006).

Common ACC systems operate in the speed range 30 - 200 km/h, while offering a choice of 3 to 4 time gap settings. Time-gap selection ranges typically from 1.0 to 2.2 seconds (Bishop, 2005). Regulations in Europe stipulate that, for regular driving, the recommended (or required, depending on the country) following time gap between vehicles is 2 s. However, user experiences thus far indicate that this is an unrealistically large gap, causing other vehicles to frequently cut in front of them (Bishop, 2005). For this reason, automakers offer shorter gap selections than those recommended by public authorities, with a default setting compliant with the recommendation. Thus, if a driver selects a gap less than what is officially allowed, he/she maintains this gap under his/her own control and responsibility.

ISO 15622:2010 contains the basic control strategy, minimum functionality requirements, basic driver interface elements, minimum requirements for diagnostics and reaction to failure, and performance test procedures for ACC systems.

ACC appears also in some variants such as the Collision Mitigation by Braking[7] (CMbyB), which is an evolution of ACC with the addition of a braking system that increases headway by braking. CMbyB systems may also detect obstacles within the road and brake accordingly. Another variant of ACC is the Automotive Collision Avoidance System (ACAS) developed by General Motors in collaboration with Delco Electronics & Safety and the University of Michigan. ACAS consists of an ACC and a Forward Collision Warning (FCW) system that assists the driver when manually driving to detect and thus avoid imminent collisions (General Motors Corporation, 2005; University of Michigan and General Motors Corporation, 2005a, 2005b). The particular FCW function provides visual warnings when following very closely (tailgating), or when approaching a vehicle too rapidly (closing).

4.1.1.2. Evaluation results

The introduction of ACC-equipped vehicles in traffic has given rise to three types of stability concerns (Pueboobpaphan and van Arem, 2010):

- *Vehicle* or *local stability*, which implies that the spacing error of ACC-equipped vehicles converges to zero when the preceding vehicle is operating at constant speed; though it is not expected to be zero if the preceding vehicle accelerates or decelerates;
- *String* or *platoon stability*, which implies that spacing and velocity errors of individual vehicles within a “string” (i.e. a series of vehicles following each other) do not amplify as they propagate upstream; and
- *Traffic flow stability*, which implies that any initial perturbations in speed and density evolution will decay and dissipate.

[7] http://ec.europa.eu/transport/road_safety/specialist/knowledge/esave/esafety_measures_unknown_safety_effects/collision_avoidance_systems.htm [15.03.2013]

Vehicle stability is the first requirement for the design of an ACC system, and hence of great concern for the automakers. On the other hand, from a traffic flow perspective, the ACC controller should also guarantee string and traffic flow stability, else traffic safety and congestion may deteriorate. That is the reason why traffic researchers and engineers focus on the investigation of these latter two types of stability. Another subject largely investigated by traffic researchers and engineers is the effect that ACC-equipped vehicles may have on traffic flow capacity and throughput.

Zwaneveld and van Arem (1997) present a review of early ACC studies relevant to the aforementioned issues. These early studies took place in the period 1991-1997 using mainly simulation; only 2 out of the 14 reviewed studies were based on real traffic experiments with single ACC equipped vehicles. Most of these early studies reported less variance in speed. Most of these studies indicated also that the operation of ACC in mixed traffic conditions may outperform manual traffic with respect to capacity if the target headway is sufficiently short; while high target headways lead to capacity decrease. It was therefore concluded that to avoid a degradation of throughput, target headways of ACC equipped vehicles should be a good compromise between safety and capacity. Zwaneveld and van Arem (1997) concluded also that, despite the significance of these early efforts, the separate effects on the achievable maximum flow of reduced target headway, modified lane change and merge behaviour, and traffic stability resulting from the ACC operation in mixed traffic still remain open research subjects.

The issue of traffic stability under the operation of ACC has been investigated by Swaroop and Rajagopal (1998). Based on macroscopic modelling which includes the effects of ACC dynamics, as well as on simulation tests, they have shown that traffic flow is unstable, if every vehicle is equipped with an ACC system that employs a CTH policy. To limit such undesired traffic instabilities, they suggest that cruise control laws should take into account their effect on traffic flow, although they point out that traffic flow stability can only be guaranteed up to the critical density value, if ACC-equipped vehicles have negligible actuation and sensing delays.

In contrast to the above results of Swaroop and Rajagopal (1998), Li and Shrivastava (2002) showed, using different simulation approaches, that on any finite length circular highway, the traffic flow induced by the CTH policy is in fact exponentially stable, a result which has also been supported by the investigations of Jiang and Wu (2006). Moreover, Li and Shrivastava (2002) found that the manner in which this CTH policy is abstracted for the different macroscopic highway traffic models must be performed consistently and with care to avoid arise of erroneous stability properties. Finally, they found out that, although ACC policy generally utilises the inter-vehicle spacing ahead of the vehicle for feedback, traffic flow stability is expected to improve as such feedback information is taken from a location further downstream of the ACC-equipped vehicle. For this reason, they suggest that it is interesting to explore whether or not any benefits could be really obtained by defining ACC headway policies using inter-vehicle spacings that are one or more vehicles ahead.

The aforementioned controversy around the implications to traffic flow stability of the CTH policy was further studied by Rajamani et al (2005). Based on simulation investigations, they reached the conclusion that, in fact, there is no controversy. The CTH policy is indeed stable but up to a critical density limit, which, according to Rajamani et al (2005), is the density at which ACC turns at space control mode. At this limit, depending on the boundary conditions, the stability properties of the CTH policy may be lost. It is due therefore to the different boundary conditions considered that the studies of Swaroop and Rajagopal (1998) and Li and Shrivastava (2002) led to different conclusions. In addition, Rajamani et al (2005) suggest replacement of CTH with alternative policies that consider the vehicle's speed, which have been proven to have stability properties for a wider range of operating densities. Such policies can improve traffic flow capacity and ensure traffic flow stability at a wider range of traffic conditions, at the expense, however, of safety (due to shorter headways). Additionally:

- No matter what policy is employed, there will be a certain critical density beyond which the traffic flow will be unstable.
- The critical parameters that can be determined by design of the ACC policy are the value of the critical density and the value of the traffic flow that can be achieved at the critical density.

Additionally to the above studies, Rajamani et al (2005) studied also the effects of ACC in mixed traffic. Their investigations concerned ACC-equipped vehicles mixed with manually-driven vehicles under various scenarios of penetration rates. For the ACC systems, the CTH and the Variable Time Headway (VTM) policies, the latter proposed by them, were considered and compared. Their results indicate that throughput increases with the proportion of ACC vehicles under below-capacity conditions, while above capacity, speed variability increases and speed drops with a CTH policy-based ACC compared to manually-driven vehicles. In addition, the VTM policy always achieves better results than the CTH in terms of capacity and traffic stability.

Similarly to Rajamani et al (2005), Yi and Horowitz (2006) studied the issue of traffic flow stability in presence of ACC-equipped vehicles, and the controversies that had emerged in past studies. Their conclusions are in accordance with the conclusions of Rajamani et al (2005) in that the boundary conditions affect the traffic flow stability under a CTH policy. In addition they derived quantitative relationships between traffic flow stability and traffic model parameters (such as flow, speed, etc.) for a generalised ACC traffic flow model.

Bose and Ioannou (1999, 2001, 2003) have studied the effects of vehicles equipped with a CTH policy-based ACC in mixed traffic, focusing mainly on their environmental effects rather than on their effects on traffic flow stability where the works mentioned so far mainly focus. The theoretical analysis and simulation results of Bose and Ioannou (1999, 2001, 2003), assuming for the ACC-equipped vehicles CTH policies of 0.5-1.5 s, lead to the following two main conclusions regarding ACC systems:

- They smooth traffic flow by filtering the response of rapidly accelerating lead vehicles;
- They decrease air pollution and increase fuel savings during transients caused by rapid acceleration manoeuvres.

In addition, experiments with three real vehicles, one of which was equipped with an ACC system with a CTH policy of 1 s, validated the aforementioned theoretical and simulation based results.

To investigate the effects of ACC on traffic flow dynamics and capacity, VanderWerf et al (2001) developed a simulation model assuming an ACC system with a CTH policy of 1.4 s. Their initial results confirmed the findings of prior studies in that the use of alternative target headways in lieu of 1.4 s can result in substantial variability, ranging from substantial increases in capacity and smoothing of traffic flows to substantial decreases in capacity and worsening of traffic flow instabilities.

Based on the aforementioned simulation model, VanderWerf et al (2002) extended later their study to estimate the capacity of a highway as a function of the proportion of ACC versus human-driven vehicles, where the capacity of the simulated highway was defined to be the maximum rate of flow that it could sustain indefinitely. To this end, they simulated a traffic stream with no trucks, using a simulation approach designed to bring demand close to the boundary at which traffic disturbances cause the flow to break down. This study, which considered CTH policies in the range 1 - 2 s and several penetration rates indicated flow improvements for all penetration rates for ACC CTHs less than 1.1 s, which had been assumed as the desired time headway for manual driving. For higher ACC CTHs, flow improvements were found to possibly occur at penetration rates not exceeding 60%. For higher penetration rates, flow was found to decrease gradually depending also on the considered ACC CTHs; the higher the CTH, the lower the penetration rate at which flow started to decrease. Finally, when a penetration rate of 100% was assumed, little additional advantage was gained by the smoothing effect of ACC, and for CTHs of 1.4 s or more, flow was actually found to reduce.

Yuan et al (2009) are another group of researchers who also investigated the traffic flow characteristics when ACC-equipped vehicles are mixed with manually-driven vehicles. To this end, they developed a hybrid modelling approach, according to which the manually-driven vehicles are described by a cellular-automata model, while the ACC-equipped vehicles follow a CTH policy and are simulated using a car-following model. With this hybrid modelling approach, Yuan et al (2009) studied the traffic breakdown probability from free flow to congested flow, and the transition probability from synchronised flow to jams. The main conclusions of their study are summarised in the following points:

- At a given desired time headway, there exists a critical penetration rate value, over which jam will not spontaneously appear from a synchronised flow.
- The introduction of ACC vehicles may either enhance or weaken the stability of free flow, depending on the penetration rate and the desired time headway. At a given penetration rate, free flow stability will be enhanced with a decrease of the desired time headway.

Using vehicle trajectories from traffic simulations and car-following models considering both ACC-equipped and manually-driven vehicles, Tapani (2010) studied the effects of ACC on vehicle acceleration and deceleration rates. His results confirm previous results in that ACC can smooth traffic conditions by reducing the acceleration and deceleration rates, and support the positive road safety and environmental effects. Moreover, manually-driven vehicles were found to be positively influenced by increasing percentages of ACC vehicles in the traffic stream. In addition, however, Tapani (2010) showed also that simulation results are largely dependent on the assumptions made regarding driving behaviour in both ACC-equipped and manually-driven vehicles, concluding that it is crucial to include appropriate assumptions regarding driver behaviour in the simulation-based analyses of ACC.

The effects ACC-equipped vehicles on traffic flow have also been studied by Davis (2004). Considering initially a 100% penetration rate, he found out that perturbations due to changes in the lead vehicle's velocity do not cause jams. Simulating also the merging of 2 lanes (one prime and an on-ramp) in a single outgoing lane, he found out that free flow conditions are maintained, if the total incoming rate does not exceed the capacity of the outgoing lane. With larger incoming flows, the flow on both lanes drops, but with exit flows remaining at capacity.

In addition, Davis (2004) studied the effects of ACC in mixed traffic. His simulation investigations indicated that, at high speeds (30 m/s), a penetration rate of 10% or less can limit the extent of formed jams; however, to prevent jam formation, a 20% rate is at least necessary. The formation of jams was also found to be sensitive to the sequence of vehicles (ACC-equipped or manual-driven). At moderate speeds (15 m/s) he did not manage to identify a critical value for the penetration rate capable to prevent jam formation, while he observed an increase of average velocity with increasing ACC penetration rate.

Finally, studying on-ramp merges with 50% ACC-equipped vehicles randomly mixed with manually-driven vehicles on the primary lane, and only manually-driven vehicles at the on-ramp, Davis (2004) found only modestly reduced travel times and larger flow rates. He also found that potential merging problems may appear since ACC-operating vehicles maintain their headways and, therefore, the ability of manually-driven vehicles to merge might be hindered by the lack of suitable safe gaps, while at the same time "*ACC-operating vehicles do not "give way" to on-ramp vehicles like some human drivers do*".

Given the above results, as well as simulation studies of 50% penetration rate ACC vehicles in mixed traffic near on-ramps, which indicated limited increase of throughput and less spatial congestion at the merging area compared to all manually-driven flow, i.e. limited positive effects, Davis (2007) suggests that the ACC vehicles should be able for cooperative merging (Davis, 2006), so as to create the gap necessary for a smooth change of lane and merging with the rest of the traffic without the need of a significant slowdown. Simulations of 50% penetration rate ACC vehicles randomly placed in mixed traffic with such a cooperative behaviour indicated that when the on-ramp demand is moderate, the cooperative merging produces significant improvement in throughput (20%). For large demand, cooperative merging could reduce but not eliminate congestion. Finally, for 100% ACC vehicles with cooperative merging, the throughput was found to be only limited by the capacity of the outgoing flow, which is determined by the assumed time headway and speed limit.

Kesting et al (2007a, 2008) studied the effects of ACC-equipped vehicles when their behaviour adapts to the prevailing traffic conditions (see Kesting et al, 2007b for preliminary investigations). More specifically, Kesting et al (2007, 2008), suggest that each ACC-equipped vehicle detects autonomously the traffic situation, which is considered to belong to one of a finite set of five situations as follows:

- free traffic,
- upstream jam front (approaching congestion),
- congested traffic,

- downstream jam front (leaving congestion), and
- bottleneck sections (infrastructural bottleneck sections such as road works or intersections),

and adapts automatically the parameters, i.e. the desired time gap, as well as the acceleration and deceleration rates of the ACC system accordingly. To avoid possible delays resulting from the autonomous detection, Kesting et al (2007, 2008) suggest also employment of vehicle to both vehicle and infrastructure (V2X) communications to supplement the means of local information.

The proposed approach consists of two main layers, the operational and the strategic. The operational layer is in fact the ACC system, which responds to the local changes in the behaviour of the preceding vehicle, based, however, on the settings received by the strategic layer. The strategic layer on the other hand, is the new feature of the proposed approach, which implements changes in the driving style, by modifying the parameters of the ACC system, in response to the local traffic situation as determined by a specially developed detection algorithm.

Traffic simulations of the proposed concept on a freeway, using the Intelligent Driver Model (IDM), showed that even with low penetration rates (5-15%) of the traffic-adaptive ACC system, traffic breakdowns are delayed and traffic flow stability and performance are improved. Although the traffic congestion in the reference case was completely eliminated when a proportion of 25% of ACC vehicles was simulated, travel times for the drivers were reduced in a relevant way for much lower penetration rates. Kesting et al (2007, 2008) point out also that these results are largely independent of the model details, the boundary conditions, and the type of road inhomogeneity.

Later on, Kesting et al (2010) extended the IDM to provide a more realistic driving behaviour especially in lane change situations and used it to investigate the influence of variable penetration rates of ACC-equipped vehicles on traffic flow characteristics. For the ACC policy, they assumed their earlier proposed concept (Kesting et al, 2007, 2008) and they considered simulation scenarios of a two-lane motorway with an on-ramp used by both cars and trucks. Their investigations revealed that via suitably-adopted parameters, their proposed traffic-adaptive strategy can have positive impacts on traffic efficiency leading to throughput and capacity increases both in free-flowing and after breakdown traffic conditions. They also revealed that the impact of ACC-equipped vehicles on traffic dynamics must be studied with a realistic level of heterogeneity in the vehicle mix (i.e. the assumed percentages of cars and trucks) to avoid reaching either discouraging or over-optimistic results.

Ioannou et al (2007) moved a step beyond Kesting et al (2007, 2008) and not only proposed that the ACC system should somehow adapt to the prevailing traffic conditions but they also developed an Integrated Roadway/Adaptive Cruise Control (IRAC) System, which integrates ramp metering and speed control strategies by taking into account V2I communication and ACC.

As far as ACC is concerned, they developed an ACC system capable of implementing any general VTH, and they proposed and analysed a new VTH policy, which is parameterised by a design constant that is interpreted as the ratio of the time gap used by ACC-equipped vehicles vs the time gap of the manually-driven vehicles (Zhang and Ioannou, 2004; Ioannou and Zhang, 2005). The study of the new system and time headway policy indicated that they can provide best performance with respect to vehicle following, environment and traffic flow characteristics, when the design constant of the VTH policy is less than 1, but not too much due to safety considerations.

Considering V2I communication ability and existence of vehicles equipped with the aforementioned ACC system in mixed traffic, Ioannou et al (2007) then designed the IRAC system. IRAC controls both the ramps and the speed distribution along the highway lanes communicating its control decisions directly to the vehicles. The control decisions are generated via corresponding strategies, which are extended and generalised versions of ALINEA (Papageorgiou et al, 1997) and are designed based on the fundamental flow-density relationship.

Investigations of the IRAC system based on a validated traffic simulation model of an existing highway under different traffic scenarios with ACC penetration rates from 0% to 100% indicated that it could lead to a better managed traffic flow system with improved travel times and smoother flows. While the magnitude of these improvements, as Ioannou et al (2007) mention, depends on the traffic situation and considered disturbances, the obtained results demonstrate consistent improvements under all considered cases.

Interesting results about the operation of ACC with regard mainly to aspects such as usage rates and safety and environmental effects, and less to traffic efficiency effects, have also been obtained through a few FOT trials conducted in different places worldwide. Below, the major findings of three FOTs, which have considered traffic efficiency ACC-effects are summarised, while as Xiao and Gao (2010) point out, several other FOTs have been conducted from or on behalf of automakers with results, however, that have been kept confidential.

Fancher et al (1998) reports on the earliest FOT that took place in USA from July 1996 to September 1997. For the purpose of this FOT, ACC-equipped vehicles were placed in the hands of 108 randomly-invited citizens for use as their personal car with no constraints on where, when, or how long to use the system.

According to the results of this FOT, it appears that drivers prefer manual control when traffic conditions are demanding and there is competition for gaps, while ACC is used in long trips and under mainly free flowing conditions. The results show also that ACC operation appears to be largely benign with regard to causing safety, traffic flow, or fuel usage problems; benefits could be gained in these areas.

As far as traffic efficiency is concerned, the obtained FOT measurements could not allow for the deduction of safe conclusions and/or generalisations for high penetration rates situations. Therefore, only piecemeal observations of phenomena occurred during the test period were used to explore traffic-related issues. In this respect, it appears that ACC systems could yield smoother, more uniform traffic, which could additionally promote fuel economy. In addition, since ACC is mostly used in free-flowing conditions, the impact on near-capacity traffic flow is expected to be minimal (since it will be switched off). However, in the near-capacity case, if not switched off, ACC may indeed have an impact on throughput depending upon its settings and the penetration rates.

A more recent FOT took place within the frame of the Roads to the Future programme of the Dutch Directorate-General for Public Works and Water Management (Rijkswaterstaat) in the Netherlands. Within the frame of this programme, 'The Assisted Driver' pilot was commissioned to provide an insight into the future use of ADAS in vehicles and to examine how users appreciate and use these systems and their impact on road safety, throughput and the environment. Among others, ACC has been examined within this pilot (Alkim et al, 2007; Viti et al, 2008). To this end, during a five-month trial, from February 2006 until June 2006, 20 people from various places of the Netherlands drove around in ACC-equipped vehicles, and several data were collected, recorded and analysed in several ways to allow for the compilation of an impact study on the effect that changes in driving behaviour due to the use of ACC would have on road safety, throughput and the environment. In addition, simulation investigations were used to estimate large-scale effects of ACC, which could not be identified due to the limited scale of the field trial.

According to this FOT results (Alkim et al, 2007; Viti et al, 2008), ACC is used primarily on motorways under free or heavy traffic; in free traffic, drivers activate ACC more than 50% of the time; in heavy traffic, this is over 35%, while in congested traffic this is less than 8%. After a short period of familiarisation with the system, most drivers select the shortest time gap option that is 1 s. The employed time gap settings reflect the normal driving behaviour of the user and the speed limits are selected in accordance to the corresponding applicable maximum limits.

In addition, with the use of ACC (Alkim et al, 2007):

- The adopted average time headway is somewhat longer than when manually driving, and its variation is smaller.
- The percentage of short time headways decreases substantially, which has a positive effect on road safety.
- The distribution in speed and acceleration is smaller, which has a positive effect on safety, comfort, fuel consumption and emissions.
- Drivers continue driving in the left lane and particularly in the middle lane for longer. As a result, there could be a disproportionate use of lanes (with a high degree of penetration).

On the basis of the above empirical findings where both negative effects (increase of time headways) and positive effects (small distribution in headway times, small distribution in speeds) were reported, the use of ACC (particularly in free traffic and heavy traffic) and the functionality of the system (ACC functional from 30 km/h onwards), it seems that throughput effects of ACC will be neutral. The simulation study also revealed that these effects largely depend on (Alkim et al, 2007):

- Time gap settings.
- Penetration rate (or relative use) of ACC.
- Conditions under which ACC is switched on and off.

The study also points out that the above, briefly described, findings are limited to the ACC tested during the particular FOT. Simulation studies indicated that in case of a full speed range ACC, the effect of the selected time gap setting is far more significant, and may impose negative effects for throughput, even at relatively low degrees of penetration. However, as the researchers point out "*it is not self-evident that drivers would choose the same headway times if they were using another ACC system*" (Alkim et al, 2007).

The most recently reported FOT is the one that took place within the European euroFOT project (Kessler et al, 2012; Benmimoun et al, 2013). euroFOT is the first large-scale FOT of multiple ADAS in Europe, aiming at evaluating the ADAS impacts on safety, traffic efficiency, environment, driver behaviour and user-acceptance in real life situations with normal drivers, by means of collected data. It started in May 2008 and ended in June 2012 with several hundred Terabyte of data collected from around 1000 drivers driving for more than 35 million km during the 3rd year of the project.

Overall, the final results of euroFOT support the positive effects on safety and fuel consumption and indicate high levels of user-acceptance. The following points summarise the main euroFOT findings as far as ACC is concerned (Kessler et al, 2012; Benmimoun et al, 2013):

- The time-headway increased significantly (about 16%) when drivers were following a lead vehicle, while the relative frequency of harsh braking events and incidents decreased; facts that indicate the positive effects of ACC on traffic safety.
- Based on the previously described positive influences on safety, there were also positive, though indirect, effects on traffic efficiency. Due to the potential reduction of accidents the annual incidental delay calculated in lost vehicle hours was estimated to be lowered by up to three million hours on an EU-27 level.
- The environmental impact, which was measured in terms of fuel consumption, showed a reduction of approximately 2-3% which results in less CO_2 emissions.
- Average speeds were generally increased. This effect was also confirmed via simulation tests, which were conducted in addition to the objective and subjective data gathered during FOT. The simulations showed that the effect on network speed is similar in size to the effect found in the FOT. More specifically, the effect was found to scale linearly with the penetration of equipped vehicles in most situations, while only in heavy traffic scenarios with less than 25% equipped vehicles, the average network speed was found to be reduced slightly stronger than the speed reduction measured for the individual FOT vehicles.

It should finally be mentioned here that during the FOT that took place for the ACAS variant of ACC, further to the conclusions that were drawn regarding the safety and user acceptance of the system, which are in line with the conclusions reported earlier from the other FOTs, an interesting observation has been made regarding the use of the FCW system (General Motors Corporation, 2005; University of Michigan and General Motors Corporation, 2005a, 2005b). In short, it was found that the use of the FCW function, even in its pure advisory mode, may lead to increased headways; it must thus have implications on traffic flow, which, however, have never been investigated.

4.1.1.3. Conclusions and recommendations

Although ACC systems had been initially conceived as safety and comfort systems, the main focus of traffic researchers and engineers is whether they can also improve traffic conditions. The relevant literature provides several simulation studies on this issue based on microscopic, macroscopic or hybrid approaches with results that occasionally appear to be controversial due to the differences in the employed simulation models and test case settings, as well as due to the differences in the assumed ACC-system parameters and penetration rates. A few FOTs have also been conducted but with their main focus being on safety, user acceptance and/or change of driving behaviour and environmental impacts, they provide a very limited insights on traffic efficiency in presence of ACC.

Despite the above limitations, there are some conclusions that may be derived with high probabi;ity or even certainty concerning the pros and cons resulting from the employment of ACC systems, and can be summarised in the following points:

- Pros:
  - ✓ Smooths traffic flow (smoother accelerations and decelerations).
  - ✓ Contributes to safety and comfort.
  - ✓ Reduces negative environmental effects of traffic.
- Cons:
  - ✓ The employed headway policy should be carefully designed; else ACC may lead to traffic flow instability and capacity reduction.
  - ✓ High ACC penetration rates in conjunction with CTH values higher than those used when driving manually, may lead to modest or even high capacity reduction.
  - ✓ Merging problems may appear at on-ramps for manually-driven vehicles not able to identify safe gaps to enter the primary lane, if low headways are followed by ACC-equipped vehicles and their penetration rate is high enough.

In addition:

- To achieve benefits in terms of congestion and jam reduction, a moderate to high penetration rate is required.
- When ACC-equipped vehicles adopt the CTH policy, the used headways should not be higher than the headways of the manually-driven vehicles.
- Traffic-adaptive settings of the employed policy parameters can improve ACC performance in terms of achieved traffic flow performance.
- V2V and V2I communication can enhance the positive effects of ACC by providing more and better information, thus allowing for the coordinated operation of the ACC-equipped vehicles.
- ACC performance at on-ramps may be improved via extension of the system to allow for cooperative merging behaviours.

Last, but certainly not least, simulation models and studies of all aspects relating to the ACC operation and impacts should be designed and executed with care to avoid reaching irrational results and conclusions. Despite the developments, especially during the last 15 years, the area is still greatly susceptible of further research. Open question is also the exploitation of the opportunities offered by the ACC technology in terms of alleviating the significant congestion problems of modern motorway networks. As the review of the previous section indicates, a few only efforts have recently appeared in this direction requiring though the technological extension of the system to allow for a more cooperative behaviour.

4.1.2. Low Speed Adaptive Cruise Control (LSACC)

4.1.2.1. Description and functions

Also known as:

- Stop and Go (S&G), or
- Stop and Go Adaptive Cruise Control (S&G-ACC), or
- Congestion Assistant (CA),

Low Speed Adaptive Cruise Control (LSACC) is an evolution of the ACC functionality, which operates in slow, congested traffic to follow the car immediately ahead smoothly yet effectively even under stop-and-go conditions (Bishop, 2005; van Driel, 2007).

The first two versions of LSACC systems were introduced in Japan in 2004, and in fact, they are "Stop and Wait" systems, since they are not able to automatically restart the vehicle from a stop (Bishop, 2005; van Driel, 2007). The one system operates from motorway speeds (approximately 40 km/h) down to a very low speed (approximately 5 km/h), below which it disengages, and it then requires the driver's interference to stop and/or restart the vehicle motion and reengage it. The other system operates to speeds down to zero, and if the vehicle ahead is stopping, it warns the driver. After the warning, if there is no response from the driver, it halts the vehicle, and then the driver needs again to reinitiate motion and reengage it.

More recently, new systems have appeared in Europe, which can bring the vehicle to a complete stop and reinitiate its movement when the traffic ahead moves, if the duration of the standstill is less than a few (e.g. 3) seconds; if the standstill is longer, a touch on the gas pedal is necessary for the vehicle to set off (van Driel, 2007).

4.1.2.2. Evaluation results

Based on microscopic simulations with the SIMONE model, Minderhoud (1999) studied the effects of several variants of ACC systems. The particular LSACC system studied therein has been assumed to be operational in the speed range of 0 to 60 km/h with a headway setting of 1.2 s, and the ability to reengage after complete vehicle stop. The study considered also several penetration rates in the range 10-100% within motorway networks of different configurations (2 to 3 lanes) considering different bottleneck types (on-ramps or symmetric weaving sections). The results of the study indicated negative impacts on capacity, which may be attributed to the relatively large time headway setting of 1.2 s.

Within the Congestion Assistant project of the German research initiative INVENT, Benz et al. (2003) studied the effects of a particular LSACC system under different time headway settings (1, 1.8 and 3 s) for a 100% market penetration rate. Among others, they investigated via simulation a traffic scenario of a two-lane motorway with speed limitation (120 km/h), where a severe braking manoeuvre until standstill on a lane caused a significant congestion. The results of this study indicated that, with a 1s time headway setting, both the mean speed in the LSACC's speed range and the traffic flow increased. Benefits were also obtained in fuel consumption and respective emissions with this low headway setting. Unfortunately, Contrary to INVENT, more details on the investigations of the effects of LSACC were provided by the STARDUST project (SINTEF et al, 2004). In the frame of this project, assessments on a microscopic level took place based on results from the cities of Oslo and

Southampton with the AIMSUN simulator and the city of Paris with the ARCHISIM simulator. The tests aimed at assessing impacts of LSACC, among other systems, on urban motorways, urban arterial roads and urban streets with the focus being on the traffic efficiency and safety impacts at four levels of market penetration: 0%, 20%, 80% and 100%.

As far as LSACC is concerned, the overall pattern of behavioural effects showed lower mean speed (in contrast to the INVENT findings), and more importantly, analysis indicated lower variance of speed and shorter start delay, which was considered as interesting effect regarding improvements of traffic flow. In addition the simulation results showed:

- Depending on the penetration level, journey times, stops and stop-time per vehicle in the journey were reduced, as LSACC increased efficiency for vehicles to start-up from stops due to short reaction times. LSACC shortened also the average time headways, harmonised traffic movements and increased saturation flows. In specific, for 100% equipped vehicles, average journey times were found to decrease up to 15% and 46% at a signal-controlled link and a roundabout, respectively, while saturation flows at signal-controlled junctions were found to increase up to 29%.
- LSACC reduced queuing time at junctions, which also contributed to reductions of journey time, but also to reductions of fuel consumption and pollutant emissions.
- Reductions in fuel consumption and pollutant emissions were also achieved by the smoothed vehicle movements during start/stop processes.

However, the level of traffic demand was found to have significant impact on the benefits of LSACC; the higher the traffic demand, the more the benefits. E.g. the increase in saturation flow results from the cumulative effects of equipped vehicles (short reaction times and controlled stopping distance) instead of being infrastructure dependent, thus the higher the number of vehicles (i.e. the level of demand), the more the resulting benefit. It was also, however, found that if the network is highly congested and demand increases beyond a certain level, there could be a breakpoint leading to a decrease in the traffic impact.

It should be noted here that the above results have not been obtained from the study of LSACC in motorway networks. However, they also apply to motorway networks given that they are often in congested traffic conditions. In case that the motorway network is in free-flowing conditions, this particular system is of no use since the prevailing speeds are higher than the speeds in its control span.

Motorway traffic simulations have, however, been undertaken by Van Driel (2007) to test a LSACC variant. This particular LSACC (see also Van Driel and Van Arem, 2008; 2010) aims at supporting the driver during congested traffic situations on motorways via three functions:

- *Warning & Information*: while driving towards the traffic jam, the driver receives a warning; while driving in the traffic jam, information about its length is displayed.
- *Active pedal*: while approaching the traffic jam, the driver can feel a counterforce of the gas pedal when the speed is too high according to the system.
- *Stop and Go*: while driving in the traffic jam, the longitudinal driving task is taken over by the system.

For the study of the effectiveness of this system, a four-lane motorway stretch with a lane drop to create congestion was studied with the ITS Modeller coupled with the Paramics software (Van Driel, 2007; Van Driel and Van Arem, 2008; Van Driel and Van Arem, 2010). Different variants of the considered system's functions and their combinations were studied assuming 10% and 50% market penetration rate and time headway settings for the LSACC of 0.8 and 1 s. All variants resulted in less congestion in comparison with the reference situation of 100% manually-driven vehicles. The active pedal alone smoothed the traffic flow at the approach to the traffic jam, resulting in slightly less congestion. LSACC-equipped vehicles followed other vehicles more efficiently than non-equipped ones when driving in and leaving the jam by adapting smaller headways and eliminating driver reaction time. This reduced the amount of congestion and significantly cut the average travel time and delay, at the expense, however, of the driver comfort which decreased due to an increase in the number of strong accelerations and decelerations; such an effect on driver discomfort had not been reported by the STARDUST project. Finally, the study of the combined operation of the active pedal and LSACC functions did not indicate any improvements compared to those obtained by LSACC alone. Conclusively, this study identified the need for further and more thorough investigations of the considered functions, their combination and their operational settings.

4.1.2.3. Conclusions and recommendations

Despite the limited investigations of this particular system, there are some conclusions that may be derived with high probability concerning its potential contributions. LSACC may:

- reduce variance of speed, start delay, journey times, stops and stop-time per vehicle in the journey;
- shorten the average time headways, reduce queuing, harmonise traffic movements and increase saturation flows; and
- reduce fuel consumption and pollutant emissions

depending strongly, however, on the market penetration rate and the level of traffic demand, both of which should be as high as possible. It should also be noted that for the above effects to be achieved, short time headway settings need to be applied, else some of its positive features may be reversed (e.g. journey times increased rather than decreased, saturation flows decreased rather than increased, etc.).

4.1.3. Full Speed Range Adaptive Cruise Control (FSRA)

4.1.3.1. Description and functions

Also known as:

- Adaptive Cruise Control with Stop and Go (ACC/S&G), or
- Adaptive Cruise Control - Low Speed Following (ACC-LSF), or
- Traffic Jam Assistant (TJA), or
- Automated Queue Assistance (AQuA).

Full Speed Range Adaptive Cruise Control (FSRA) is an ACC system, which also functions at low speeds and is capable to bring a vehicle to complete stop and accelerate it again if the preceding vehicle does so.

According to ISO 22179:2009, FSRA is an "*enhancement to adaptive cruise control systems, which allows the subject vehicle to follow a forward vehicle at an appropriate distance by controlling the engine and/or power train and the brake down to standstill*".

FSRA is fundamentally intended to provide longitudinal control of equipped vehicles while travelling on highways under both free-flowing and congested traffic conditions. FSRA provides support within the speed domain of standstill up to the designed maximum speed of the system. ISO 22179:2009[8] contains the basic control strategy, minimum functionality requirements, basic driver interface elements, minimum requirements for diagnostics and reaction to failure, and performance test procedures for FSRA systems.

Although, there was a debate within the industry as to whether highway-speed ACC and low-speed ACC should remain separate in terms of driver activation, or instead be integrated into a "full-speed range" ACC, which would seamlessly transition between highway cruise and traffic congestion conditions (Bishop, 2005), the ISO standard provides the strategy and requirements for an integrated approach.

Finally, Ehmanns and Spannheimer (2004) suggested the extension of FSRA by the means of communication to a FSRA plus Foresight (FSRA+Foresight) so that far-away vehicles are involved into the longitudinal control and traffic jams are taken into account before the drivers are able to see them e.g. in curves. This way traffic flow and safety are expected to increase.

4.1.3.2. Evaluation results, conclusions and recommendations

Despite the fact that the FSRA is reported as a system in the relevant literature (see e.g. Ehmanns and Spannheimer, 2004; Alkim et al, 2007; Viti et al, 2008; Hoeger et al, 2011; Shladover, 2012a; iMobility Forum, 2013) and the International Organization for Standardization has already released a relative ISO standard, the literature does not report on any significant investigations of the effects of this particular system on road efficiency. The only study that has been identified to report on such FSRA aspects has been provided by Minterhoud (1999).

Based on microscopic simulations with the SIMONE model, Minderhoud (1999) studied the effects of several variants of ACC systems. Among the considered systems, two versions of a FSRA system have been studied. Both versions have been assumed to be operational in the speed range of 0 to 150 km/h with the one version assuming also the support of the full acceleration/deceleration range of the vehicle in contrast to the other which supports a more limited range. For this latter FSRA variant, investigations considered only a headway setting of 1.2 s, while for the other system, due to its extended acceleration/deceleration capabilities, headway settings of 0.8 and 1.2 s have been investigated. Finally, both system versions assumed the ability to reengage after a complete vehicle's stop. The study took place for several penetration rates in the range 10-100% within motorway networks of different configurations (2 to 3 lanes) considering different bottleneck types (on-ramps or symmetric weaving sections), and traffic conditions such that road capacity is reached and sustained. The aforementioned FSRA variants were also compared with different ACC and LSACC system configurations. The study and comparisons revealed the following:

[8] http://www.iso.org/iso/home/store/catalogue_tc/catalogue_detail.htm?csnumber=40753 [accessed 18.10.2013]

- The impact of ACC on motorway capacity depends on the type of bottleneck, headway setting, market penetration rate and system's characteristics such as speed and acceleration/deceleration range.
- No matter what particular ACC system is considered, capacity can increase only as long as the employed headway settings are lower than the settings maintained by manually-driven vehicles.
- The maximum capacity gains can be achieved by a FSRA supporting the whole speed and acceleration/deceleration range with the lower possible headway settings; such an FSRA performs better than ACC only at low headway settings, else their impacts are comparable.
- The capacity drop phenomenon disappears only at large penetration rates.

Despite the fact that the FSRA system is an ISO defined and generally known system, the available investigations are limited to allow for concrete conclusions regarding its performance. Intuitively, one could guess that the ability of the system to operate at the whole speed spectrum, in combination with appropriate system settings (low time headways, wide acceleration/deceleration range) gives it an advantage compared to both the common ACC and the LSACC as it extends its employment potential to a larger spectrum of conditions. However, more investigations are required to highlight the whole spectrum of its potential effects.

4.1.4. Cooperative Adaptive Cruise Control (CACC)

4.1.4.1. Description and functions

Also known as Communication-Based Longitudinal Control (CBLC), Cooperative Adaptive Cruise Control (CACC), uses wireless connection among equipped vehicles to allow them to respond in a smoother way to disruptions in traffic flow.

Preliminary CACC ideas and concepts can be found in the Cooperative Following (CF) system described by Tampère et al (1999). CF has been suggested to combine automated longitudinal control with V2V communication to allow for anticipation to severe braking manoeuvres in emerging shock waves with the aim of smoothing traffic flow and enhancing traffic safety. Just like Cooperative-Merging (CM), the rationale behind CF is the limitation of the impact of shock waves. However, while CM tries to avoid the emergence of shock waves during lane change manoeuvres only, CF aims at limiting their progression and severity by damping them, regardless of their origin (Tampère et al, 1999).

CACC represents a more sophisticated form of ACC (Bishop, 2005; Popescu-Zeletin et al, 2010). In its simplest form a CACC-equipped vehicle can communicate actively with its preceding vehicle so that their speed changes can be coordinated, permitting significantly closer vehicle following at, e.g., time gaps of 0.5 s (VanderWerf et al, 2001; Bishop, 2005). This CACC form is also the easiest to implement since it does not require any complicated architectural schemes or infrastructure. CACC systems have also been proposed that allow communication and cooperation among several vehicles in a lane (see e.g. Maihöfer et al, 2004). CACC systems, however, are still under R&D, and, as a consequence, field trials focussed mainly on the employed technologies, while simulation investigations are limited and focus also mainly on technologies.

Since CACC-equipped vehicles communicate and coordinate their speed changes, significantly closer vehicle following is permitted, in e.g. time gaps of 0.5 s. In contrast to ACC, therefore, the desired gap among vehicles under CACC is not a fixed time gap, but it is chosen so that, if the lead vehicle brakes at its maximum rate and the following reacts immediately by braking at its own maximum rate, they will not collide. To enable such an operation, several CACC-equipped vehicles must co-exist in a network. When a CACC vehicle drives behind a vehicle that is not similarly equipped, or it is manually driven, it behaves like an ACC system with all the resulting consequences to traffic flow, throughput and capacity (see ACC review for details).

4.1.4.2. Evaluation results

Preliminary investigations of CACC can be found in the study of CF by Tampère et al (1999). This study has led to two major suggestions:

- The nature of the CF-controller should prevent excessive response to new warnings and manage adequately speed warnings coming from different vehicles and times.
- CF logic should be integrated with systems such as Adaptive Cruise Control (ACC) so as to ensure continuous and stable control.

The last suggestion seems to have been addressed quite well from CACC, which may be considered as a CF evolution.

More recent studies of CACC-related concepts can be found in VanderWerf et al (2001, 2002), who developed models to address the long-term advances in ACC capabilities, and used them to compare the effects of ACC, CACC and manually-driven vehicles in traffic flow. The developed CACC model assumed the simplest form of CACC where a vehicle communicates with its preceding vehicle only. A perfectly reliable and instantaneous transmission of the velocity, acceleration and braking capability of the lead vehicle is assumed.

The initial simulation tests of VanderWerf et al (2001) involved cases where all vehicles were either manually-driven or equipped with an ACC or a CACC system with constant time gaps 1.4 s and 0.5 s, respectively. Considered was a single protected motorway lane, near or above capacity, with a junction consisting of a single-lane off-ramp followed immediately by a single-lane on-ramp. The simulation tests indicated a slight and a significant capacity increase downstream of the ramps in the cases of ACC and CACC, respectively, compared to the case where all vehicles were driven manually.

Later on, VanderWerf et al (2002) analysed cases with mixed vehicle populations in order to estimate the motorway capacity as a function of the proportions of ACC, CACC, and manually-driven vehicles. The results of these analyses indicated that the gain in capacity increases quadratically with CACC penetration rate due to the fact that the reduced time gaps are only achievable between pairs of CACC-equipped vehicles.

Given the above findings, VanderWerf et al (2002) concluded that CACC can represent an important step towards motorway automation, since, at high penetration rates, it has the potential to double capacity. They also concluded that, since the capacity effect is very sensitive to the penetration rate, it is important to gather the highest possible proportion of

CACC vehicles into the same lane, a fact that provides a strong justification for giving priority access to a special lane for CACC vehicles.

Using MIXIC simulations also of the simplest CACC type in mixed traffic on a 4-lane Dutch motorway with a bottleneck due to a road narrowing, Visser (2005) performed some more thorough investigations confirming the previous findings of VanderWerf et al (2002) in that CACC has indeed the ability to improve traffic flow performance. This study also confirmed the previous finding that the extent of improvements depends heavily on the penetration rate; heavy dependence on the traffic flow conditions has additionally been identified. In addition, according to Visser (2005), string stability improves more with CACC than ACC, as CACC vehicles, thanks to their communication capabilities, reduce the reaction delays in braking and accelerating actions of the vehicles: "*A very small, almost negligible communication delay replaces the reaction delay of the driver and the sensor delay of the autonomous ACC. This makes the CACC controller smoother and more natural in response*". String stability in its turn, reduces the occurrence and severity of shock waves due to braking actions and in this sense improves the traffic flow stability. These effects though, as Visser (2005) points out, can only be observed in sufficiently high CACC penetration rates; traffic flow stability on the high-intensity motorway stretch upstream of the bottleneck, measured as a reduction of the number of shock waves, was found to improve in the range 25% for a 20% CACC penetration rate to 90% for a 100% CACC penetration rate. For CACC penetration rates less than 40%, the traffic stability improvement was not found to result in a better throughput, while slightly lower average speeds were measured on all links. Finally, when a 60% or higher of the vehicle fleet was equipped with CACC, an improved traffic flow performance was established on the motorway stretch upstream of the bottleneck, compared to the case of only manually driven vehicles.

Visser (2005) studied also the impact of a dedicated lane for CACC-equipped vehicles and found out that this depends heavily on the CACC penetration rate. A CACC penetration rate lower than 40% lead to a degradation of performance, with lower speeds, higher speed variances and more shock waves, due to the increase of the density on the other lanes and the relatively high number of lane-changes, as manually-driven vehicles were leaving the lane before it turned into a CACC-lane. As a result, an unbalanced division of vehicles over the lanes was observed. According to Visser (2005), the potential improvement of traffic performance of a CACC-lane compared to a motorway configuration without CACC-lane was only confirmed for the high-density stretch upstream of the bottleneck for CACC penetration rates of over 50%. Finally, the study of Visser (2005) confirmed the negative effects of CACC on the merging process, and brought forward the necessity of potential system extensions such as e.g. cooperative merging.

The impact of CACC systems on traffic performance and particularly on traffic dynamics, flow rate and average speed, has also been studied by Arnaout and Bowling (2011). To this end, they used a microscopic agent-based simulation of a motorway, first without any on-ramps and then with an on-ramp that was used to induce perturbations and to trigger stop-and-go traffic conditions. In this study, the time-gap setting of the CACC was set to 0.5 s, if following a CACC vehicle, while when following a truck or a non-CACC equipped vehicle, the time gap was set to a value uniformly distributed between 0.8 s for younger/aggressive drivers and 1.0 s for older/considerate drivers. Finally, the considered CACC system has been assumed to communicate with the preceding vehicle only.

The results of the aforementioned study confirmed the previous findings of other researchers in that CACC can highly increase the motorway capacity, especially in high density traffic hours, by increasing the average speed and the rate of flow. They showed also that this effect is highly dependent and proportional on the CACC penetration rate; at a penetration level of 40% CACC or higher, a significant improvement could be observed in the traffic dynamics. Further studies of Arnaout and Bowling (2013) showed that by giving CACC vehicles priority access to existing High-Occupancy Vehicle (HOV) lanes, instead of creating special CACC lanes, the motorway capacity could be significantly improved with a CACC penetration rate as low as 20%. Despite these findings, Arnaout and Bowling (2011) point out that with such small time gaps, "*even if the technology was practically proven to be efficient and safe, having the public to accept it and feel comfortable in using it will always be a challenge facing the success of the CACC technology*".

Confirmation of the aforementioned findings regarding the CACC effects on motorway traffic flow performance has also been demonstrated by a study of Shladover et al (2010, 2011). This particular study involved also a small-scale FOT of 16 drivers, randomly selected from general public. The results of this FOT showed that drivers had a very favourable reaction to CACC and were more likely to use it when traffic was flowing well than when traffic was getting heavily congested; the tested system was not designed to cope with stop-and-go traffic. In addition, drivers tended to use the shortest provided time-gap settings, a fact which has favourable implications for use of CACC to improve motorway capacity and traffic flow.

4.1.4.3. Conclusions and recommendations

Despite the limited studies on CACC systems, there are some conclusions that may be derived with high probability concerning their pros and cons, and can be summarised in the following points:

- Pros:
  - ✓ Significant capacity increase may be gained compared to both manually-driven and ACC-equipped vehicles.
  - ✓ Improved string and traffic stability compared to ACC-equipped vehicles.
- Cons:
  - ✓ High penetration rates are necessary for any positive impacts to traffic flow performance.
  - ✓ Severe lane change and merging problems appear; worse than with ACC due to the shorter time-gaps.
  - ✓ There is a question regarding user acceptance of very short (0.5 s) gaps.

In addition:

- Given the significant capacity increase, which can only be achieved with high concentrations of CACC-equipped vehicles, special dedicated lanes might be useful. However, for low penetration rates, such dedicated lanes may lead to performance degradation due to the increase of the intensity on the other lanes and the increase of the lane-changes of non-equipped vehicles. Until high penetration rates can be achieved, therefore, providing access of CACC vehicles to existing HOV lanes may provide the ground to gain their positive effects even at low penetration rates.

- Extensions for cooperative lane change and merging manoeuvres are necessary since the corresponding problems become even worse than with the ACC system.

CACC systems represent a more advanced ACC form, which is at a rather early stage of development. The first indications seem promising from a traffic-flow perspective, there is still, however, plenty of room for further investigations.

4.2. Speed adaptation systems

4.2.1. Fuel Efficiency Advisor (FEA)

4.2.1.1. Description and functions

The Fuel Efficiency Advisor [9] (FEA) is an advisory-only system that provides in real time the current location of the vehicle, its fuel consumption, messages, driver times, service intervals, etc. to support fuel-efficient or eco-driving. It aims at supporting the driver in maintaining the engine speed in the "green area" towards optimal usage of the vehicle with respect to fuel efficiency (Kessler et al, 2012). The driver is also alerted, when the engine speed is outside the "green area" longer than a pre-set limit, when a certain speed threshold is reached or when the engine is on idle for an extended time.

4.2.1.2. Evaluation results, conclusions and recommendations

FEA was specifically designed to help reduce fuel consumption. Its evaluation, therefore, that took place within the European euroFOT project (Kessler et al, 2012), focused on the environmental impact and did not consider possible side effects that may impact traffic efficiency and safety. The system was tested in 50 trucks that drove more than 3.6 million kilometres, and its evaluation showed a reduction in fuel consumption of 1.9%.

Since the system only gives advice and does not intervene, its effectiveness depends on the willingness of the driver to follow its instructions. Hence, as Kessler et al (2012) point out, it is difficult to distinguish between its fuel saving potential and the influences that originate from the driving style of its user.

4.2.2. Active Green Driving (AGD)

4.2.2.1. Description and functions

Active Green Driving (AGD) is an application designed within the HAVEit EC project so as to coach the driver with the aim to reduce fuel consumption and pollution (Hoeger et al, 2011). Its intention is to optimise the powertrain control of hybrid buses, based on forecasts of their movements over the next period of time (e.g. 30 seconds).

More specifically, sensor-based information from the external traffic environment is used to predict the future driving horizon (Hoeger et al, 2011). By predicting near future changes (within the horizon), as for example speed and elevation, the vehicle’s hybrid powertrain can be found and executed automatically without intervention from the driver. In addition, information within the prediction horizon is also used in a Driver Coaching System to help the driver handle the vehicle in a more fuel efficient manner by advice via graphical display and haptic accelerator pedal.

[9] http://www.eurofot-ip.eu/en/intelligent_vehicle_systems/fea/ [accessed 11.03.2013]

4.2.2.2. Evaluation results, conclusions and recommendations

The AGD application was tested mainly for its technical feasibility and acceptance within the HAVEit EC project (Hoeger et al, 2011). The undertaken validation tests indicated a fuel saving potential of 6-8%, depending on drive cycle and driving style, but more on-road tests were identified as necessary to evaluate the real fuel saving potential by this application.

4.2.3. Intelligent Speed Adaptation (ISA)

4.2.3.1. Description and functions

Also known as:

- Intelligent Speed Assistant (ISA), or
- Intelligent Speed Assist (ISA), or
- Intelligent Speed Information (ISI), or
- External Vehicle Speed Control (EVSC), or
- Speed Alerting and Limiting System (SALS), or
- Speed Alert or Warning System (SAWS), or
- Speed Limit Assistance (SLA), or
- Speed Regulation System (SRS),

Intelligent Speed Adaptation[10] (ISA) is primarily used to maintain speed within the legal (posted) limits (Bishop, 2005). However, more advanced versions of ISA allow for dynamic speed limits that may be adjusted based on factors such as traffic conditions, time of day, and weather conditions. ISA is increasingly appreciated as a flexible method for speed management and control, particularly in urban areas (Liu and Tate, 2004) as well as in roadworks and congestion. For example, a system called Automated assistance in Roadworks and Congestion (ARC) has been developed within the HAVEit (Highly Automated VEhicles for Intelligent Transport) project with the goal to support highly automated driving in roadwork areas on highways by automatically adapting the vehicle speed to the statutory speed limits (Hoeger et al, 2011). This particular system keeps also vehicles in safe distance to front and side vehicles and stationary objects.

ISA systems are differentiated by the level of support and the kind of feedback they give to the driver. According to these characteristics, the following four ISA types can be found (Carsten and Tate, 2000, 2005; SWOV, 2011; Vlassenroot et al, 2011b):

- *Advisory* or *informing* or *informative* systems: they display the speed limit and remind the driver of changes in it.
- *Warning* or *open* systems: they warn (via visual or audio means) the driver when the posted speed limit is exceeded at a given location, but the driver finally decides whether to use or ignore this information and has the sole responsibility to adjust speed.
- *Supporting* or *supportive* or *voluntary* or *driver select or semi-open* or *half-open* systems: they give a force feedback through the accelerator, if the driver tries to

[10] http://www.eurofot-ip.eu/en/intelligent_vehicle_systems/sl/ [accessed 12.08.2013]

exceed the speed limit; but he/she is able to drive faster than the limit, by applying sufficient force.

- *Mandatory* or *compulsory* or *controlling* or *limiting* or *closed* systems: they automatically limit maximum speed of the vehicle to the speed limit in force, and ignore the driver's requests for speeds beyond this speed limit.

The first two ISA types, referred also as Speed Alert (SA), are relatively simple, and some route navigation systems already include them as an additional feature (Marchau et al, 2010).

ISA systems, knowing the location of a vehicle (via, e.g., a GPS) may adapt to two types of speed limits[11]:

- *Fixed speed limits*: these are the posted speed limits. Sometimes, these limits may include additional information about even lower speed limits at particular locations such as sharp curves, construction sites, school zones, etc. and/or certain days and time zones such as the days/time zones that schools are open. Such limits are called variable by some researchers (Carsten and Tate, 2000, 2005; SWOV, 2011; Vlassenroot et al, 2011b), but, in fact, they are also speed limits that are fixed either at all times or at specific time zones. It should also be noted here, that other researchers distinguish the speed limits of this type as fixed, when set by the user, and variable when they are location dependent (Boriboonsomsin et al, 2008; Blum et al, 2012).
- *Dynamic speed limits*: these limits take into account the actual road and traffic conditions (weather, traffic density) and use the posted speed limits as maximum limits (Carsten and Tate, 2000, 2005; SWOV, 2011; Vlassenroot et al, 2011b). Dynamic speed limits are, therefore, not only location or time dependent, but also traffic dependent. ISA systems that use dynamic speed limits are often called *Dynamic Speed Adaptation* systems (iMobility Forum, 2013).

For setting up dynamic speed limits based on the prevailing traffic conditions, control strategies are necessary that may be based on a responsive or an anticipating logic (Tampère et al, 1999):

- A *following* or *reactive* strategy monitors the traffic conditions (e.g. in a bottleneck), and provides appropriately adapted speed limits for upcoming traffic, when traffic flow breaks down.
- An *anticipating* strategy aims at preventing the breakdown of traffic in the bottleneck by reducing earlier the speed limit.

To set up dynamic speed limits, V2I communication is necessary (van Driel, 2007).

4.2.3.2. Evaluation results

One of the first studies of ISA contributions to more stable traffic flow for better throughput and safer driving on motorways has been reported by Tampère et al (1999) and Hogema

[11] http://ec.europa.eu/transport/road_safety/specialist/knowledge/speed/new_technologies_new_opportunities/intelligent_speed_adaptation_isa.htm [accessed 20.10.2013]
http://ec.europa.eu/transport/road_safety/specialist/knowledge/speed/new_technologies_new_opportunities/dynamic_speed_limits.htm [accessed 20.10.2013]

(2002). For the purpose of this study, simulations with the MIXIC tool took place considering a motorway with a bottleneck due to a lane drop. The study analysed criteria for throughput and safety with gradually increasing traffic demand until capacity was reached, for several ISA penetration rates from 10% to 50%. Considered was a mandatory ISA system with dynamic speed limits calculated by an anticipating algorithm based on occupancy measurements upstream of the bottleneck. The logic of this algorithm was inspired by algorithms existing in the Netherlands for ramp metering.

The results of the simulation indicated clearly the homogenisation of traffic that could be expected with ISA: speed variance of vehicles within one lane, and speed difference between lanes were decreased. In addition, the division over lanes was found to slightly shift towards equally balanced traffic loads. The results indicated also decrease in average speed, which was expected due to the mandatory nature of the considered ISA system, and a decrease in the average traffic volume as well as the maximally observed traffic volume with increasing ISA penetration rates. This latter result could not be considered as a definite ISA impact, since it could not be confirmed without further research on whether it was due to the ISA system itself or due to the limitations of the mandatory lane change model of MIXIC, which had been designed for non-equipped vehicles. With respect to traffic safety, the study indicated decrease in the number of vehicles, which were involved in severe shock waves during the merging process, a result that, combined with the lower speed variance, indicates that the effects of ISA on traffic safety are expected to be positive.

Based on the above findings, the study recommended that the above results should be further validated taking into account and investigating more thoroughly the drivers’ behaviour in presence of ISA (Tampère et al, 1999; Hogema et al, 2002).

Despite these early promising findings regarding the ISA effects on traffic performance and the fact that there is already a significant amount of research regarding control strategies that aim at speed management and control, which could be adopted by ISA systems with dynamic speed limits, the majority of ISA literature concerns studies focussing on the ISA effects on speed, travel time, safety and user acceptance. Only one study by Boriboonsomsin et al (2008) has been identified to focus in the development of methods to determine control speeds for dynamic ISA systems under various levels of motorway congestion.

Boriboonsomsin et al (2008) made an effort to develop methods aiming at achieving energy/emissions reduction while eliminating or minimising any potential travel time increase. To this end, they proposed a speed calculation scheme based on the levels-of-service (LOS) categories defined in the Highway Capacity Manual 2000 (TRB, 2000). According to the Highway Capacity Manual 2000, level-of-service is a qualitative measure that describes the operational conditions within a traffic stream, based on service measures such as speed and travel time, freedom to manoeuvre, traffic interruptions, comfort and convenience. According to the same manual, six LOS exist, from A to F, with A denoting free-flowing conditions and F the worst case. For each LOS, Boriboonsomsin et al (2008) proposed that speed should be calculated as an average (measured) traffic speed plus a certain amount of speed adjustment aiming at compensating high speed peaks that are eliminated as a result of the ISA speed control mechanism. Initial results via simulation tests with PARAMICS showed that the calculated speeds under different levels of congestion, as categorised by the

LOS, were reasonable, suggesting that further relevant investigations would be useful to advance the future employment of this technology.

A different aspect of ISA systems has been investigated by Hegeman (2002), who studied urban traffic flows in presence of ISA and compared them with the flows in presence of traffic lights using the INTEGRATION modelling tool. According to Hegeman (2002), the roots for this particular study lie in the thought that, if some vehicles were equipped with ISA systems, the platoons formed at the main road would lead to gaps that allow vehicles from the minor roads to easily cross or merge the mainstream without the need of traffic lights. The results of this study indicated that ISA could indeed replace the traffic lights at junctions, which however have a clear major flow.

The rest of the ISA relevant literature focuses mainly in the study of ISA effects on speed, travel time, safety and user acceptance, as mentioned earlier and reviewed below.

From 1997 to 2000, a UK ISA-relevant project (Carsten and Tate, 2000, 2005) took place. Within this project, field trials and simulation analysis with the DRAKULA micro-simulation modelling tool were undertaken to study mainly the supporting and mandatory types of ISA.

The field trials within the aforementioned project led to some significant conclusions as summarised below:

- Drivers tend to switch-off the supporting ISA system, when traffic conditions allowed them to drive at higher speeds.
- The speed change for drivers using the supporting system was approximately half that of drivers with the mandatory ISA system.
- Drivers were feeling frustration and low levels of satisfaction when driving in conditions where their vehicle was the only one equipped with a mandatory ISA system. The frustration and low satisfaction was due to the overtaking by other vehicles, which was more frequent than when they did not drive with ISA. As a result of these findings, the study suggested that mandatory ISA systems should not be implemented until a significant number of vehicles are equipped.

The simulation investigations within the same project considered a mandatory ISA system using variable speed limits in three types of road networks: urban under peak and off-peak traffic conditions, rural and motorway networks. According to these investigations, ISA was found to be more effective in less-congested traffic conditions, since in congested conditions the prevailing speeds were lower than the applicable limits, thus ISA had no effects (Liu and Tate, 2004). It was also found that ISA reduced excessive traffic speeds, speed variation and fuel consumption across the network, while it increased the travel times, especially under off-peak traffic conditions in the urban network. To achieve such results, a 100% penetration rate was necessary in the urban network, while a 60% rate was sufficient in the rural network (Carsten and Tate, 2000). No conclusions could be extracted for the motorway case, since the simulated network was so congested that the ISA system had a negligible effect; hence. the prevailing speeds were by far lower than the maximum applicable speed limits (Carsten and Tate, 2000). In addition to the above, the simulation investigations revealed also that savings of 20% and 37% of injury and fatal accidents, respectively, could be achieved with a voluntary system, while the savings could increase to 36% and 59%, respectively, with the mandatory ISA type (Liu and Tate, 2004).

A similar, but of a far larger scale, project by the Swedish National Road Administration took also place from 1999 to 2002. This project involved only field trials, of advisory, warning and supporting systems (Biding and Lind, 2002) operated in urban areas. In contrast to the findings of the UK study (Carsten and Tate, 2000), travel times remained unchanged despite the lower driving speeds in specific areas. This fact was explained (Biding and Lind, 2002) by the less stopping and fewer braking situations with ISA, whereby delays in queue situations and at junctions were reduced, thus the average travel time was not affected. As far as the road-users were concerned, they expressed that they experienced travelling times as unchanged or marginally longer, while measurements from the supporting system indicated that travel times were even marginally shorter.

Várhelyi and Mäkinen (2001) provide a review of the results of another field trial that took place within the frame of a European R&D project in the Netherlands, Spain and Sweden. The aim of the project was to investigate the effects of a supporting ISA system, triggered automatically by transmitters attached to speed limit signs. The trial was carried out on urban and rural roads as well as motorways considering all the speed limit categories in the respective countries, ranging from 30 to 120 km/h. The results of the trial showed that the effects of the considered system were greatest in free driving conditions outside platoons, although effects in congested traffic were also identified. Generally, momentary excessive speeds were suppressed effectively, resulting in less speed variation, a result that is in line to the findings of the other studies. Approach speeds at roundabouts, junctions and curves became smoother, and car-following behaviour became safer in the speed range of 30~50 km/h. On the other hand, in the speed range of 70~90 km/h a slightly higher number of identified short time-gaps suggested less safe car-following behaviour. Other negative behavioural effects were slightly increased travel times and the increased frustration and stress for the drivers caused by the system; the more frequent the system was interfering, the more frustrated the drivers felt. However, the majority of the drivers accepted the system, while half of them would accept it voluntarily in their own vehicles.

A more recent and relevant FOT took place within the European euroFOT project (Benmimoun et al, 2012; Kessler et al, 2010). Within euroFOT, a SRS consisting of a Speed Limiter (SL) and a CC system was studied. SL is in fact a voluntary speed adaptation system which does not include the intelligence of ISA in the sense that speed is limited to user-specified values. Within SRS, SL and CC could not operate simultaneously, thus allowing reaching some useful conclusions regarding the SL based on the behaviour of 35 drivers/users, which was studied for a 9-months period during which they travelled more than 500.000 km. According to the results of this FOT (Benmimoun et al, 2012; Kessler et al, 2010):

- The system was used, often, on all roads except motorways.
- Drivers had positive expectations at the beginning of the FOT, which were confirmed. Overall there was no statistically significant change of acceptance and trust over time. Also, there was no statistically significant increase of driver comfort and pleasure to drive as a result of the system’s usage, which was generally judged as necessary, good, assisting the driving and useful.
- Junctions, curves, or rush hours reduced the likelihood of using the system.
- The system was used on all speed limits, but it seemed that it was mainly used when the likelihood of being caught by a speed enforcement camera was high.

In addition to the above results that came from the FOT's recorded data, simulation analysis indicated that the use of the system made the speed distribution, and as a consequence the variation in speeds, to reduce. This particular result is in line with all the aforementioned results of the other theoretical and real-world studies.

Summarising the results of various studies, a recent SWOV Fact sheet on ISA (SWOV, 2010) concludes that ISA systems appear to have a number of positive safety effects on driving speed; ISA-equipped vehicles show an average speed reduction of approximately 2-7 km/h, as well as a reduction in speed variance and speed limit violations. Given these reductions, the magnitude of which depends upon the ISA type, there are expectations of positive effects on traffic efficiency and environment, with the more intervening ISA types seeming to be the more effective.

According to the same Fact Sheet (SWOV, 2010), the results of micro-simulation modelling studies showed that in congested traffic conditions, ISA would not have a significant effect on network total travel time, as driving speeds are largely limited by the congestion. In less dense traffic conditions, travel times would rather increase due to the lower average speeds, especially with increasing ISA penetration rates.

Finally, the SWOV Fact Sheet (SWOV, 2010) review of studies on user acceptance of ISA indicates that the more intervening the system is, the less it will be accepted by the drivers, although it is expected to have larger effects on speed and road safety. There is therefore a trade-off between effectiveness and user acceptance. As the SWOV Fact Sheet points out "*It seems that drivers whose speed behaviour would benefit most from ISA, least accept it. Hence, there is a danger of a self-selection bias when ISA is introduced on a voluntary basis. Drivers who "need" ISA most will be least willing to use it*".

Similar conclusions have also been reached by an Australian cost-benefit analysis of ISA (Doecke and Woolley, 2010), which also reviews results of trials reported in the literature, focusing in the changes on speed behaviour achieved.

Vlassenroot et al (2011b) who also reviewed and summarised findings of several studies of the ISA system, conclude that although in the last decades a lot of research concerning ISA has been performed and several trials with different ISA types have shown that this system can be an efficient and effective way to reduce speed and speeding and as such have a positive effect on traffic safety, fuel consumption, emissions, dust and noise, large-scale implementation of the most effective ISA type, seems far away. In addition, no coherent acceptance indications have been described, and the attitudinal research on ISA was not sufficiently rigorous, thus allowing the opponents of ISA the chance to criticise the benefits of the system. According to the review of Vlassenroot et al (2011b), ISA is a system that presents the acceptance versus effectiveness paradox; the more effective ISA is on road safety, the less accepted it is by the users, a fact that hinders its implementation. However, as they point out "*after a test-period of 25 years the time has come to allow a broader public to experience the benefits of ISA. Only then an answer to the question how people react when using ISA in the real world would be given and maybe then we will know what the long-term effects would be*".

In general, as Marchau et al (2010) and Vlassenroot et al (2011a) summarise, several simulation studies and field trials indicate that ISA:

- reduces mean speed, speed variation, speeding and speed limit violations,
- is effective for traffic safety,
- is expected to be beneficial for the environment because of the estimated reduction in speed and speed variance, and
- can lead to a more homogeneous traffic flow.

For these to be effectuated, however, the acceptance by the potential users should be increased, especially for the more intervening systems that can maximise the aforementioned benefits. As a recent survey that took place in Belgium and the Netherlands suggests, although the support for ISA is high, the more the implemented ISA system intervenes in the perceived control of the driving experience, the higher the penetration rate has to be for the system to be accepted by the drivers/users (Vlassenroot et al, 2011a).

Given the above, as Marchau et al (2010) suggest, “*The main challenges with respect to ISA deployment relate to its social and political feasibility. Overall, a more active role of public authorities is recommended on ISA deployment, especially for ISA systems that actively intervene in the driving task*”.

4.2.3.3. Conclusions and recommendations

In the last decades, there have been considerable advancements in ISA developments. In addition, ISA’s future perspectives seem very promising in terms of increasing traffic safety and efficiency. However, there is still large uncertainty, especially as far as traffic efficiency is concerned, about the real-world effects of a large-scale ISA employment. In addition, the results on user acceptance indicate an uncertainty regarding the success or otherwise of such an employment.

Despite the above limitations, however, there are some conclusions that may be derived with high probability concerning the pros and cons resulting from the deployment of ISA systems, and can be summarised in the following points:

- Pros:
  - ✓ Reduction of speed violations.
  - ✓ Reduction in excessive speeds and speed variation.
  - ✓ Traffic homogenisation.
  - ✓ Decrease of accidents (due to speeding), thus increase of safety.
- Cons:
  - ✓ Use can be frustrating at low penetration rates.
  - ✓ Potential decrease of average speeds and, as a consequence, travel times increase.

In addition:

- The magnitude of both pros and cons depends on the type of ISA; the more intervening ISA types seem to have more significant effects. They are, however, less accepted by drivers.
- The effects of ISA in congested conditions seem to be negligible, since at such conditions, the prevailing speeds are usually less than the applicable speed limits. However, ISA systems with dynamic speed limit calculations may limit congestion or even prevent it by using anticipating rather than reactive speed calculation algorithms.

Finally, it should be noted that, despite the numerous simulation and field investigations of ISA, there is a great lack of studies concerning the ISA effects in traffic flow performance and the development of strategies aimed specifically for variable ISA systems, which seem to be the most promising from a traffic management perspective.

4.2.4. Cooperative Variable Speed Limit System (CVSLS)

4.2.4.1. Description and functions

The Cooperative Variable Speed Limit System (CVSLS) is a suggested extension of the Variable Speed Limit (VSL) system, which, employing V2I communication via a roadside unit, communicates the speed limits directly to the vehicles upstream on the road (Grumert et al, 2013).

For this system, it is suggested (Grumert et al, 2013) that speed recommendations are given to the vehicles at predefined points in time. These speed recommendations depend on the current speeds of the vehicles, the speed limits given from the roadside unit located in front of them and their distance from this unit. The speed limits communicated by the roadside unit are the limits already available by an existing VSL system.

The advantages of the CVSLS compared to the traditional VSL can be summarised in the following two points (Grumert et al, 2013):

- Information about the speed limit is received at an earlier point in time.
- Vehicles receive individual speed limits determined by their current speed and position.

As a result of this approach, the vehicles have the possibility to decelerate/accelerate more smoothly at their approach to the VSL location.

4.2.4.2. Evaluation results

To test and compare the effectiveness of CVSLS with VSL, the SUMO simulation of an open motorway stretch without on- or off-ramps was used (Grumert et al, 2013). The simulated road was divided into 500 m segments, with one detector and one VSL per lane on each segment. For the three last segments, the road was narrowed down from 3 to 2 lanes resulting in a bottleneck. Finally, for the CVSL case a 100% market penetration rate was assumed, while in both CVSLS and VSL cases, the speed limits were assumed compulsory.

The results of the simulation tests indicated a reduction in the mean speed with CVSLS, especially during the congested period, without, however, negative impacts on travel times, which did not present big differences among the CVSLS and VSL cases. Therefore, this reduction was attributed (Grumert et al, 2013) to the fact that vehicles in the VSL case had a less harmonised driving style, with more varying speed patterns. This was also confirmed by the fact that higher acceleration/deceleration rates appeared more frequently in the VSL case.

4.2.4.3. Conclusions and recommendations

Although this particular system has not been studied very thoroughly, it seems that the aimed individualised speed information and its communication directly to the vehicles may indeed contribute to more harmonised acceleration/deceleration and less varying speed patterns. These, on their turn, may lead to smoother traffic flows and reduced environmental impacts.

However, it should be mentioned that CVSLS can be viewed as an ISA system of advisory type that operates under dynamic speed limits, which are provided at specific network locations.

4.3. Lane change/merge assistance systems

4.3.1. Cooperative Merging (CM)

4.3.1.1. Description and functions

Also known as Cooperative Merging Assistance (CMA), Cooperative Merging (CM) combines automated longitudinal control with V2V or V2I communication in order to assist the driver in lane changing manoeuvres by creating and maintaining an appropriate gap in the target lane (Tampère et al, 1999).

CM provides a safer, automatic way for a vehicle to join a flowing traffic without disrupting it. It eliminates the driver misunderstandings by letting the vehicles decide the best way to join, based on the exchange of information (such as velocities and positions) between vehicles (Popescu-Zeletin et al, 2010).

Just like Cooperative-Following (CF), the rationale behind CM is the limitation of the impact of shock waves. However, while CF aims at limiting the progression and severity of shock waves by damping them, regardless of their origin, CM tries to avoid their emergence during lane change manoeuvres only. This can also have a stabilising effect on traffic flow (Tampère et al, 1999); for this to be achieved though, it is necessary for the CM-equipped vehicles to be able to communicate with other similarly equipped vehicles in the target lanes.

As reviewed by Tampère et al (1999), CM may appear in different variants:

- V2V communication allows vehicles to announce their intended lane manoeuvres to the vehicles in the target lane so as for the gaps necessary for the accomplishment of these manoeuvres to be created and maintained.
- V2I communication allows vehicles to announce their intended lane change manoeuvres to the infrastructure, which is responsible for the creation and maintenance of the gaps in the target lanes that are necessary for the accomplishment of these manoeuvres.

4.3.1.2. Evaluation results, conclusions and recommendations

Although CM seems to be a promising system, the literature does not report on any specific evaluation results for the case of system’s employment in mixed traffic consisting of both CM-equipped and manually driven vehicles. CM concepts, however, may be found in the literature that relates to the highly automated platooning systems.

4.3.2. Lane Change Decision Aid System (LCDAS)

4.3.2.1. Description and functions

Also known as:

- Lane Change Assistant (LCA), or
- Lane Change Support (LCS), or
- Side Object Monitoring System (SOMS),

Lane Change Decision Aid Systems (LCDAS) are systems, which according to ISO 17387:2008 [12] (Intelligent transport systems - Lane change decision aid systems (LCDAS) - Performance requirements and test procedures) "*are fundamentally intended to warn the driver of the subject vehicle against potential collisions with vehicles to the side and/or to the rear of the subject vehicle, and moving in the same direction as the subject vehicle during lane change manoeuvres. This standardization addresses LCDAS for use on forward moving cars, vans and straight trucks in highway situations*". The system prevents lateral related accidents and assists the driver in bad visibility conditions (Popescu-Zeletin et al, 2010).

ISO 17387:2008 differentiates between the following three different types of systems (Bartels et al, 2012):

- *Blind Spot Warning*, which monitors the blind spot on the left and right adjacent to the driver's own vehicle
- *Closing Vehicle Warning*, which monitors the adjacent lanes to the left and right behind the driver's own vehicle in order to detect vehicles approaching from behind
- *Lane Change Warning*, which combines both the functions of the two aforementioned system types.

Although existing LCDAS are, simply, in-vehicle warning systems, vehicle manufacturers are developing systems capable of communicating with each other so that vehicles will be able to know their position and will be able to change lanes safely (Visvikis et al, 2008). In addition, several researchers are working towards the automation of the whole process, as discussed below.

4.3.2.2. Evaluation results

Tideman et al (2007) identified, in their review of lateral driver support systems,some early efforts towards the automation of lane change support systems:

- Godbole et al (1997) divided the lane change manoeuvre into a gap selection, gap alignment, and move-over step. For each of these steps, they designed two different algorithms, one for lane changing under normal conditions and one for lane changing under emergency conditions, and they formulated the synthesis of the trajectories of the three steps as an optimal control problem.
- Jula et al (1999; 2000) developed an algorithm to calculate whether a particular lane changing/merging manoeuver is safe, i.e. free of collisions and an algorithm to calculate the minimum longitudinal spacings that vehicles should initially have so as to avoid collisions during the lane changing/merging manoeuvers.
- Smith et al (2003) examined the feasibility of using four driving states (low risk, conflict, near crash, and crash-imminent) to characterise lane-change driving performance. They also observed that drivers seem to anticipate the longitudinal gap opening and closing and so they often start lane changes when there is another vehicle in the adjacent proximity. This feature, as Tideman et al (2007) point out, will also be necessary for future lane assistance systems, but it is unlikely to be easily accommodated by the respective algorithms.

[12] http://www.iso.org/iso/home/store/catalogue_tc/catalogue_detail.htm?csnumber=43654 [accessed 14.11.2013]

More recently, a few new efforts have appeared towards the development of more autonomous lane change approaches and systems:

- Habenicht et al (2011) developed a manoeuver-based LCDAS, which supports the driver from his/her first lane change intention through the final movement of the vehicle from the initial to the target lane. The system provides manoeuver recommendations covering lane change timing, lane change direction, as well as the required acceleration or deceleration. Habenicht et al (2011) have developed the system architecture with the modules to supply the necessary functionalities, a Human-Machine Interface (HMI) and a core module to detect the driver intention, which are currently being implemented in a prototype vehicle in order to be validated and compared to other common LCDAS.
- Wan et al (2011) developed an automated lane change algorithm that, based on the recognition of the surrounding vehicle situation (distance and velocity) obtained by on-board sensing devices, generates the desired longitudinal and lateral acceleration signals with the appropriate lane change timing.
- Knake-Langhorst et al (2013) report on a system called merge and exit assistant, which has been developed within the German project FAMOS. Although primarily developed to support drivers while merging onto or exiting from motorways, the developed functionality is equally applicable in all lane change/merge cases. The developed concept is based on four configuration levels selectable by the driver:
    - *Basic functions*: They form the basic configuration level and include warning of unintentionally leaving a lane and information about critical distances to preceding vehicles, occupied target lanes while changing lane, optimum choice of speed related to the geometry of the road.
    - *Gap finder*: Contains the whole functionality of the basic functions with an additional detection and evaluation of all gaps available in the target lane. This information is presented to the driver to support the orientation processes.
    - *Gap guidance*: Enhances the gap finder level by a prioritisation of all identified gaps and supports the action-planning processes by suggesting, in addition, a target position to aim at within the gap of the highest priority, and an acceleration that will lead the vehicle into the vicinity of the suggested target position.
    - *Automated longitudinal control*: This is the highest configuration level, which actually controls the velocity of the vehicle, taking into account speed limits and road geometry; the driver has to steer manually, and can override the automation.

The system was initially tested and verified in a driving simulator, and then it was integrated into a test vehicle. The validation of the system under real conditions on public roads demonstrated its potential for driver assistance.

Finally, Tomar and Verma (2012) review several approaches that have been proposed for the prediction of the trajectory of a lane change manoeuvre and propose a neural network based one. If accurate predictions of this trajectory are communicated to the vehicles involved in lane change manoeuvres, the collision avoidance element of this manoeuvre is expected to improve.

4.3.2.3. Conclusions and recommendations

Existing LCDAS are in-vehicle warning systems. Currently, vehicle manufacturers are making efforts to developing cooperative systems that will increase their safety impacts, while several researchers are working towards the automation of the whole process.

Since the existing systems are safety and comfort oriented, they have no implications on traffic flow. The systems, however, that are in a conceptual or even test stage and aim towards the automation of the lane change/merge process may have such implications, which should, sooner or later, be analysed and understood.

4.4. Combined-functionality systems

4.4.1. Integrated Full-Speed Range Speed Assistant (IRSA)

4.4.1.1. Description and functions

Integrated full-Speed Range Speed Assistant (IRSA) is a system developed and tested within the SUMMITS research programme conducted in The Netherlands in 2003-2006 and financed by TNO (Wilmink et al, 2006; van Arem et al, 2007).

IRSA can be generally viewed as a combination of ISA with a, cooperative or conventional, FSRA system extended with the concepts of CM. Triggered by road geometry, traffic or weather conditions, or any combination of these, it informs and helps drivers to maintain a safe speed under a multitude of circumstances, such as sharp curves, reduced speed limit zones and traffic jams.

Similarly to ISA, IRSA has been designed to operate in three modes: advisory, intervening and controlling. In all modes, the system calculates a desired acceleration, which is then:

- presented to the driver in the form of audible or visual information in the advisory mode; or
- passed on in an active way, e.g. by a haptic gas pedal in the intervening mode; or
- directly given to the vehicle in the controlling mode.

The functions that IRSA has been conceived to perform include speed assistance and/or warnings, adaptive cruise control and headway advice. The speed assistance and/or warnings of IRSA concern:

- (reduced) speed limit zones;
- curved road segments;
- approaching a traffic jam;
- leaving a traffic jam;

and are communicated to the driver either via V2I or via V2V communication means.

The adaptive cruise control functionality of IRSA is activated in the controlling mode, and its particular form depends on the situation the equipped vehicle is in and can be:

- Conventional CC, if the equipped vehicle has no predecessor;
- ACC, if there is no possibility for V2V communication;

- CACC involving one or more preceding vehicles, if there is the ability of V2V communication.

For the CACC functionality, two different controllers have been designed:

- CACC1 is a CACC controller, in which acceleration is determined in relation to the distances and speeds of a number of similarly equipped preceding vehicles (the first predecessor vehicle does not necessarily need to be similarly equipped since IRSA can measure with its own means the distance and speed);
- CACC2 is a variant of CACC1, which considers only speeds and in particular the speed difference with the direct predecessor, as well as the average speeds of similarly equipped vehicles that are further ahead.

Finally, the headway advice functionality of IRSA is activated at the approach of merging and weaving sections, aiming at increasing the gaps between vehicles to create smooth merging flows.

4.4.1.2. Evaluation results

To assess the impact of IRSA on traffic flows, three scenarios were studied with the ITS modeller (Wilmink et al, 2006; van Arem et al, 2007):

1. *Approaching a reduced speed limit zone*: A reduction of speed from 120 to 80 km/h is required in order to improve air quality and reduce noise annoyance at a particular motorway zone. In this case, IRSA aims at helping drivers to slow down in a safe and comfortable way.
2. *Approaching a traffic jam*: A three-lane motorway with a lane drop halfway is considered in this scenario. The traffic is near-capacity, so congestion occurs near the lane drop. Similarly to the previous scenario, IRSA aims at helping drivers to slow down in a safe and comfortable way.
3. *Leaving the head of a queue*: In this scenario, IRSA aimed at helping drivers to accelerate in an efficient way, and at improving the safety and throughput at traffic lights.

In all scenarios, different penetration rates were considered to reflect the gradual introduction of the system.

The results of the first scenario were in line with what is expected from an ISA system. It was also confirmed once more that a controlling system can lead to the best performance in every respect.

The results of the second scenario showed that the system had a positive impact on traffic flow. Under all considered controllers, vehicles slowed down earlier, having to brake less hard, and the congestion was reduced, while safety indicators stayed at the same level or improved slightly. Again, this is what one would expect by a FSRA or even a LSACC. In addition, however, the CACC2 controller had the best performance indicating that the incorporation of speed information from preceding, similarly equipped vehicles may improve the controller performance. Results also indicated that performance may be further improved if information is additionally incorporated regarding speed drops of similarly equipped vehicles below 70% of the speed limit.

Finally, the results of the third scenario indicated that faster acceleration may increase throughput but may decrease safety. These results do not conform to the results of other LSACC or FSRA investigations, which do not report on negative safety effects, although there is certainly a trade-off among faster acceleration and safety.

4.4.1.3. Conclusions and recommendations

As mentioned earlier, IRSA is rather a combination of functions. The investigation results are generally in line with results expected by the particular functions that have been incorporated in IRSA. However, issues of great interest but not previously studied, such as the heading advice function, and the operation of IRSA in scenarios where all functions could be simultaneously used, have not been examined.

4.4.2. Cooperative Following and Merging (CFM)

4.4.2.1. Description and functions

Cooperative Following and Merging (CFM) is a combination of the following two functions (Tampère et al, 1999):

- Cooperative Following (CF), which combines automated longitudinal control with V2V communication to allow for anticipation to severe braking manoeuvres in emerging shock waves with the aim of smoothing traffic flow and enhancing traffic safety.
- Cooperative Merging (CM), which combines automated longitudinal control with V2V or V2I communication in order to assist the driver in lane changing manoeuvres by creating and maintaining an appropriate gap in the target lane.

The rationale behind these functions is the limitation of the impact of shock waves. CM tries to avoid the emergence of shock waves during lane change manoeuvres only, while CF aims at limiting their progression and severity by damping them, regardless of their origin (Tampère et al, 1999).

Depending on the nature of the CM function, CFM may need only V2V communication or both V2V and V2I communications.

4.4.2.2. Evaluation results, conclusions and recommendations

Although CFM seems to be a promising system, the literature does not report on any specific evaluation results for the case of system’s employment in mixed traffic consisting of both CFM-equipped and manually driven vehicles. CFM concepts, however, may be found in the literature that relates to the highly automated platooning systems.

4.4.3. Highway Pilot (HP)

4.4.3.1. Description and functions

Highway pilot (HP) is a vehicle application, which will support the driver on motorways and motorway similar roads with high level of automation in longitudinal and lateral control of the vehicle at speeds between 0 and 130 km/h (iMobility Forum, 2013).

Such a system has been developed and validated regarding its technological feasibility within the HAVEit EC project (Hoeger et al, 2011). The so-called Temporary Auto Pilot (TAP) is a system that supports the driver on motorways and motorway similar roads with different levels of automation in longitudinal and lateral control of the vehicle at speeds between 0 and 130 km/h. In the highest level of automation, TAP manages completely steering, accelerating and braking, but only if certain boundary conditions are fulfilled, e.g. the vehicle is driving on a motorway with less than 130 km/h. If the boundary conditions are not fulfilled, a lower level of automation is offered to the driver in the sense that the driver can activate other assistance systems like AC and/or emergency brake, etc. TAP can always be overridden by the driver who is always responsible for the vehicle behaviour and has therefore to monitor the system and be ready for an intervention, if and when necessary.

4.4.3.2. Evaluation results, conclusions and recommendations

TAP has been tested within the HAVEit project, and its technical concept and designed architecture were proved as valid. However, more thorough testing is necessary including beyond technical feasibility issues such as the impacts on traffic flow conditions from its integrated functions.

4.5. Vehicle Platooning Systems (VPS)

4.5.1. Description and functions

The term Vehicle Platooning Systems (VPS) has been used to denote vehicles travelling in close coordination under partial or fully automated longitudinal and lateral control (Bishop, 2005; Shladover, 2012a; iMobility Forum, 2013). Longitudinal control aims at keeping the vehicles in a platoon as closely spaced as possible without jeopardising safety, while the basic goal of lateral control, also called steering actuator control, is (platoon) lane keeping. It has also been suggested for vehicles to be platooned at a lateral offset to allow simultaneous ploughing of several motorway lanes (Bishop, 2005).

Typically, a platoon is formed by a number of vehicles following a leading one, which is responsible for the guidance of the whole platoon. Currently, however, many concept variants exist due to variations in:

- the employed communication modes (use of in-vehicle sensors, V2V and/or V2I communications);
- the considered mixture of vehicles (cars and/or trucks and/or buses);
- the infrastructure requirements (use or not of dedicated lanes);
- the functions that are indeed automated (lane keeping, speed control, collision avoidance, gap keeping, join and split of vehicles), as well as their controlling parameters (gaps, speeds), technological implementation and corresponding automation level.

4.5.2. Evaluation results

The VPS concept has attracted great attention with the PATH’s Automated Highway Systems (AHS) program in the decade of 90s. The PATH’s AHS program was motivated by the need to produce a significant increase in the capacity of a motorway lane, so as to minimise the need of new infrastructure constructions in order to accommodate travel demand increases (Michael et al, 1998; Bergenheim et al, 2012a). Within the frame of this program, eight vehicles travelled at a fixed separation distance of 6.5 m at all speeds up to full motorway speed at full automated longitudinal and lateral control involving split and re-join of vehicles. To avoid potential safety problems with mismatched masses of vehicles if they collide, the PATH research concentrated on homogeneous platoons, i.e. of platoons of only cars, buses or trucks led by an also automated vehicle. For safety reasons also, PATH platoons were travelling in dedicated lanes. According to PATH (1997), the investigated platooning configuration represents a pipeline capacity of about 5700 vehs/h/lane, which, if reduced by 25% to allow for the manoeuvring needed at entry and exit points, corresponds to an effective throughput of about 4300 veh/h/lane. This reduced throughput is still significantly larger than the throughput under normal manual driving conditions, which is approximately 2000-2200 veh/h/lane.

More recently, the VPS concept has regained attention in the relevant research community due to the rapid advances in vehicle automation. Recent examples of relevant research projects include the CHAUFFEUR and CHAUFFEUR2 projects, which involved platooning of heavy trucks only (Bonnet, 2003; Bishop, 2005; van Arem et al, 2006; Shladover, 2012a), the German KONVOI project and the Japan's Energy ITS project, which developed concepts that concern also truck-only platoons (Alam et al, 2010; Alam, 2011; Shladover, 2012a; Tsugawa, 2014), as well as the SARTRE[13] (SAfe Road TRains for the Environment) EC project, which developed a concept of a platoon led by a manually driven truck, with a mixture of fully automated trucks and cars following close behind to save fuel and emissions (Bergenheim et al, 2012a, 2012b; Shladover, 2012a; iMobility Forum, 2013; SARTRE, 2013).

CHAUFFEUR and CHAUFFEUR2 projects (Bonnet, 2003) involved platooning of two and three heavy trucks only, with the leading truck manually driven and the following using automatic steering and speed control to follow the trajectory of the first at close distance (6-12 m) (Bishop, 2005; Shladover, 2012a). This VPS concept was highly cooperative as it involved close communication between the leading and following trucks. Simulation results within the frame of these projects indicated a better usage of road capacity, up to 20% reduction in fuel consumption and increased safety (van Arem et al, 2006). It was also, however, concluded that platooning is mostly feasible at night or on low-traffic volume sections because, under dense traffic conditions, the abnormal dynamic length of the platoon may create problems (PROMOTE-CHAUFFEUR Consortium, 1996). As Bishop (2005) notes, "*platoons were shown to be most viable in low traffic situations, given their tendency to impede lane changes for surrounding vehicles in more dense traffic*". Another conclusion of this project was that for an economically viable platoon operation, dedicated truck lanes are necessary[14].

Aiming at investigating the benefits and deployment issues associated with platooning, the Germany sponsored KONVOI project studied also truck platoons operating in mixed traffic (Shladover, 2012a) and reached a conclusion that is in line with the CHAUFFEUR and CHAUFFEUR2 project conclusions regarding the economic viability of the concept. KONVOI concluded that the aim of platoons operating in mixed-traffic motorways is in fact an impediment to achieving efficiency benefits (Shladover, 2012a). As Shladover (2012a) mentions in his review of this project, the traffic dynamics generated by all the other vehicles impose disturbances on the truck platoon, which interrupt constant speed cruising and prevent

[13] http://www.sartre-project.eu/en/Sidor/default.aspx [accessed 10.01.2014]
[14] http://www.transport-research.info/web/projects/project_details.cfm?id=15277 [accessed 10.01.2014]

smoothing out its driving profile enough to save fuel at a level that could be considered really significant.

Another truck platoon concept has also been developed by the Japan's Energy ITS project. This particular VPS concept involved the lane keeping, speed control, collision avoidance, and gap keeping functions among 3 heavy (25 ton) and a light truck driving at 80 km/h with gaps of 10 and 4 m (Tsugawa, 2014). In this case, platoons were operating in dedicated lanes, thus demonstrating the full magnitude of potential benefits (Tsugawa, 2014):

- Field measurements indicated a mean energy saving of 13% at 10 m gap and 18% at 4.7 m gap with empty trucks driving at 80 km/h, while for trucks ordinarily loaded and driving at 80 km/h, fuel saving of 8% at 10 m gap, and 15% at 4 m gap were found.
- Simulation tests showed also that for heavy trucks platooning penetration of 40%, a CO_2 reduction of 2.1% is expected at 10 m gap and 4.8% when the gap is 4 m.

Overall, the gap keeping function was found to contribute to the aforementioned energy savings, while the other functions contribute to the increase of safety and the decrease of the drivers' workload.

Finally, SARTRE, in contrast to all previous projects, developed VPS involving both trucks and cars following a leading manually driven truck (Bergenheim et al, 2012a, 2012b; Shladover, 2012a; iMobility Forum, 2013; SARTRE, 2013). SARTRE VPS concept has also been developed with the aim to be applicable in mixed-traffic infrastructures (SARTRE, 2013). Demonstrated functions included longitudinal and lateral control as well as split and re-join of vehicles (Bergenheim et al, 2012a; SARTRE, 2013). A vital part of the SARTRE concept was the V2V communication of the vehicles since the use of only local sensors was found to lead to lateral and longitudinal instability, increasing oscillations, and unsafe behaviour of the platoon (Bergenheim et al, 2012b; SARTRE, 2013). The demonstration of the SARTRE concept involved five vehicles (two trucks followed by 3 cars) travelling in public roads in Barcelona, with evaluations mainly involving the technical feasibility of the concept. In addition, field tests as well as simulation investigations confirmed the potential of VPS to contribute to a more efficient fuel usage (Davila, 2013). However, the reported project results do not allow reaching conclusions regarding the viability of the VPS concept in mixed-traffic conditions, while it is also recognised that for a successful concept introduction there is a need of supportive measures like free usage of bus lanes to assure instant user and lead vehicle benefits for the first customers (Brännström, 2013). It is therefore indirectly recognised that, until a high market penetration is reached, real benefits can only be obtained through dedicated infrastructures.

Although platooning has been considered as a complex system (Ehmanns and Spannheimer, 2004), the simulation and field tests across Europe, USA and Japan, as summarised above, indicate that it is quite advanced and mature from a technical point of view (iMobility Forum, 2013). In addition, both simulation and field tests seem to agree on the following VPS manifold benefits:

- Increased passenger comfort due to the decrease of speed variation and the elimination of sudden and/or unnecessary accelerations/decelerations.

- Increased comfort of the drivers of the following vehicles due to their release from the driving task and responsibility.
- Improved safety by enabling a safe distance between vehicles and by eliminating the human effects from the driving task; statistics indicate that human error is responsible for nearly 90% of car accidents[15].
- Increased motorway capacity due to shorter inter-vehicle spacing. Motorway capacity can be further increased if, instead of in-vehicle sensors, V2V communication is enabled to allow the exchange of operational information such as speeds acceleration and deceleration among not only immediate neighbouring vehicles but also among vehicles in a whole neighbourhood. According to Tientrakool et al (2011), motorway capacity can be increased up to 43% if all vehicles enable platooning using in-vehicle sensors and up to 273% by the additional use of V2V communications.
- Reduced congestion due to better utilisation of lane area (iMobility Forum, 2013).
- Fuel savings and reduced environmental pollution due to the reduction of the aerodynamic forces when acting upon closely-spaced platoons, as well as due to the avoidance of sudden and/or unnecessary accelerations/decelerations. Simulation investigations (Alam et al, 2010; Alam, 2011) with a platoon of two trucks have shown that a maximum fuel reduction of 4.7-7.7% can be obtained at set speed equal to 70 km/h, depending on the time gap; the less the time gap, the more the benefits. In case that the lead vehicle is 10 t lighter or 10 t heavier, the fuel reductions are in the ranges 3.8-7.4% and 4.3-6.9%, respectively.

It should be noted, however, that the above benefits depend largely on the platoon configuration (mixture and mass of involved vehicles), the considered headway and speed, as well as the infrastructure arrangements (dedicated or mixed-traffic lanes) and the market penetration rate. However, there is no doubt that VPS offers a great potential to achieve these benefits, and, for this reason, research is still ongoing in an effort to further advance several VPS related aspects including:

- Development of control algorithms, which are applicable to different types of vehicles and guarantee:
  - String stability in longitudinal direction to avoid creation of shock-waves, and in lateral direction to avoid leading vehicles in wrong lanes (after e.g. lane change manoeuvres).
  - Robustness in communication delays, random dropouts and loss of messages. According to Hedrick et al (2001), there are control algorithms that cannot guarantee string stability under all conditions, due to delays in the communication information.
  - Robustness under uncertain environments in order to maintain the safety and comfort of the passengers.
- Identification of appropriate and feasible platooning parameters concerning headways, speeds, and number of cooperating vehicles.
- Minimisation of the data requirements for the application of the corresponding longitudinal and lateral control laws (see e.g. Lee and Kim, 2002).

[15] http://www.alertdriving.com/home/fleet-alert-magazine/international/human-error-accounts-90-road-accidents [accessed 10.01.2014]

- Investigation of existing and/or development of new communication technologies. To this end, V2I communication is examined as well as in-vehicle sensors and/or V2V communication, since the latter two approaches allow a wider concept utilisation by avoiding the coupling with the infrastructure. Communication protocols are also among the fields of current research to ensure vehicles' communication coupling and decoupling during join and split manoeuvres, as well as security of the whole VPS concept (Hedrick et al, 2001).
- Collision avoidance and obstacle detection technologies and methodologies to ensure safety of the VPS concept.

Kavathekar (2012) and Kianfar (2013) provide recent reviews of these fields of VPS related research.

4.5.3. Conclusions and recommendations

VPS offer a great potential to reduce motorway congestion, increase capacity and limit the negative environmental effects of traffic, as well as to increase the safety and comfort of the vehicles' drivers and passengers. For such benefits though to be gained, careful design is necessary of its control laws and their corresponding parameters such as headways, speeds, as well as of the employed communication technologies and their performance with regard to delays and random drop outs. The mixture and mass of the involved vehicles also affects the efficiency of the platoons, as well as their interactions with other, not similarly equipped vehicles.

The platooning concept is not new, but it has regained attention due to the rapid advances in vehicle automation. Some researchers consider it as the CACC concept taken to its maximum limit (Bishop, 2005), while others use CACC-equipped vehicles to form platoons (see e.g. the Collaborative Driving System (CBS) proposed by Hallé and Chaib-draa (2005)).

Although VPS and CACC indeed share several similarities, especially as far as their impacts to traffic and environment and the implementation technologies are concerned, they also have two main differences:

- The CACC concept involves the cooperation of a vehicle with its preceding one, or with some vehicles in its neighbourhood. In VPS, on the other hand, each following vehicle cooperates at least with its preceding vehicle as well as with the vehicle that leads the platoon.
- The CACC concept involves only longitudinal control with the driver of the vehicle always responsible for the necessary lane keeping, change and merging manoeuvres. In VPS, on the other hand, lateral control (i.e. lane keeping) is part of the system's automation, which, in some cases, is also responsible for the lane change and merging manoeuvres.

In addition to the above, VPSs were initially conceived for running in dedicated infrastructures, while CACC has emerged as an enhancement of the ACC system developed for infrastructures carrying mixed-traffic of both equipped and non-equipped vehicles. Currently, these approaches seem to reverse:

- Researchers studying VPS investigate their operation in mixed-traffic infrastructures in an effort to increase the viability of the concept by eliminating any necessary infrastructure modifications.
- Researchers studying CACC suggest use of dedicated lanes, i.e. infrastructure modifications, to ensure and maximise expected benefits.

The truth, however, is that to achieve a market penetration rate high enough to ensure the expected benefits of such concepts without the need of infrastructure modification, incentives should be given for the first users that may involve use of dedicated and/or bus and/or HOV lanes as available and possible.

4.6. Navigation assistance systems (NAVS)

4.6.1. Description and functions

A Navigation System [16] (NAVS) is a system that provides location and route guidance information to the driver, as well as other functions that allow connection of equipment such as cameras, portable music devices, microphones, speakers, etc. in order to provide various services for a driver (Nagaki, 2012). Several different types of systems (e.g. OEM (Original Equipment Manufacturing) fitment, after-market solution) with different display positions and technologies (e.g. central information display, head-up, or separate detachable display) are already on the market.

The primary role of the in-vehicle NAVSs is to assist and advice the driver to plan a journey and reach the final destination, based on the awareness of the vehicle's position, speed, and heading at all times (Skog and Händel, 2012). Modern in-vehicle NAVSs consist of mainly three building blocks (Skog and Händel, 2012):

- The *information source* block, which is responsible to retrieve the vehicle's position information from global navigation satellite systems (GNSSs), vehicle motion sensors, road maps and/or other sources.
- The *information fusion* block, which consists of algorithms and structures responsible for the fusion and conversion of the information from the different information sources into a reliable navigation solution.
- The *user interface* block which is responsible to present to the user the information that has been generated by the information fusion block.

Through these building blocks, the NAVSs perform their main functions, which are (Nagaki, 2012) matching of car location on a map, route planning, and route guidance. Route planning and following guidance may be based on several criteria with travelled distance and travel time to be the most commonly adopted. To account for travel times, historical and/or real-time traffic data are used considering recurrent and/or non-recurrent traffic conditions.

Recently, special NAVS are emerging that base route planning and guidance on fuel consumption reduction such as the Green Driving Assistant (GDA). According to Nagaki (2012), automotive companies aim to reduce CO_2 emissions and promote technological developments, and in-vehicle NAVSs can enable such pursued goals by proposing routes that

[16] http://www.eurofot-ip.eu/en/intelligent_vehicle_systems/safehmi/ [accessed 11.03.2013]

not only avoid traffic jams and road hazards, but also calculate the fuel consumption for each route leading from the start to the destination of a trip, and propose the route with minimal fuel consumption. These NAVSs operate on the principle that (Nagaki, 2012) as the route is planned using road links, which are segments of road networks, an average speed calculation for each road link based on distance and time can be used to allow the estimation of the fuel consumption of the alternative routes and enable a route suggestion based on the minimisation of this consumption.

Early in-vehicle NAVSs worked at a stand-alone mode, while the next generations used one-way communication to get road and traffic information (Nagaki, 2012). Recently, in-vehicle NAVSs have been developed that can communicate to an outside server through the mobile phone network, thus establishing a “probe car” system (Nagaki, 2012). The probe car can, not only get the road information about traffic jams, accidents, and highway regulations from this central server, but also send to the server data regarding its position and running speed. In addition, in 2004, the Portable Navigation Device (PND) was developed and introduced into the commercial market, creating a new and large market domain with its relatively inexpensive price (Nagaki, 2012).

4.6.2. Evaluation results, conclusions and recommendations

Main research efforts in the area of NAVSs cover the following areas:

- Technological aspects regarding vehicle positioning and communications (Nagaki, 2012).
- Contextual optimisation of navigation information, including maps’ presentation to reduce the drivers’ perceptual load (Lee et al, 2008), and inclusion of landmarks within the provided navigation information (May et al, 2005).
- Aesthetics and usability of NAVSs’ displays (Lavien et al, 2011).
- Drivers trust of NAVSs’ assistance and performance (Ma and Kaber, 2007).
- Performance comparisons and user perception of different NAVSs regarding the calculation basis (real and/or historical recurrent and/or non-recurrent traffic congestion information) and the potential to override systems’ suggestions (Eby and Kostyniuk, 1999).
- Analyses of real-time traffic capabilities of PNDs and traffic smartphone applications (apps) (Belzowski and Ekstrom, 2013).
- Data recording applications, including both hardware and software (McNally et al, 2003).
- Development of practical routing algorithms (Flinsenberg, 2004; Jahn et al, 2005; Kaparias et al, 2007; Schultes, 2008; Buscena et al, 2009; Delling and Wagner, 2009; Delling et al, 2009; Kaparias and Bell, 2009, 2010; Lee and Yang, 2012).

The results of the studies in all of the above areas indicate that there is still enough space for research and development since the real-time capabilities and accuracy of NAVSs are still below the user-desired levels.

In general, route selection is a complex decision problem (Pang et al, 2002), which includes many alternative solutions (routes) and is affected by many factors. Travel time and distance are the main factors affecting a user’s route choice, but others also exist, such as cost, number of traffic signals, stop signs, right and/or left turns, width of road, pavement or road surface type and slope, etc. Route choice is also affected by the type of the trip undertaken in the sense that for a business trip the shortest in terms of travel time route is preferred, while for a leisure trip routes with good scenery are generally preferable (Pang et al, 2002). Obviously, the number of factors that can affect the route choice of a user is large. In addition, several studies (Pang et al, 2002) have indicated high variability in the preferences and priorities of the different users concerning these factors. Therefore, a NAVS should allow consideration of as many factors as possible and expression of user's preferences and priorities to them.

In addition to the above, NAVSs should avoid system-optimum route suggestions, since drivers dislike routes that do not satisfy their personal criteria but some system-optimum ones (Pang et al, 2002); but, at the same time, NAVS should provide suggestions that can optimise the network traffic conditions, e.g., by avoiding traffic congestion on alternative recommended routes due to drivers' overreaction; a problem not satisfactorily solved so far. Although a significant bulk of research work has been produced in the past to address advanced related issues, such as consistency of the provided information or recommendation, the objectives of system versus user optimum, the role and significance of traffic prediction, feedback versus iterative algorithms, the impact of penetration rates and more (Papageorgiou et al, 2003, 2007), the current systems employ relatively simple algorithms, mainly based on the Dijkstra (Dijkstra, 1959) and A* (Hart et al, 1968) ones. To cope with the computational intensiveness and to increase the real-time applicability of these algorithms, several variants (Flinsenberg, 2004; Kaparias et al, 2007; Schultes, 2008; Delling and Wagner, 2009; Delling et al, 2009; Kaparias and Bell, 2009, 2010; Lee and Yang, 2012) as well as heuristic approaches have also been developed (see Fu et al, 2006, for a review). Nevertheless, focusing mainly on the issue of real-time applicability, the currently employed approaches seem to ignore the impacts of the NAVSs routing suggestions on traffic. They act individually and "selfishly", and, in case of massive use and high penetration rates, they are very likely to lead to congestion problems, which, although acknowledged (see e.g. Jahn et al, 2005; Buscena et al, 2009), have not been studied so far in a systematic way. This is therefore also an issue of great importance for the years to come, given the continuously increasing penetration of both in-vehicle and portable navigation devices in our driving habits.

5. Classification and analysis of motorway traffic related VACS

5.1. Introduction

Motorways had been conceived as the types of facilities that could provide virtually unlimited mobility to the road users. However, the continuous increase of car-ownership and the steady expansion of land use in metropolitan areas have led to the daily appearance of extended and ever-growing recurrent motorway congestion in Europe and elsewhere. Specifically, traffic data analyses indicate that nearly all real-world traffic breakdowns are caused by simultaneous action of three factors (Treiber and Kesting, 2013), a sufficiently high traffic load, a bottleneck, and disturbances of traffic flow caused by individual drivers.

Bottlenecks are network locations characterised by the existence of local capacity reductions. They appear as:

- Permanent attributes of the infrastructure such as on and off ramps, lane drops and road curves, uphill and downhill road gradients, tunnels, etc.;
- Long lasting but temporary features such as road-works and construction sites;
- Temporary results of incidents, i.e. unexpected external events, such as stalled vehicles or accidents, which reduce the motorway capacity due to blocking of lanes or driver rubber-necking by an unpredictable amount.

When traffic breaks down at a bottleneck and congested traffic is formed upstream of it, the bottleneck is said to be activated. Bottleneck activation is typically accompanied by a further 10-20% drop in the already low local capacity (Treiber and Kesting, 2013).

For bottleneck activation, it suffices to have an inflow exceeding its own local capacity, i.e. the traffic flow that can pass through it. Bottleneck activation is typically triggered by individual drivers with an abrupt driving behaviour, given that the traffic load is sufficiently high. Individual drivers that accelerate or decelerate, change lanes or overtake abruptly create traffic flow perturbations. In case of low enough traffic loads, such perturbations are absorbed and do not grow and propagate. In presence, however, of sufficiently high traffic loads, abrupt driving styles can trigger speed breakdown and bottleneck activation.

Although some of the aforementioned factors that may lead to traffic breakdowns are unavoidable, the frequency of breakdowns appearances as well as the duration and severity, should they appear, could be reduced, and motorway traffic efficiency could be generally improved if MTM managed to smooth, stabilise and redistribute homogeneously traffic flow:

- Smoothing will avoid sudden and/or unnecessary speed variations that may trigger negative waving phenomena.
- Stabilisation will prevent grow and propagation of traffic flow disturbances, should they appear.
- Homogeneous redistribution will allow utilisation of the available motorway capacity to the maximum possible extent.

To achieve traffic flow smoothing, stabilisation and redistribution, MTM should be able to make control decisions regarding speeds, headways, and lane change/merge manoeuvres of the vehicles, as well as to provide route guidance. To this end, efficient control algorithms and strategies are necessary. Even if such algorithms and strategies were available, suitable actuators would be necessary to enable the materialisation of the control decisions and recommendations. These actuators may be provided by motorway traffic related VACS depending upon:

- the particular functions they perform and
- their level of autonomy, which defines their functional requirements, as well as their deployment potential by a MTM system.

To identify the VACS that seem promising in this respect, the systems reviewed in Chapter 4 are examined and classified according to their enabled functions and level of autonomy. In addition, their relevance in response to the MTM needs concerning the three factors that lead to traffic breakdowns is studied. The aim is to identify those VACS that have a real potential to contribute to the current and future MTM needs. Following sections provide the results of this endeavour.

5.2. VACS classification according to enabled functions

As mentioned in Section 5.1, to improve motorway efficiency, MTM should be able to make and impose control decisions regarding speeds, headways and lane change/merge manoeuvres as well as to provide route guidance. In this respect, motorway traffic related VACS are relevant, which enable the aforementioned functions, as well as any combinations of these functions.

To identify the VACS that are relevant to each of the aforementioned control and recommendation needs of MTM, the systems reviewed in Chapter 4 are classified in the following categories, which reflect the particular function or functions that are enabled:

- *Speed control systems*: This category includes systems that allow speed control at different levels of automation. These levels vary from speed information and recommendations to the driver to fully intervening systems, i.e. systems that impose the recommended speed levels. Table 5.1 lists and briefly describes from this aspect the relevant VACS. In addition to the issues mentioned in Section 4.2, speed control systems may be used as mainline metering devices upstream of bottlenecks and merges (Papageorgiou et al, 2008; Carlson et al, 2011).
- *Headway (gap) control systems*: This category includes systems that enable a vehicle to keep a specified distance from the vehicle in front of it. The distance, which may be defined in terms of time (time headway) or space (space headway), must preserve safety under all circumstances. Table 5.2 lists and briefly describes from this aspect the relevant VACS.
- *Lane change/merge systems*: This category includes systems that assist the execution of lane change and merge manoeuvres. They range from purely assisting systems, in that they only provide advice and recommendations, to fully automated systems that undertake all the tasks necessary to drive the vehicle from the current to the aimed lane. Table 5.4 lists and briefly describes from this aspect the relevant VACS.
- *Platooning systems*: This category includes systems that can be used to form vehicle platoons. They range from systems that enable headway control of individual vehicles, which can be grouped together to form platoons, to systems that have been

specifically developed and/or deployed for vehicle platooning purposes. Table 5.4 lists and briefly describes from this aspect the relevant VACS.

- *Route guidance systems*: This last category includes systems that enable route guidance. By its nature, route guidance is only provided in an informative manner, in that route recommendations are provided to the vehicle driver who chooses to follow or ignore them. Table 5.4 lists and briefly describes from this aspect the relevant VACS.

It should be noted that the above classification is not strict in that VACS may appear in more than one category, if they enable more than one function.

Finally, it should be noted that beyond the aforementioned VACS, ramp metering and motorway-to-motorway control are known, from multiple field applications, to be valuable in mitigating congestion (Papageorgiou and Kotsialos, 2002; Papageorgiou and Papamichail, 2007). These conventional MTM systems can be employed via conventional traffic signals or via other emerging means (V2I).

Table 5.1. Speed control systems

System	Description	Sources of info
Active Green Driving (AGD)	Identifies and has the ability to impose speeds that reduce fuel consumption and pollution	Hoeger et al, 2011
Cooperative Variable Speed Limit System (CVSLS)	Provides speed recommendations	Grumert et al, 2013
Fuel Efficiency Advisor (FEA)	Identifies and provides fuel efficient speed recommendations	Kessler et al, 2012; http://www.eurofot-ip.eu/en/intelligent_vehicle_systems/fea/ [accessed 11.03.2013]
Integrated Full-Speed Range Speed Assistant (IRSA)	Supports speed maintenance within fixed or dynamic limits and adjusts them to preserve a desired time or space gap from the preceding vehicle; ranges from purely advisory to completely mandatory types	Wilmink et al, 2006; van Arem et al, 2007
Intelligent Speed Adaptation (ISA)	Supports speed maintenance within fixed or dynamic limits; ranges from purely advisory to completely mandatory types	Tampère et al, 1999; Carsten and Tate, 2000, 2005; Varhelyi and Makinen, 2001; Biding and Lind, 2002; Hegeman, 2002; Hogema et al, 2002; Liu and Tate, 2004; Bishop, 2005; van Driel, 2007; Boriboonsomsin et al, 2008; Doecke and Woolley, 2010; Marchau et al, 2010; SWOV, 2010; Hoeger et al, 2011; Vlassenroot et al, 2011a, 2011b; Benmimoun et al, 2012; Blum et al, 2012; Kessler et al, 2012; iMobility Forum, 2013

Table 5.2. Headway control systems

System	Description	Sources of info
Adaptive Cruise Control (ACC)	Automatically adjusts speeds to preserve a desired time or space gap from the preceding vehicle; operates at high speed levels	Zwaneveld and van Arem, 1997; Fancher et al, 1998; Swaroop and Rajagopal, 1998; Bose and Ioannou, 1999, 2001, 2003; VanderWerf et al, 2001, 2002; Li and Shrivastava, 2002; Davis, 2004, 2006, 2007; Zhang and Ioannou, 2004; Bishop, 2005; Ioannou and Zhang, 2005; General

System	Description	Sources of info
		Motors Corporation, 2005; University of Michigan and General Motors Corporation, 2005a, 2005b; Rajamani et al, 2005; Visser, 2005; Jiang and Wu, 2006; Rajamani, 2006; Yi and Horowitz, 2006; Alkim et al, 2007; Ioannou et al, 2007; Kesting et al, 2007a, 2007b, 2008, 2010; Viti et al, 2008; Yuan et al, 2009; Pueboobpaphan and van Arem, 2010; Xiao and Gao, 2010; Kessler et al, 2012; Tapani, 2012; Benmimoun et al, 2012, 2013; http://www.eurofot-ip.eu/en/intelligent_vehicle_systems/acc/ [accessed 11.03.2013]
Cooperative Adaptive Cruise Control (CACC)	Automatically adjusts speeds to preserve a desired time or space gap from the preceding vehicle	VanderWerf et al, 2002, 2001, 2007; Maihöfer et al, 2004; Bishop, 2005; Visser, 2005; Popescu-Zeletin et al, 2010; Shladover et al, 2010, 2011; Arnaout and Bowling, 2011, 2013
Cooperative Following and Merging (CFM)	Automatically adjusts speeds to preserve a desired time or space gap from the preceding vehicle and assists lane changing manoeuvres by creating and maintaining an appropriate gap in the target lane	Tampère et al, 1999
Full Speed Range Adaptive Cruise Control (FSRA)	Automatically adjusts speeds to preserve a desired time or space gap from the preceding vehicle; operates at all speed levels	Minderhoud, 1999; Ehmanns and Spannheimer, 2004; Bishop, 2005; Alkim et al, 2007; Viti et al, 2008; Hoeger et al, 2011; Shladover, 2012a; iMobility Forum, 2013
Highway Pilot (HP)	Automatically adjusts speeds to preserve a desired time or space gap from the preceding vehicle; operates at the speed range 0-130 km/h	iMobility Forum, 2013; Hoeger et al, 2011
Integrated Full-Speed Range Speed Assistant (IRSA)	Supports speed maintenance within fixed or dynamic limits and adjusts them to preserve a desired time or space gap from the preceding vehicle; ranges from purely advisory to completely mandatory types	Wilmink et al, 2006; van Arem et al, 2007
Low Speed ACC (LSACC)	Automatically adjusts speeds to preserve a desired time or space gap from the preceding vehicle; operates at low speed levels	Minderhoud, 1999; Benz et al, 2003; SINTEF et al, 2004; Bishop, 2005; van Driel, 2007; van Driel and van Arem, 2008, 2010

Table 5.3. Lane change/merge systems

System	Description	Sources of info
Cooperative Following and Merging (CFM)	Automatically adjusts speeds to preserve a desired time or space gap from the preceding vehicle and assists lane changing manoeuvres by creating and maintaining an appropriate gap in the target lane	Tampère et al, 1999
Cooperative Merging (CM)	Assists the driver in lane changing manoeuvres by creating and maintaining an appropriate gap in the target lane	Tampère et al, 1999; Popescu-Zeletin et al, 2010
Lane Change Decision Aid System (LCDAS)	Support lane change and merge vehicle manoeuvres; ranges from warning to more autonomous systems, which support the driver all the way from the lane change intention until placement in the target lane	Godbole et al, 1997; Jula et al, 1999, 2000; Smith et al, 2003; Tideman et al, 2007; Visvikis et al, 2008; Popescu-Zeletin et al, 2010; Habenicht et al, 2011; Wan et al, 2011; Bartels et al, 2012; Tomar and Verma, 2012; Knake-Langhorst et al, 2013

Table 5.4. Platooning systems

System	Description	Sources of info
Adaptive Cruise Control (ACC)	Automatically adjusts speeds to preserve a desired time or space gap from the preceding vehicle; several vehicles following each other, if equipped with such a system can form a vehicle platoon	Zwaneveld and van Arem, 1997; Fancher et al, 1998; Swaroop and Rajagopal, 1998; Bose and Ioannou, 1999, 2001, 2003; VanderWerf et al, 2001, 2002; Li and Shrivastava, 2002; Davis, 2004, 2006, 2007; Zhang and Ioannou, 2004; Bishop, 2005; Ioannou and Zhang, 2005; General Motors Corporation, 2005; University of Michigan and General Motors Corporation, 2005a, 2005b; Rajamani et al, 2005; Visser, 2005; Jiang and Wu, 2006; Rajamani, 2006; Yi and Horowitz, 2006; Alkim et al, 2007; Ioannou et al, 2007; Kesting et al, 2007a, 2007b, 2008, 2010; Viti et al, 2008; Yuan et al, 2009; Pueboobpaphan and van Arem, 2010; Xiao and Gao, 2010; Kessler et al, 2012; Tapani, 2012; Benmimoun et al, 2012, 2013; http://www.eurofot-ip.eu/en/intelligent_vehicle_systems/acc/ [accessed 11.03.2013]
Cooperative Adaptive Cruise Control (CACC)	Automatically adjusts speeds to preserve a desired time or space gap from the preceding vehicle; several vehicles following each other, if equipped with such a system can form a vehicle platoon	VanderWerf et al, 2002, 2001, 2007; Maihöfer et al, 2004; Bishop, 2005; Visser, 2005; Popescu-Zeletin et al, 2010; Shladover et al, 2010, 2011; Arnaout and Bowling, 2011, 2013
Cooperative Following and Merging (CFM)	Automatically adjusts speeds to preserve a desired time or space gap from the preceding vehicle and assists lane changing manoeuvres by creating and maintaining an appropriate gap in the target lane; several vehicles following each other, if equipped with such a system can form a vehicle platoon	Tampère et al, 1999
Full Speed Range Adaptive Cruise Control (FSRA)	Automatically adjusts speeds, at all levels, to preserve a desired time or space gap from the preceding vehicle; several vehicles following each other, if equipped with such a system can form a vehicle platoon	Minderhoud, 1999; Ehmanns and Spannheimer, 2004; Bishop, 2005; Alkim et al, 2007; Viti et al, 2008; Hoeger et al, 2011; Shladover, 2012a; iMobility Forum, 2013
Highway Pilot (HP)	Automatically adjusts speeds, in the range 0-130 km/h, to preserve a desired time or space gap from the preceding vehicle; several vehicles following each other, if equipped with such a system can form a vehicle platoon	iMobility Forum, 2013; Hoeger et al, 2011
Integrated Full-Speed Range Speed Assistant (IRSA)	Supports speed maintenance within fixed or dynamic limits and adjusts them to preserve a desired time or space gap from the preceding vehicle; several vehicles following each other, if equipped with such a system can form a vehicle platoon	Wilmink et al, 2006; van Arem et al, 2007
Low Speed ACC (LSACC)	Automatically adjusts speeds, at low levels, to preserve a desired time or space gap from the preceding vehicle; operates at low speed levels; several vehicles following each other, if equipped with such a system	Minderhoud, 1999; Benz et al, 2003; SINTEF et al, 2004; Bishop, 2005; van Driel, 2007; van Driel and van Arem, 2008, 2010

System	Description	Sources of info
	can form a vehicle platoon	
Vehicle Platooning System (VPS)	Involves a variety of options for forming closely-spaced semi or full automated vehicle platoons, aiming at more convenient, safe, fuel-efficient and traffic-efficient driving	PATH, 1997; Michael et al, 1998; Hedrick et al, 2001; Lee and Kim, 2002; Bonnet, 2003; Ehmanns and Spannheimer, 2004; Bishop, 2005; Hallé and Chaib-draa; 2005; van Arem et al, 2006; Alam et al, 2010; Alam, 2011; Tientrakool et al, 2011; Bergenheim et al, 2012a, 2012b; Kavathekar, 2012; Shladover, 2012a; Brännström, 2013; Davila, 2013; iMobility Forum, 2013; Kianfar, 2013; SARTRE, 2013; Tsugawa, 2014;

Table 5.5. Route guidance systems

System	Description	Sources of info
Navigation System (NAVS)	Provides personalised location and route guidance information in order to assist and advice the driver in planning a journey	Eby and Kostyniuk, 1999; Pang et al, 2002; McNally et al, 2003; Flinsenberg, 2004; Jahn et al, 2005; May et al, 2005; Kaparias et al, 2007; Ma and Kaber, 2007; Lee et al, 2008; Schultes, 2008; Buscena et al, 2009; Delling and Wagner, 2009; Delling et al, 2009; Kaparias and Bell, 2009, 2010; Lavien et al, 2011; Lee and Yang, 2012; Nagaki, 2012; Skog and Händel, 2012; Belzowski and Ekstrom, 2013

5.3. VACS classification according to level of autonomy

As mentioned in Section 5.1, the level of autonomy of VACS is a significant factor from a MTM aspect, since it does not only define their functional requirements, but also their deployment potential by a MTM system. Obviously, the deployment potential increases for systems that are somehow able to communicate with a MTM system so that this system can inform them about its control decisions and recommendations.

To identify the VACS, which are relevant to MTM in the aforementioned respect, the systems reviewed in Chapter 4 are classified in the following categories, which reflect their level of autonomy:

- *Autonomous systems*: This category includes VACS that carry on board all technology and logic necessary to perform their functions. They are autonomous in that their behaviour and effectiveness depends entirely upon their embedded sensors and intelligence, without provisions to directly communicate with other vehicles or to receive controls or recommendations by a MTM system. Table 5.6 lists and briefly describes from this aspect the relevant VACS.
- *Cooperative systems*: This category includes systems, the behaviour and effectiveness of which depends not only upon their embedded sensors and intelligence, but also on their communication and cooperation with other similar systems and/or the infrastructure. Cooperative systems are further classified in:
    - *V2V systems*: This category includes systems that require communication and cooperation with other similar systems in order to carry out their functions. Similarly to autonomous systems, it is not possible to directly communicate and/or impose them control decisions and recommendations externally defined by a MTM system. Table 5.7 lists and briefly describes from this aspect the relevant VACS.

- *V2I systems*: This category includes systems that require communication and cooperation with the infrastructure in order to carry out their functions. In contrast to the systems of the previous categories, these systems can receive directly, and implement according to their respective level of support (informative or intervening systems) control decisions and recommendations externally defined by a MTM system. Dual communication also enables vehicle data to be transmitted from the vehicles to the MTM system, which increases the nature, quality and quantity of centrally available real-time information. Table 5.8 lists and briefly describes from this aspect the relevant VACS.
- *V2X systems*: This last category includes systems, which feature the characteristics of both the V2V and V2I systems categories. Table 5.9 lists and briefly describes from this aspect the relevant VACS.

It should be noted that the above classification is not strict in that VACS may appear in more than one category, if they have the ability to carry out their functions under different communication settlements.

Table 5.6. Autonomous systems

System	Description	Sources of info
Active Green Driving (AGD)	Autonomous system that carries on board all technology and logic necessary for the identification and imposing of "green speeds"	Hoeger et al, 2011
Adaptive Cruise Control (ACC)	Autonomous system that carries on board all technology and logic necessary to preserve the desired gap from the preceding vehicle	Zwaneveld and van Arem, 1997; Fancher et al, 1998; Swaroop and Rajagopal, 1998; Bose and Ioannou, 1999, 2001, 2003; VanderWerf et al, 2001, 2002; Li and Shrivastava, 2002; Davis, 2004, 2006, 2007; Zhang and Ioannou, 2004; Bishop, 2005; Ioannou and Zhang, 2005; General Motors Corporation, 2005; University of Michigan and General Motors Corporation, 2005a, 2005b; Rajamani et al, 2005; Visser, 2005; Jiang and Wu, 2006; Rajamani, 2006; Yi and Horowitz, 2006; Alkim et al, 2007; Ioannou et al, 2007; Kesting et al, 2007a, 2007b, 2008, 2010; Viti et al, 2008; Yuan et al, 2009; Pueboobpaphan and van Arem, 2010; Xiao and Gao, 2010; Kessler et al, 2012; Tapani, 2012; Benmimoun et al, 2012, 2013; http://www.eurofot-ip.eu/en/intelligent_vehicle_systems/acc/ [accessed 11.03.2013]
Fuel Efficiency Advisor (FEA)	Autonomous system that carries on board all technology and logic necessary for the identification of fuel efficient speeds	Kessler et al, 2012; http://www.eurofot-ip.eu/en/intelligent_vehicle_systems/fea/ [accessed 11.03.2013]
Full Speed Range Adaptive Cruise Control (FSRA)	Autonomous system that carries on board all technology and logic necessary to preserve the desired gap from the preceding vehicle	Minderhoud, 1999; Ehmanns and Spannheimer, 2004; Bishop, 2005; Alkim et al, 2007; Viti et al, 2008; Hoeger et al, 2011; Shladover, 2012a; iMobility Forum, 2013
Highway Pilot (HP)	Autonomous system that carries on board all technology and logic necessary to preserve the desired gap from the preceding vehicle	iMobility Forum, 2013; Hoeger et al, 2011
Intelligent Speed	V2I cooperation is necessary to perform its	Tampère et al, 1999; Carsten and Tate, 2000,

System	Description	Sources of info
Adaptation (ISA)	functions in full extent; in an elementary form it may operate as autonomous system with fixed and on-board stored or adaptive speed limits	2005; Varhelyi and Makinen, 2001; Biding and Lind, 2002; Hegeman, 2002; Hogema et al, 2002; Liu and Tate, 2004; Bishop, 2005; van Driel, 2007; Boriboonsomsin et al, 2008; Doecke and Woolley, 2010; Marchau et al, 2010; SWOV, 2010; Hoeger et al, 2011; Vlassenroot et al, 2011a, 2011b; Benmimoun et al, 2012; Blum et al, 2012; Kessler et al, 2012; iMobility Forum, 2013
Lane Change Decision Aid System (LCDAS)	Autonomous system that carries on board all technology and logic necessary to support lane change and merge vehicle manoeuvres; V2V cooperation has been suggested to enhance its capabilities	Godbole et al, 1997; Jula et al, 1999, 2000; Smith et al, 2003; Tideman et al, 2007; Visvikis et al, 2008; Popescu-Zeletin et al, 2010; Habenicht et al, 2011; Wan et al, 2011; Bartels et al, 2012; Tomar and Verma, 2012; Knake-Langhorst et al, 2013
Low Speed ACC (LSACC)	Autonomous system that carries on board all technology and logic necessary to preserve the desired gap from the preceding vehicle	Minderhoud, 1999; Benz et al, 2003; SINTEF et al, 2004; Bishop, 2005; van Driel, 2007; van Driel and van Arem, 2008, 2010

Table 5.7. V2V systems

System	Description	Sources of info
Cooperative Adaptive Cruise Control (CACC)	V2V cooperation is necessary to perform its functions in full extent; in absence of V2V cooperation, it functions as ACC	VanderWerf et al, 2002, 2001, 2007; Maihöfer et al, 2004; Bishop, 2005; Visser, 2005; Popescu-Zeletin et al, 2010; Shladover et al, 2010, 2011; Arnaout and Bowling, 2011, 2013
Cooperative Following and Merging (CFM)	V2V cooperation is necessary to perform its following function, while V2V or V2I cooperation is necessary for the accomplishment of the merging function	Tampère et al, 1999
Cooperative Merging (CM)	V2V or V2I cooperation is necessary to accomplish the merging function	Tampère et al, 1999; Popescu-Zeletin et al, 2010
Integrated Full-Speed Range Speed Assistant (IRSA)	V2V or V2I cooperation is necessary so that speed limits are directly communicated to the vehicle, while V2V cooperation is necessary to perform its CACC similar function; in absence of V2V cooperation, it functions as ACC	Wilmink et al, 2006; van Arem et al, 2007
Vehicle Platooning System (VPS)	V2V cooperation suffices to form and maintain vehicle platoons; combination of V2V and V2I cooperation has also be used	PATH, 1997; Michael et al, 1998; Hedrick et al, 2001; Lee and Kim, 2002; Bonnet, 2003; Ehmanns and Spannheimer, 2004; Bishop, 2005; Hallé and Chaib-draa; 2005; van Arem et al, 2006; Alam et al, 2010; Alam, 2011; Tientrakool et al, 2011; Bergenheim et al, 2012a, 2012b; Kavathekar, 2012; Shladover, 2012a; Brännström, 2013; Davila, 2013; iMobility Forum, 2013; Kianfar, 2013; SARTRE, 2013; Tsugawa, 2014;

Table 5.8. V2I systems

System	Description	Sources of info
Cooperative Merging (CM)	V2V or V2I cooperation is necessary to accomplish the merging function	Tampère et al, 1999; Popescu-Zeletin et al, 2010
Cooperative Variable Speed Limit System	V2I cooperation is necessary so that speed limits are directly communicated to the vehicle	Grumert et al, 2013

System	Description	Sources of info
(CVSLS)		
Intelligent Speed Adaptation (ISA)	V2I cooperation is necessary to perform its functions in full extent; in an elementary form it may operate as autonomous or as V2V system	Tampère et al, 1999; Carsten and Tate, 2000, 2005; Varhelyi and Makinen, 2001; Biding and Lind, 2002; Hegeman, 2002; Hogema et al, 2002; Liu and Tate, 2004; Bishop, 2005; van Driel, 2007; Boriboonsomsin et al, 2008; Doecke and Woolley, 2010; Marchau et al, 2010; SWOV, 2010; Hoeger et al, 2011; Vlassenroot et al, 2011a, 2011b; Benmimoun et al, 2012; Blum et al, 2012; Kessler et al, 2012; iMobility Forum, 2013
Navigation System (NAVS)	V2I cooperation is necessary to receive location and route guidance information, as well as for the establishment of a "probe car" system	Eby and Kostyniuk, 1999; Pang et al, 2002; McNally et al, 2003; Flinsenberg, 2004; Jahn et al, 2005; May et al, 2005; Kaparias et al, 2007; Ma and Kaber, 2007; Lee et al, 2008; Schultes, 2008; Buscena et al, 2009; Delling and Wagner, 2009; Delling et al, 2009; Kaparias and Bell, 2009, 2010; Lavien et al, 2011; Lee and Yang, 2012; Nagaki, 2012; Skog and Händel, 2012; Belzowski and Ekstrom, 2013

Table 5.9. V2X systems

System	Description	Sources of info
Cooperative Following and Merging (CFM)	V2V cooperation is necessary to perform its following function, while V2V or V2I cooperation is necessary for the accomplishment of the merging function	Tampère et al, 1999
Integrated Full-Speed Range Speed Assistant (IRSA)	V2V or V2I cooperation is necessary so that speed limits are directly communicated to the vehicle, while V2V cooperation is necessary to perform its CACC similar function; in absence of V2V cooperation, it functions as ACC	Wilmink et al, 2006; van Arem et al, 2007
Vehicle Platooning System (VPS)	V2V cooperation suffices to form and maintain vehicle platoons; combination of V2V and V2I cooperation has also be used	PATH, 1997; Michael et al, 1998; Hedrick et al, 2001; Lee and Kim, 2002; Bonnet, 2003; Ehmanns and Spannheimer, 2004; Bishop, 2005; Hallé and Chaib-draa; 2005; van Arem et al, 2006; Alam et al, 2010; Alam, 2011; Tientrakool et al, 2011; Bergenheim et al, 2012a, 2012b; Kavathekar, 2012; Shladover, 2012a; Brännström, 2013; Davila, 2013; iMobility Forum, 2013; Kianfar, 2013; SARTRE, 2013; Tsugawa, 2014;

5.4. Relevance assessment from a traffic management perspective

5.4.1. Introductory concepts

Summarising the classification results of Sections 5.2 and 5.3, the classification matrix of Table 5.10 is obtained, which provides an overview of the different VACS functions, which may be deployed to address different traffic management needs, as well as their corresponding level of autonomy, which may trigger different traffic management solutions.

To identify the VACS that may indeed contribute to the MTM objective of improving traffic efficiency and releasing motorway networks from the significant congestion problems and their negative consequences to the environment and the overall quality of life, their characteristics and specific impacts on traffic flow characteristics (such as capacity flow, congestion formation, stop-and-go waves, capacity drop) should be studied. Such a study should unfold their strengths, i.e. their characteristics, which, if appropriately deployed by a MTM system, may assist in achieving the traffic flow efficiency improvement objective; as well as their weaknesses, i.e. their characteristics, which may impose barriers to the achievement of the aforementioned objective. In addition, the study should identify any threats, i.e. any related external factors that can impose further barriers to the achievement of the traffic flow efficiency improvement objective, as well as any opportunities, i.e. external factors that can enhance the strengths of VACS so as to remove as much as possible their weaknesses and cope with the threats. In short, a SWOT (Strengths-Weaknesses-Opportunities-Threats) analysis seems appropriate to identify, which of the VACS, which have been identified as related to motorway traffic in the sense that their operation affects traffic flow, are mostly relevant from a MTM perspective in that they have a great potential to contribute to the objective of improving traffic flow efficiency.

Table 5.10. Classification matrix

	Function					Level of autonomy			
System	**Speed control**	**Headway control**	**Lane change/ merge**	**Platooning**	**Route guidance**	**Autonomous**	**V2V**	**V2I**	**V2X**
AGD	x					x			
ACC		x		x		x			
CACC		x		x			x		
CFM		x	x	x			x		x
CM			x				x	x	
CVSLS	x							x	
FEA	x					x			
FSRA		x		x		x			
HP		x		x		x			
IRSA	x	x		x			x		x
ISA	x					x		x	
LCDAS			x			x			
LSACC		x		x		x			
NAVS					x			x	
VPS				x			x		x

A SWOT analysis is a structured planning method used to evaluate the strengths, weaknesses, opportunities, and threats involved in a project or in a business venture. It involves specifying the objective of the project and business venture and identifying the internal (strengths and weaknesses) and external (opportunities and threats) factors that are favourable and/or unfavourable to achieving that objective. Although SWOT analyses are most often applied in a business context, they can be equally useful for single products, industries or persons, etc.

In the present case, SWOT will not be used to analyse motorway traffic related VACS as standalone products, but to provide an insight into the strengths and weaknesses of their functions from a MTM perspective, as well as to identify any opportunities offered, which may be exploited to enhance these strengths, limiting at the same time, or even eliminating, the weaknesses and potential threats that may comprise barriers to achieving the MTM objective of improving motorway traffic flow efficiency. Following subsections present the relevant analyses performed and summarise their findings.

5.4.2. SWOT analysis of motorway traffic related VACS

The aim of MTM is to improve the traffic efficiency of motorway networks and preserve their capacity at high levels, especially when endangered by traffic breakdowns due to the co-presence of the three factors mentioned earlier in Section 5.1, i.e. a relatively high traffic load, bottlenecks and disturbances caused by individual drivers. The systems reviewed in Chapter 4 have a potential to assist this difficult MTM task.

The analysis in this section starts with the ACC system, which, according to the review of Chapter 4 seems to be the most mature one from a market perspective. ACC, as mentioned in Section 4.1.1, is an autonomous system that carries on board all technology and logic necessary to preserve a user-defined gap from the preceding vehicle, while maintaining the speed up to user-defined limits. Its analysis indicates that it has the potential, not only to increase safety and comfort, but also to smooth traffic flow, thus also decreasing fuel consumption and related environmental pollution problems, as well as to enable formation of vehicle platoons (see Section 4.5) with possible benefits to traffic efficiency, motorway capacity and the environment, but without the need of dedicated infrastructures. Due to its autonomous nature, ACC has the potential to offer the aforementioned services without the need of any external assistance. Thus, autonomy comprises a strength of ACC. This, however, reflects also a weakness in that it is not possible to directly impose to it, or even provide advice on system settings for the speed and gap, which will be beneficial at a network level. As a consequence, when used with gaps lower than those used by manually-driven vehicles, ACC can also lead to capacity and throughput increases, while under conservative use, i.e. use with gaps higher than those commonly used by manually-driven vehicles, it can lead to a, possibly dramatic, decrease of motorway capacity. Some of these weaknesses may possibly be mitigated if the ACC system includes autonomous traffic-adaptive capabilities, e.g. as proposed in Kesting et al (2010).

Other weaknesses of the system include its operation at higher speeds only, a fact that limits its use to under- or near-capacity flow traffic conditions, while in dense or stop-and-go traffic conditions it becomes useless. In addition, under high penetration rates, on-ramp flow problems may appear when short gaps are prevailing, i.e. mainstream benefits may come at the expense of traffic flow trying to merge from on-ramps; while, at higher gaps, frequent cut-in of lane-changing vehicles may lead to frustration for the ACC-equipped vehicle driver and possible de-activation of the system. Finally, simulation investigations of ACC indicate that the control laws currently employed cannot guarantee traffic flow stability under all circumstances.

Opportunities to surpass the aforementioned weaknesses and further enhance the strengths of ACC have already appeared thanks to the rapid technological advances:

- Enabling V2I communication will enable a MTM system to provide advice and recommendations on gap, speed and other parameter settings that are beneficial at a network level. Navigation devises could be alternatively used in this respect. Intervention could also be enabled by some ISA systems capable of imposing dynamic speed limits (see Section 4.2.3). Until, however, technology is mature enough to directly communicate advices and/or intervene in the driving task, traditional VMSs could be used to provide recommendations for location-specific, preferably traffic-responsive, gap and speed settings.

- ACC systems operating at low speed ranges are already in the market. Extending the capabilities and usability of the common ACC system under dense and congested traffic conditions. LSACC (see Section 4.1.2) with all its additional strengths of reducing start delay, journey times, and stops and stop-time per vehicle in the journey, can also enhance the benefits gained by a common ACC. A FSRA (see Section 4.1.3) with the ability to operate for the whole speed spectrum, in combination with appropriate system settings, gives without doubt a competitive advantage compared to both the common ACC and the LSACC, as it extends their employment potential to a larger spectrum of traffic conditions.

In addition to the above, the continuous research on control-theoretical aspects provides the opportunity to develop more efficient ACC control laws that, by adapting to the prevailing traffic conditions, will eventually ensure traffic flow stability under all traffic conditions.

Despite all the aforementioned ACC-relevant strengths and opportunities, the gains from a MTM aspect can only be ensured with relatively high penetration rates. High penetration rates in combination with V2V communication, which will enable the preservation of even shorter, though still safe gaps, can also enhance the capacity-increase effects of ACC, as the analyses of CACC (see Section 4.1.4) and VPS (see Section 4.5) indicate. In case though of high penetration rates, even with common ACC systems operating under short gap settings, on-ramp flow merging problems may deteriorate even more, as mentioned earlier. V2V and/or V2I communication should therefore be necessary to also assist and smooth the merging process. Related opportunities can be offered by the advances in the field of LCDAS reported in Section 4.3.2. Although existing LCDAS are simply warning systems, manufacturers and researchers are making efforts to automating the whole merging process and developing cooperative systems.

A significant issue is the need to increase public awareness of the strengths and opportunities offered by ACC systems so as to increase user acceptance of the system in terms of both purchase intention and frequent activation after purchase. A significant barrier in this effort is the cost of the system. As, however, technology will mature and demand will gradually increase, price will eventually fall to bearable levels. Also important in this context is the increase of public’s awareness on those system characteristics that seem significant for the user, such as safety increase and fuel economy. On the other hand, MTM should mature and get prepared to adapt to the rapid evolution of ACC, V2V and V2I systems, else the weaknesses discussed above may lead to a further degradation of the already degraded infrastructure with all the devastating consequences that such a deterioration of traffic conditions will have to the environment and the quality of life.

Table 5.11 summarises the key points of the SWOT analysis of ACC. Similar results and conclusions may also be reached by a SWOT analysis of the HP. HP is a vehicle application with an operation and traffic flow implications similar to FSRA as suggested by the analysis of Section 4.4.3. Its only additional strength would be that it will also support the driver in the lateral control (steering) of the vehicle, should the system finally enter the market and mature.

As mentioned earlier in the SWOT analysis of ACC, a significant enhancement of its strengths may result by externally imposing system settings such as speed limits, as well as by assisting the merging process of on-ramp flows, especially under high penetration rates and short gaps. Such abilities are offered by the ISA and LCDAS systems, respectively, which are analysed below.

Table 5.11. SWOT analysis of ACC

Strengths	Weaknesses
- Autonomy in that all necessary technology and knowledge is available on board - Increases safety and comfort - Smoothens traffic flow - Decreases fuel consumption - Decreases environmental pollution - Capacity increase under short gaps - Enables forming of vehicle platoons	- Autonomy implies that network-wide beneficial settings cannot be directly communicated and/or imposed - Capacity decrease under conservative gaps - On-ramp flow merging problems under short gaps and high penetration rates - Limited speed-range operation - Control laws that do not ensure traffic stability under all circumstances
Opportunities	**Threats**
- Advice/recommendations on network-wide beneficial system settings via traditional VMS or navigation devices or build-in (autonomous) extensions - Enabling network-wide beneficial system settings via V2I communication - LSACC/FSRA extend speed-range operation, thus applicability to all traffic conditions - CACC enables even shorter gaps - V2V and/or V2I communication may assist and smooth on-ramp merging flows - Control-theoretical research may provide more efficient control laws - Technology maturity may reduce system cost	- User acceptance in terms of both purchase intention and frequent activation after purchase - Cost - MTM delayed adaptation

To start with, ISA is a system, which, as mentioned in Section 4.2.3, supports speed maintenance within fixed or dynamic limits and ranges from purely advisory to completely mandatory types. Among the strengths of ISA is its ability to reduce speed violations, excessive speeds and speed variation, traffic homogenisation, to enable mainstream metering and to decrease accidents. However, according to usage results, it can be frustrating at low penetration rates and lead to a potential decrease of average speeds and, consequently, to an increase of travel times.

From a MTM perspective, the most significant ISA strength is its ability to limit or even prevent congestion, thus affecting positively both traffic efficiency and the environment. To this end, however, mandatory systems types imposing dynamic speed limits are necessary along with sufficiently high penetration rates. However, as the analysis of Section 4.2.3 indicates, users are presently more receptive to the advisory ISA types; it is therefore necessary to increase their acceptance of more intervening systems in terms of both purchase intention and frequent activation after purchase. To this end, communication to the users of the system's strengths that are of most significance for them may be helpful. Such strengths include the safety increase, the fuel economy resulting from the decrease in speed variation, as well as the decrease of the likelihood to be caught by a speed enforcement camera. As technology will mature and demand will increase, the relevant cost will also decrease to bearable levels. In the meantime, MTM should also mature and get prepared to exploit the maximum of ISA system's capabilities, by providing speed limits that dynamically adapt to the prevailing traffic conditions.

Only if ISA related strengths and opportunities are fully exploited, will it be possible to overcome the weaknesses identified in the mandatory system types, which, although the most beneficial, are, for the time being, the least accepted by the users. Table 5.12 summarises the SWOT analysis of ISA.

Table 5.12. SWOT analysis of ISA

Strengths	Weaknesses
- Can operate autonomously with fixed and on-board stored speed limits - Reduces excessive speeds and speed violations, therefore the likelihood of being caught by a speed enforcement camera - Reduces speed variation - Homogenises traffic - Increases safety - Reduces congestion and resulting negative environmental effects when allowed to impose dynamic speed limits	- True positive effects on traffic flow efficiency come from mandatory system types imposing dynamic speed limits under sufficiently high penetration rates - Can be frustrating at low penetration rates - Can lead to a potential decrease of average speeds and, consequently, to an increase of travel times
Opportunities	**Threats**
- Technology maturity may reduce system cost - Enables novel MTM applications (e.g. mainstream metering)	- User acceptance in terms of both purchase intention and frequent activation after purchase - Cost - MTM delayed adaptation

Unlike ISA, LCDAS is an autonomous system that carries on board all technology and logic necessary to support lane change and merge vehicle manoeuvres. This autonomy, similarly to the case of ACC, is a strength in that it allows the standalone operation of the system. From the MTM perspective, however, it is a weakness, since it does not allow a MTM system to exploit its capabilities for network-wide benefits. Existing LCDAS systems are mainly, as mentioned in Section 4.3.2, safety-oriented warning systems. However, vehicle manufacturers and researchers are currently making efforts to automate the whole lane-change and merging process so as to increase the system's impact on safety and user comfort.

V2V or V2I cooperative lane-change and merging operation has also been proposed to avoid the emergence of shock waves and stabilise traffic flow during lane-change manoeuvres (see CM in Section 4.3.1). Such cooperative operation could be also exploited in the context of MTM aiming to homogeneously redistribute traffic across all motorway lanes so as to maximise utilisation of all available capacity. For such benefits though, sufficiently high penetration rates will be necessary so that equipped vehicles will be able to communicate and cooperate with others and/or the infrastructure. Despite these expected benefits and the availability of the necessary technology for V2V and V2I communication, automated and/or cooperative LCDAS systems are still an evolving endeavour, which, as in the cases of the previous systems, will be threatened by user acceptance, related cost and potential delay of MTM adaptation to its evolution. Table 3.13 summarises the SWOT analysis of LCDAS.

At this point, it should be mentioned that:

- the IRSA system, described in Section 4.4.1, may be viewed as a FSRA combined with ISA and CM, while

- the CFM system, described in Section 4.4.2, may be viewed as a combination of CACC and CM.

As such, their realisation is expected to lead to systems that combine the strengths of their components, and exploit in a better way the opportunities offered to further enhance them for the benefit of overall traffic efficiency. They are however, evolving systems, not yet thoroughly investigated, and, despite their enhanced expected strengths, it is also expected to be threatened just like their component systems by user acceptance, related cost and potential delay of MTM adaptation to their evolution.

Table 5.13. SWOT analysis of LCDAS

Strengths	Weaknesses
- Autonomy in that all necessary technology and intelligence is available on board - Increases safety and comfort	- Autonomy does not allow for network-wide benefits
Opportunities	**Threats**
- V2V and/or V2I cooperation may avoid emergence of shock waves and stabilise traffic flow during lane-change manoeuvres - V2V and/or V2I cooperation may enable better utilisation of available motorway capacity - Technology advances may allow automation of the whole lane-change and merging process - Technology maturity may reduce system cost	- User acceptance in terms of both purchase intention and frequent activation after purchase - Cost - MTM delayed adaptation

Beyond the previously analysed systems, two more systems exist that offer the potential of speed control, FEA and CVSLS. FEA, as mentioned in Section 4.2.1, is an autonomous advisory system that aims at supporting the driver in maintaining the speed in the "green area" in the interest of fuel efficiency. A more intervening form in the sense of a haptic accelerator pedal, the AGD system (see Section 4.2.2), has also been proposed to further assist the driver in handling the vehicle in a more fuel-efficient manner. Although these systems have been developed specifically aiming at fuel economy, the penetration and spread of ACC-related and ISA systems under settings that will ensure traffic flow homogenisation and stability may soon reduce their importance, as fuel economy is among the strengths resulting from their overall operation. The penetration and spread of ISA systems is expected to put aside also CVSLS, as this latter system (see Section 4.2.4) comprises basically an advisory ISA system operating with dynamic speed limits, which are provided at specific network locations.

The last VACS identified as relevant to motorway traffic is NAVS. Unlike all previously discussed systems, the major strength of NAVS (see Section 4.6) within a MTM context lies in its route guidance ability that enables traffic redistribution, not within a limited motorway stretch but within a whole motorway network. This ability may contribute to the maximisation of infrastructure utilisation if efficient routing algorithms are employed. These routing algorithms need also to take into account, in contrast to the currently prevailing ones, their own effects on traffic. Else, massive use of NAVS under high penetration rates may lead to severe congestion problems at some network locations, while others will be underutilised. Research in this field is still ongoing, likewise in other related fields, such as positioning and communication systems, aesthetics, contextual optimisation, etc. The real-time capabilities and accuracy of NAVSs are still below the user-desired levels, which may hinder, not their spread and penetration as infotainment devices, but as trustful routing devises, which is of concern to MTM. On the other hand, MTM should get prepared to adapt to their evolution and penetration in our driving habits by providing more efficient algorithms as well as sources for trustful real time traffic data.

Table 5.14. SWOT analysis of NAVS

Strengths	**Weaknesses**
- Can contribute to the maximisation of network infrastructure utilisation	- Employed routing algorithms ignore their own impact on traffic, thus may lead to severe congestion problems, if massive use and high penetration rates prevail
Opportunities	**Threats**
- Continuous research on practical and efficient routing algorithms - Alternative use of PNDs	- User acceptance in terms of purchase intention - User trust - MTM delayed adaptation

Considering the functions that have been identified as being of concern from a MTM perspective (see Section 5.2), as well as the results of the above SWOT analyses, it seems that the most promising VACS are ACC, ISA, LCDAS, and NAVS. However, the analyses also indicated that benefits may be maximised should the functions of these VACS be undertaken cooperatively, and under the coordination of a MTM system that will be able to provide relevant advices and recommendations, or even impose if necessary, network-wide beneficial settings for their operation. The conservative and/or selfish and myopic use of VACS may not endanger their safety and comfort features, but may dramatically deteriorate the prevailing traffic flow efficiency and congestion levels (see grey sector in Figure 2.5), especially in cases of high market penetration rates and usage.

In order, however, to avoid the aforementioned conservative, selfish and myopic use of VACS, MTM should get prepared and adapt quickly to the evolution and penetration of VACS. To this end, modelling and simulation tools, and control concepts and techniques that will allow the study, analysis, design and application of more effective MTM strategies exploiting the mix of the current and evolving VACS capabilities are necessary, and it is the aim of TRAMAN21 project to contribute in this respect.

6. Current trends and future perspectives of motorway traffic related VACS

Motivated mainly from safety and environmental concerns, an enormous continuing interdisciplinary effort has been devoted by the automobile industry as well as by numerous research institutions around the world to plan, develop, test and start deploying a variety of VACS, which undertake different vehicle functions at varying levels of automation that, enhanced by communication features enabling varying levels of cooperation among vehicles and/or vehicles and the infrastructure, aim at assisting and easing the driving task.

VACS are expected to revolutionise the features and capabilities of individual vehicles within the next decades in favour of the safety and convenience of their users, i.e. the drivers. According to the review and analysis of the previous sections, FOTs of VACS, which mainly concern:

- technological aspects of VACS,
- safety effects,
- changes in driving behaviour,
- user acceptance, and
- environmental impacts

indicate that users tend to prefer less intervening systems, and use VACS in a way that resembles their personal driving style. User acceptance tends to increase after actually using the system in real traffic conditions, and safety and environmental considerations seem to be pretty well addressed by available and evolving VACS.

The review and analysis of the previous chapters indicate also that traffic flow implications of VACS are mainly studied via simulation investigations. The results of these investigations suggest that, beyond their safety, convenience and environmental features, some VACS have implications on traffic flow efficiency at varying levels. They also suggest that:

- the identified effects are not always positive,
- controversial conclusions sometimes emerge,
- no unified study approach is available,
- effects are still neither fully analysed nor fully understood.

Finally, they suggest that VACS contribution to the improvement of traffic efficiency may be enabled or enhanced by:

- the use of traffic-adaptive settings,
- the extension of their communication and cooperation capabilities,
- the increase of the market penetration rate, and
- the combination of different functions.

Last not least, since the reviewed simulation investigations of VACS indicate that they can affect traffic flow both positively and negatively, they may lead to a deterioration of the overall traffic conditions, if left unsupervised to serve their individual users' aims in a conservative, myopic and/or selfish for the collective traffic flow way. On the other hand, VACS may offer significant benefits, if deployed appropriately by traffic management, and if traffic management is allowed and prepared to "intervene" cooperatively at varying levels and different aspects of the driving task to influence the driving behaviour in favour of the global traffic conditions.

Where should we therefore go? The review and analysis presented herein indicates that we should go towards:

- VACS that:
  - provide traffic-adaptive functions; thus responding to the prevailing traffic conditions;
  - enable multiple functions; thus responding to multiple needs;
  - allow for V2V and V2I cooperation; thus achieving goals not achievable by autonomously operated systems.
- MTM systems capable to intervene, if and when necessary. It is in the human nature to dislike getting orders, but sometimes, it is also necessary to be prevented from acting at the expense of the overall benefit.
- Infrastructures capable to cooperate with VACS and support their operation for network-wide benefits. Individual actions that are coordinated and supported by a system with a wider perspective may lead to positive effects not only locally, but at a network-wide level.
- Modelling and simulation tools, and control concepts and techniques that will allow the study, analysis, design and application of more effective motorway traffic management strategies exploiting the mix of the current and evolving VACS capabilities.

The review and analysis presented herein also indicates that both VACS evolution and related R&D endeavours seem to follow this path. This is, however, only a small share of the whole venture, since other, equally significant VACS aspects that should also be considered and studied thoroughly include (Ehmanns and Spannheimer, 2004):

- *Pure technical aspects*, which concern communication protocols, data management, security, sensors and control systems of VACS, etc.
- *Societal aspects* of involved costs and general acceptance.
- *Political aspects*, which concern the removal of regulatory barriers to introducing new technologies.
- *Legal aspects*, which concern the liability of manufacturer, owner, driver and public authorities. The responsibility of all these stakeholders will be questioned depending upon the degree of driver assistance.

Last not least, *human-related aspects* concerning the human-machine interface (HMI), as well as the user acceptance and usability, and the degree of driver assistance acceptance and involved costs should be given considerable thought. For the real question is "*How much authority are we really willing and prepared to pay for and give to our automobiles?*" and the answer to this question will finally determine the path for all future developments.

References

Alam A (2011). Fuel-Efficient Distributed Control for Heavy Duty Vehicle Platooning. Licentiate Thesis in Automatic Control, KTH School of Electrical Engineering, Stockholm, Sweden. http://kth.diva-portal.org/smash/get/diva2:447050/FULLTEXT01 [accessed 09.04.2013]

Alam A, Gattami A, Johansson K (2010). An experimental study on the fuel reduction potential of heavy duty vehicle platooning. Proceedings of the 13th International IEEE Conference on Intelligent Transportation Systems (ITSC), Funchal 306-311.

Alkim T, Bootsma G, Looman P (2007). The Assisted Driver: Systems that support driving. Ministry of Transport, Public Works and Water Management, Rijkswaterstaat, The Netherlands. http://www.mobileye.com/wp-content/uploads/2011/09/DutchMinistryReport1.pdf [accessed 04.04.2013]

Arnaout G, Bowling S (2011). Towards reducing traffic congestion using cooperative adaptive cruise control on a freeway with a ramp. Journal of Industrial Engineering and Management 4(4), 699-717.

Arnaout GM, Bowling S (2013). A progressive deployment strategy for cooperative adaptive cruise control to improve traffic dynamics. International Journal of Automation and Computing. http://www.ijac.net/EN/article/downloadArticleFile.do?attachType=PDF&id=1397 [accessed 24.07.2013]

Bartels A, Meinecke M-M, Steinmeyer S (2012). Lane change assistance. In Eskandarian A (Ed), Handbook of Intelligent Vehicles, Springer-Verlag London Ltd., 729-757.

Batavia PH (1999). Driver-Adaptive Lane Departure Warning Systems. PhD Thesis. The Robotics Institute, Carnegie Mellon University, Pittsburgh, Pennsylvania, USA. http://www.cs.cmu.edu/afs/cs/user/parag/www/research/papers/thesis.pdf [accessed 02.04.2013]

Belzowski BM, Ekstrom A (2013). Stuck in Traffic: Analyzing Real Time Traffic Capabilities of Personal Navigation Devices and Traffic Phone Applications. University of Michigan Transportation Research Institute Study for TomTom Group.

Benmimoun M, Pütz A, Aust ML, Faber F, Sánchez D, Metz B, Saint Pierre G, Geißler T, Guidotti L, Malta L (2012). Final Evaluation Results. Deliverable D6.1 of the euroFOT ICT for Cooperative Systems European Project. http://www.eurofot-ip.eu/download/library/deliverables/eurofotsp620121207v11dld61_final_evaluation_results.pdf [accessed 03.04.2013]

Benmimoun M, Pütz A, Zlocki A, Eckstein L (2013). Impact assessment of adaptive cruise control (ACC) and forward collision warning (FCW) within a field operational test in Europe. Annual Meeting of the Transportation Research Board, Washington DC, USA.

Benz T, Christen F, Lerner G, Schulze M, Vollmer D (2003). Traffic Effects of Driver Assistance Systems - The Approach within INVENT. http://orbi.ulg.ac.be/bitstream/2268/102893/1/ITS%20Paper%20VRA%20V2.pdf [accessed 18.04.2013]

Bergenheim C, Shladover S, Coelingh E (2012a). Overview of platooning systems. Proceedings of the 19th ITS World Congress, Vienna, Austria. http://publications.lib.chalmers.se/records/fulltext/174621/local_174621.pdf [accessed 10.01.2014]

Bergenhem C, Hedin E, Skarin D (2012b). Vehicle-to-Vehicle communication for a platooning system. Procedia - Social and Behavioral Sciences 48, 1222-1233.

Biding T, Lind G (2002). Intelligent Speed Adaptation (ISA), Results of large-scale trials in Borlänge, Lidköping, Lund and Umeå during the period 1999-2002. Publication 2002:89 E, Swedish National Road Administration. http://publikationswebbutik.vv.se/upload/2636/2002_89_E_Intelligent_speed_adaption.pdf [accessed 02.04.2013]

Bishop R (2005). Intelligent Vehicle Technology and Trends. Artech House Inc, Norwood, USA. http://203.158.253.140/media/e-Book/Engineer/Automotive/Intelligent%20Vehicle%20Technology%20and%20Trends.pdf [accessed 18.04.2013]

Blum JJ, Eskandarian A, Arhin SA (2012). Intelligent Speed Adaptation (ISA). In Eskandarian A (Ed), Handbook of Intelligent Vehicles, Springer-Verlag London, 581-602.

Bonnet C (2003). The platooning application, CHAUFFEUR Final Presentation. International Workshop on Vehicle Safety Communications (ARIB), Tokyo, Japan. http://www.itsforum.gr.jp/Public/E4Meetings/P01/fremont5_2_2.pdf [accessed 10.01.2014]

Boriboonsomsin K, Servin O, Barth M (2008). Selection of control speeds in dynamic intelligent speed adaptation system: A preliminary analysis. UCTC Research-Faculty papers, Summer 848, University of California Transportation Center (UCTC), USA. http://www.uctc.net/papers/848.pdf [accessed 12.08.2013]

Bose A, Ioannou P (1999). Analysis of traffic flow with mixed manual and semiautomated vehicles. California PATH Research Report UCB-ITS-PRR-99-14. California PATH Program, University of California, State of California Business, Transportation, and Housing Agency, Department of Transportation and United States Department of Transportation, Federal Highway Administration. http://www.path.berkeley.edu/PATH/Publications/PDF/PRR/99/PRR-99-14.pdf [accessed 27.04.2013]

Bose A, Ioannou P (2001). Analysis of Traffic Flow With Mixed Manual and Intelligent Cruise Control Vehicles: Theory and Experiments. California PATH Research Report UCB-ITS-PRR-2001-13. California PATH Program, University of California, State of California Business, Transportation, and Housing Agency, Department of Transportation and United States Department of Transportation, Federal Highway Administration. http://escholarship.org/uc/item/2tw8q0h8.pdf [accessed 27.04.2013]

Bose A, Ioannou P (2003). Analysis of traffic flow with mixed manual and semiautomated vehicles. IEEE Transactions on Intelligent Transportation Systems 4(4), 173-188.

Brännström M (2013). Commercial Viability, Deliverable 5.1. SAfe Road TRains for the Environment project. http://www.sartre-project.eu/en/publications/Documents/SARTRE_5_001_PU.pdf [accessed 10.01.2014]

Burton D, Delaney A, Newstead S, Logan D, Fildes B (2004). Effectiveness of ABS and Vehicle Stability Control Systems. Research Report No 04/01 of Royal Automobile Club of Victoria (RACV) Ltd, Australia. http://www.monash.edu.au/miri/research/reports/other/racv-abs-braking-system-effectiveness.pdf [accessed 02.04.2013]

Buscema D, Ignaccolo M, Inturri G, Pluchino A, Rapisarda A, Santoro C, Tudisco S (2009). The impact of real time information on transport network routing through intelligent agent-based simulation. Proceedings of the 2009 IEEE Toronto International Conference on Science and Technology for Humanity (TIC-STH), Toronto, ON, 72-77.

Carlson RC, Papamichail I, Papageorgiou M (2011). Local feedback-based mainstream traffic flow control on motorways using variable speed limits. IEEE Transactions on Intelligent Transportation Systems 12, 1261-1276.

Carsten OMJ, Tate FN (2000). External Vehicle Speed Control, Final Report: Integration. Deliverable 17, External Vehicle Speed Control Project, Report prepared by the Institute of Transport Studies for the Vehicle Standards and Engineering Division of the Department of the Environment, Transport and the Regions, UK. http://www.righttoride.eu/virtuallibrary/warningcontrolsystems/del17.pdf [accessed 12.08.2013]

Carsten OMJ, Tate FN (2005). Intelligent speed adaptation: accident savings and cost-benefit analysis. Accident Analysis & Prevention 37(3), 407-416.

Davila A (2013). Report on Fuel Consumption. Deliverable 4.3. SAfe Road TRains for the Environment project. http://www.sartre-project.eu/en/publications/Documents/SARTRE_4_003_PU.pdf [accessed 10.01.2014]

Davis LC (2004). Effect of adaptive cruise control systems on traffic flow. Physical Review E 69(6), 066110.

Davis LC (2006). Effect of cooperative merging on the synchronous flow phase of traffic. Physica A: Statistical Mechanics and its Applications 361(2), 606-618.

Davis LC (2007). Effect of adaptive cruise control systems on mixed traffic flow near an on-ramp. Physica A: Statistical Mechanics and its Applications 379(1), 274-290.

Delling D, Sanders P, Schultes D, Wagner D (2009). Engineering route planning algorithms. In Lerner J, Wagner D, Zweig KA (Eds) Algorithmics of Large and Complex Networks (Lecture Notes in Computer Science Vol. 5515), Springer, 117-139.

Delling D, Wagner D (2009). Time-dependent route planning. In Ahuja RK, Möhring RH, Zaroliagis CD (Eds) Robust and online large-scale optimization (Lecture Notes in Computer Science Vol. 5868), 207-230.

Deram P (2004). Vehicle Based Detection of Inattentive Driving for Integration in an Adaptive Lane Departure Warning System - Distraction Detection. MSc Thesis IR-SB-EX-0414. Royal Institute of Technology, Department of Signals, Sensors & Systems, Signal Processing, Stockholm, Sweden. http://www.ee.kth.se/php/modules/publications/reports/2004/IR-SB-EX-0414.pdf [accessed 04.04.2013]

Dijkstra EW (1959). A note on two problems in connexion with graphs. Numerische Mathematik 1, 269-271.

Doecke S, Woolley JE (2010). Cost Benefit Analysis of Intelligent Speed Assist. Prepared by the Centre for Automotive Safety Research for the Department of Transport and Main Roads (QLD), Australia. http://s3.amazonaws.com/zanran_storage/www.tca.gov.au/ContentPages/2505989266.pdf [accessed 09.04.2013]

Eby DW, Kostyniuk LP (1999). An on-the-road comparison of in-vehicle navigation assistance systems. Human Factors: The Journal of the Human Factors and Ergonomics Society 41(2), 295-311.

Ehmanns D, Spannheimer H (2004). Roadmap. Deliverable D2D of ADASE (Advanced Driver Assistance Systems in Europe) European IST project. http://www.esafetysupport.org/download/working_groups/Implementation_Road_Maps/Related_documents/ADASE2Roadmap.pdf [accessed 18.04.2013]

Fagerberg K (2004). Vehicle-Based Detection of Inattentive Driving for Integration in an Adaptive Lane Departure Warning System - Drowsiness Detection. MSc Thesis IR-SB-EX-0413. Royal Institute of Technology, Department of Signals, Sensors & Systems, Signal Processing, Stockholm, Sweden. http://www.ee.kth.se/php/modules/publications/reports/2004/IR-SB-EX-0413.pdf [accessed 02.04.2013]

Fancher P, Ervin R, Sayer J, Hagan M, Bogard S, Bareket Z, Mefford M, Haugen J (1998). Intelligent Cruise Control Field Operational test, Final Report No. DOT HS 808 849 prepared by the University of Michigan Transportation Research Institute for the National Highway Traffic Safety Administration U.S. Department of Transportation. http://www.google.com/url?sa=t&rct=j&q=Intelligent+Cruise+Control+Field+Operational+test%2C+Final+Report&source=web&cd=1&cad=rja&ved=0CCkQFjAA&url=http%3A%2F%2Fwww.nhtsa.gov%2FDOT%2FNHTSA%2FNRD%2FMultimedia%2FPDFs%2FCrash%2520Avoidance%2F1998%2Ficc1998.pdf&ei=ZQrVUajBCsrmswabsYHYBA&usg=AFQjCNEEqMAfp8n4x7IU5CKPml9T1WRJqg&bvm=bv.48705608,d.Yms [accessed 03.07.2013]

Flinsenberg ICM (2004). Route Planning Algorithms for Car Navigation. PhD Thesis, Technische Universiteit Eindhoven, The Netherlands.

Fu L, Sun D, Rilett LR (2006). Heuristic shortest path algorithms for transportation applications: State of the art. Computers & Operations Research 33, 3324-3343.

General Motors Corporation (2005). Automotive Collision Avoidance System Field Operational Test (ACAS FOT) Final Program Report. Report No DOT HS 809 886 prepared for the Office of Impaired Driving and Occupant Protection, National Highway Traffic Safety Administration, U.S. Department of Transportation, Washington, USA. http://www.nhtsa.gov/DOT/NHTSA/NRD/Multimedia/PDFs/Crash%20Avoidance/2005/ACAS%20FOT%20Final%20Program%20Report%20DOT%20HS%20809%20886.pdf [accessed 02.04.2013]

Godbole DN, Hagenmeyer V, Sengupta R, Swaroop D (1997). Design of emergency manoeuvres for automated highway system: obstacle avoidance problem. Proceedings of the 36th IEEE Conference on Decision and Control.

Grover C, Knight I, Okoro F, Simmons I, Couper G, Massie P, Smith B (2008). Automated Emergency Brake Systems: Technical Requirements, Costs and Benefits. Published Project Report PPR 227 for DG Enterprise, European Commission. http://ec.europa.eu/enterprise/sectors/automotive/files/projects/report_aebs_en.pdf [accessed 03.04.20013]

Grumert E, Ma X, Tapani A (2013). Effects of a cooperative variable speed limit system on traffic performance and exhaust emissions. Annual Meeting of the Transportation Research Board, Washington DC, USA.

Habenicht S, Winner H, Bone S, Sasse F, Korzenietz P (2011). A maneuver-based lane change assistance system. 2011 IEEE Intelligent Vehicles Symposium (IV), 375-380. http://www.fzd.tu-darmstadt.de/media/fachgebiet_fzd/publikationen_3/2011_1/2011_Habenicht_Maneuverbased_Lane_Change_Assistance.pdf [accessed 07.11.2013]

Hallé S, Chaib-draa B (2005). A collaborative driving system based on multiagent modelling and simulations. Transportation Research Part C: Emerging Technologies 13(4), 320-345.

Hart PE, Nilsson NJ, Raphael B (1968). A formal basis for the heuristic determination of minimum cost paths. IEEE Transactions of Systems Science and Cybernetics 4, 100-107.

Hedrick J, Chen Y, Mahal S (2001). Optimized Vehicle Control/Communication Interaction in an Automated Highway System. California PATH Research Report UCB-ITS-PRR-2001-29, University of California at Berkeley, USA. http://www.path.berkeley.edu/PATH/Publications/PDF/PRR/2001/PRR-2001-29.pdf [accessed 10.01.2014]

Hegeman G (2002). Green light for ISA? The effect of intelligent speed adaptation on the traffic flow. ICTCT (International Co-operation on Theories and Concepts in Traffic Safety) Workshop on intelligent speed adaptation, Nagoya, Japan. http://www.ictct.org/workshop.php?workshop_nr=16 [accessed 02.04.2013]

Hoeger R, Zeng H, Hoess A, Kranz Th, Boverie S, Strauss M, Jakobsson E, Beutner A, Bartels A, To T-B, Stratil H, Fürstenberg K, Ahlers F, Frey E, Schieben A, Mosebach H, Flemisch F, Dufaux A, Manetti D, Amditis A, Mantzouranis I, Lepke H, Szalay Z, Szabo B, Luithardt P, Gutknecht M, Schoemig N, Kaussner A, Nashashibi F, Resende P, Vanholme B, Glaser S, Allemann P, Seglö F, Nilsson A (2011). The Future of Driving – Final Report. Deliverable D61.1 of HAVEit ICT for intelligent vehicles and mobility services European Project. http://haveit-eu.org/LH2Uploads/ItemsContent/24/HAVEit_212154_D61.1_Final_Report_Published.pdf [accessed 03.04.2013]

Hogema J, Schuurman H, Tampère CMJ (2002). ISA effect assessment: From driving behavior to traffic flow. ICTCT (International Co-operation on Theories and Concepts in Traffic Safety) Workshop on intelligent speed adaptation, Nagoya, Japan. http://www.ictct.org/workshop.php?workshop_nr=16 [accessed 02.04.2013]

IEA (2013). CO_2 Emissions from Fuel Combustion: Highlights. International Energy Agency, Paris, France. http://www.iea.org/publications/freepublications/publication/CO2EmissionsFromFuelCombustionHighlights2013.pdf [accessed 06.10.2013]

iMobility Forum (2013). Roadmap Automation in Road Transport. Draft Version, April 2013.

Ioannou P, Wang Y, Chang H (2007). Integrated Roadway/Adaptive Cruise Control System: Safety, Performance, Environmental and Near Term Deployment Considerations. California PATH Research Report UCB-ITS-PRR-2007-8, California PATH Program, Institute of Transportation Studies, University of California, Berkeley. http://www.path.berkeley.edu/PATH/Publications/PDF/PRR/2007/PRR-2007-08.pdf [accessed 12.07.2013]

Ioannou PA, Zhang J (2005). Roadway/vehicle integrated transportation system. Workshop on Modeling and Control of Complex Systems, Ayia Napa, Cyprus, June 30 - July 1. http://seacorn.cs.ucy.ac.cy/pub/bscw.cgi/d39710-1/*/MCCS%20Ioannou.pdf [accessed 30.07.2013]

Jahn O, Möhring RH, Schulz AS, Stier-Moses NE (2005). System-optimal routing of traffic flows with user constraints in networks with congestion. Operations Research 53(4), 600-616.

Jiang R, Wu Q-S (2006). The adaptive cruise control vehicles in the cellular automata model. Physics Letters A 359(2), 99-102.

Jula H, Kosmatopoulos EB, Ioannou PA (1999). Collision avoidance analysis for lane changing and merging. California PATH Research Report UCB-ITS-PRR-99-13, California PATH Program, Institute of Transportation Studies, University of California, Berkeley. http://www.path.berkeley.edu/PATH/Publications/PDF/PRR/99/PRR-99-13.pdf [accessed 14.11.2013]

Jula H, Kosmatopoulos EB, Ioannou PA (2000). Collision avoidance analysis for lane changing and merging. IEEE Transactions on Vehicular Technology, 49(6), 2295-2308.

Kaparias I, Bell MGH (2009). Testing a reliable in-vehicle navigation algorithm in the field. IET Intelligent Transport Systems 3(3), 314-324.

Kaparias I, Bell MGH (2010). A reliability-based dynamic re-routing algorithm for in-vehicle navigation. Proceedings of the 13th International IEEE Annual Conference on Intelligent Transportation Systems, Madeira Island, Portugal, 974-979.

Kaparias I, Bell MGH, Chen Y, Bogenberger, K (2007). ICNavS: a tool for reliable dynamic route guidance. IET Intelligent Transport Systems 1(4), 225-233.

Kavathekar P (2012). Cognitive Vehicle Platooning in the ERA of Automated Electric Transportation. MSc Thesis in Electrical Engineering, Utah State University, USA. http://digitalcommons.usu.edu/cgi/viewcontent.cgi?article=2396&context=etd [accessed 09.04.2013]

Kessler C, Etemad A, Alessandretti G, Heinig K, Chalmers S, Brouwer R, Cserpinszky A, Hagleitner W, Benmimoun M (2012). Final Report. Deliverable D11.3 of the euroFOT ICT for Cooperative Systems European Project. http://www.eurofot-ip.eu/download/library/deliverables/eurofotsp120121212v11dld113_final_report.pdf [accessed 03.04.2013]

Kesting A, Treiber M, Helbing D (2010). Enhanced intelligent driver model to access the impact of driving strategies on traffic capacity. Philosophical Transactions of the Royal Society A 368, 4585-4605.

Kesting A, Treiber M, Schönhof M, Helbing D (2007a). Extending adaptive cruise control to adaptive driving strategies. Transportation Research Record: Journal of the Transportation Research Board 2000, 16-24.

Kesting A, Treiber M, Schönhof M, Helbing D (2008). Adaptive cruise control design for active congestion avoidance. Transportation Research Part C: Emerging Technologies 16(6), 668-683.

Kesting A, Treiber M, Schonhof M, Kranke F, Helbing D (2007b). Jam-avoiding adaptive cruise control (ACC) and its impact on traffic dynamics. In Traffic and Granular Flow 2005, Springer, 633-643.

Kianfar R (2013). On Control Strategy and Safety Verification of Automated Vehicles. Thesis for the Degree of Licentiate of Engineering, Department of Signals and Systems, Chalmers University of Technology, Göteborg, Sweden. http://publications.lib.chalmers.se/records/fulltext/173698/173698.pdf [accessed 09.04.2013]

Knake-Langhorst S, Löper C, Schebitz N, Köster F (2013). Merge and exit support for the driver. ATZ worldwide 115(4), 82-87.

Laugier Ch, Sekhavat S,Large F, Hermosillo J, Shiller Z (2001). Some steps towards autonomous cars. Proceedings of the 4th IFAC Symposium on Intelligent Autonomous Vehicles, Sapporo Japan IFAC Symposium on Intelligent Autonomous Vehicles. http://www.ariel.ac.il/sites/shiller/papers/iav-01.pdf [accessed 02.04.2013]

Lavien T, Oron-Gilad T, Meyer J (2011). Aesthetics and usability of in-vehicle navigation displays. International Journal of Human-Computer Studies 69, 80-99.

Le L, Festag A, Baldessari R, Zhang W (2009). V2X communication and intersection safety: Smart systems for safety, sustainability, and comfort. In Meyer G, Valldorf J, Gessner W (Eds), Advanced Microsystems for Automotive Applications 2009, VDI-Buch 2009, 97-107.

Lee GD, Kim SW (2002). A longitudinal control system for a platoon of vehicles using a fuzzy-sliding mode algorithm. Mechatronics 12(1), 97-118.

Lee J, Forlizzi J, Hudson SE (2008). Iterative design of MOVE: A situationnally appropriate vehicle navigation system. International Journal of Human-Computer Studies 66, 198-215.

Lee J, Yang J (2012). A fast and scalable re-routing algorithm based on shortest path and genetic algorithms. International Journal of Computers Communications & Control 7(3), 482-493.

Li PY, Shrivastava A (2002). Traffic flow stability induced by constant time headway policy for adaptive cruise control vehicles. Transportation Research Part C: Emerging Technologies 10(4), 275-301.

Liu R, Tate J (2004). Network effects of intelligent speed adaptation systems. Transportation 31(3), 297-325.

Ma R, Kaber DB (2007). Effects of in-vehicle navigation assistance and performance on driver trust and vehicle control. International Journal of Industrial Ergonomics 37, 665-673.

Maihöfer C, Brenzel C, Coletti L, Provera M, Nelisse M, Verburg D, Schulz WH, Tian J, Burmeister H (2004). Final Report 01.08.2001 – 31.07.2004. Deliverable D15 of CarTALK IST European Project. http://digitalcommons.calpoly.edu/cgi/viewcontent.cgi?article=1066&context=csse_fac [accessed 21.04.2013]

Marchau V, van Nes N, Walta L, Morsink P (2010). Enhancing speed management by in-car speed assistance systems. IET Intelligent Transportation Systems 4(1), 3-11.

Marsden G, Lyons G, Beecroft M, Chatterjee K (2002). Transport Visions - Vehicles and Infrastructure. Fourth Report of the Transport Visions Network, Transportation Research Group, University of Southampton, UK. http://www.trg.soton.ac.uk/TVNetwork/TVN/reports/report4.pdf [accessed 02.04.2013]

May A, Ross T, Osman Z (2005).The design of next generation in-vehicle navigation systems for the older driver. Interacting with Computers 17, 643-659.

McNally MG, Marca JE, Rindt CR, Koos AM (2003). TRACER: In-vehicle, GPS-based, Wireless Technology for Traffic Surveillance and Management. California PATH Research Report UCB-ITS-PRR-2003-23, California Partners for Advanced Transit and Highways. http://escholarship.org/uc/item/5sp425vb [accessed 13.11.2013]

Michael JB, Godbole DN, Lygeros J, Sengupta R (1998). Capacity analysis of traffic flow over a single-lane Automated Highway System (AHS). ITS Journal - Intelligent Transportation Systems Journal: Technology, Planning, and Operations 4(1-2), 119-122.

Milanés V, Alonso L, Villagrá J, Godoy J, de Pedro T, Oria JP (2012). Traffic jam driving with NMV avoidance. Mechanical Systems and Signal Processing 31, 332-344.

Minderhoud MM (1999). Supported Driving: Impacts on Motorway Traffic Flow. PHD Thesis, TRAIL Thesis Series T99/4, The Netherlands TRAIL Research School, Delft University Press, The Netherlands. http://repository.tudelft.nl/assets/uuid:2c3220ef-d60c-4a2a-8f05-89b09ab5b57b/ceg_minderhoud_19990907.PDF [accessed 02.04.2013]

Nagaki K (2012). Evolution of in-car navigation systems. In Eskandarian A (Ed), Handbook of Intelligent Vehicles, Springer-Verlag London Ltd., 463-487.

Pang GKH, Takahashi K, Yokota T, Takenaga H (2002). Intelligent route selection for in-vehicle navigation systems, Transportation Planning and Technology 25(3), 175-213.

Papageorgiou M, Ben-Akiva M, Bottom J, Bovy PHL, Hoogendoorn SP, Hounsell NB, Kotsialos A, McDonald M (2007). ITS and traffic management. In Barnhart C, Laporte G (Eds) Transportation (Handbooks in Operations Research and Management Science Vol. 14). North-Holland, Elsevier, 715-774.

Papageorgiou M, Diakaki C, Dinopoulou V, Kotsialos A, Wang Y (2003). Review of road traffic control strategies. Proceedings of the IEEE 91, 2043-2067.

Papageorgiou M, Haj-Salem H, Middelham F (1997). ALINEA local ramp metering: Summary of field results. Transportation Research Record 1603, 90-98.

Papageorgiou M, Kotsialos A (2002). Freeway ramp metering: An overview. IEEE Transactions on Intelligent Transportation Systems 3, 271-281.

Papageorgiou M, Papamichail I (2007). Handbook of Ramp Metering. Deliverable 7.5, Report of the Information Society Project EURAMP (IST-2002-23110), IST Office, Brussels, Belgium.

Papageorgiou M, Papamichail I, Spiliopoulou AD, Lentzakis AF (2008). Real-time merging traffic control with applications to toll plaza and work zone management. Transportation Research C 16, 535-553

PATH (1997). Vehicle Platooning and Automated Highways. PATH Factsheet of California PATH-Partners for Advanced Transit and Highways, USA. http://www.path.berkeley.edu/PATH/Publications/Media/FactSheet/VPlatooning.pdf [accessed 02.04.2013]

Popescu-Zeletin R, Radusch I, Rigani MA (2010). Vehicular-2-X Communication: State-of-the-Art and Research in Mobile Vehicular Ad hoc Networks. Springer-Verlag Berlin Heidelberg.

PROMOTE-CHAUFFEUR Consortium (1996). User, Safety, and Operational Requirements. Deliverable D03.1.1, Version 2.0 of CHAUFFEUR Transport Telematics Project Number TR1009. ftp://ftp.cordis.europa.eu/pub/telematics/docs/tap_transport/chauffeur_d3.1.1.pdf [accessed 31.01.2014]

Pueboobpaphan R, van Arem B (2010). Driver and vehicle characteristics and platoon and traffic flow stability - Understanding the relationship for design and assessment of cooperative adaptive cruise control. Transportation Research Record: Journal of the Transportation Research Board 2189, 89-97.

Rajamani R (2006). Vehicle Dynamics and Control. Springer.

Rajamani R, Levinson D, Michalopoulos P, Wang J, Santhanakrishnan K, Zou X (2005). Adaptive Cruise Control System Design and its Impact on Traffic Flow. Report No CTS 05-01 prepared for the Intelligent Transportation Systems Institute, Center for Transportation Studies, University of Minnesota. http://nexus.umn.edu/Projects/ACC/CTS-05-01.pdf [accessed 27.04.2013]

Regan MA, Triggs TJ, Young KL, Tomasevic N, Mitsopoulos E, Staphan K, Tingvall C (2006). On-Road Evaluation of Intelligent Speed Adaptation, Following Distance Warning and Seatbelt Reminder Systems: Final Results of the TAC SafeCar Project. Report No 253 for the Victorian Transport Accident Commission (TAC) and the Ford Motor Company of Australia, Monash University Accident Research Centre, Australia. http://www.monash.edu.au/miri/research/reports/muarc253.pdf [Volume 1; accessed 03.04.2013] http://www.monash.edu.au/miri/research/reports/muarc253app.pdf [Volume 2: Appendices; accessed 03.04.2013]

Roessler B, Fuerstenberg K (2009). Cooperative intersection safety – The EU project INTERSAFE-2. In Meyer G, Valldorf J, Gessner W (Eds), Advanced Microsystems for Automotive Applications 2009, VDI-Buch 2009, 77-86.

SARTRE (2013). Project Final Report. SAfe Road TRains for the Environment project. http://www.sartre-project.eu/en/publications/Documents/SARTRE_Final-Report.pdf [accessed 10.01.2014]

Schultes D (2008). Route Planning in Road Networks. PhD Thesis, Fakultät für Informatik der Universität Fridericiana zu Karlsruhe (TH), Germany.

Sengupta R, Rezaei S, Shladover SE, Cody D, Dickey S, Krishnan H (2007). Cooperative collision warning systems: Concept definition and experimental implementation. Journal of Intelligent Transportation Systems: Technology, Planning, and Operations 11(3), 143-155.

Shladover SE (2012a). Recent International Activity in Cooperative Vehicle - Highway Automation Systems. Report No. FHWA-HRT-12-033 of the Office of Corporate Research, Technology, and

Innovation Management, Federal Highway Administration, USA. http://www.fhwa.dot.gov/advancedresearch/pubs/12033/12033.pdf [accessed 03.04.2013]

Shladover SE (2012b). Literature Review on Recent International Activity in Cooperative Vehicle-Highway Automation Systems. Report no. FHWA-HRT-13-025 prepared for the Office of Corporate Research, Technology, and Innovation Management, Federal Highway Administration, USA. http://www.fhwa.dot.gov/advancedresearch/pubs/13025/13025.pdf [accessed 02.04.2013]

Shladover SE, Lu X-Y, Cody D, Nowakowski C, Qiu Z, Chow A, O'Connell J, Nienhuis J, Su D (2010). Development and Evaluation of Selected Mobility Applications for VII. California PATH Research Report UCB-ITS-PRR-2010-25. http://www.path.berkeley.edu/PATH/Publications/PDF/PRR/2010/PRR-2010-25.pdf [accessed 12.04.2013]

Shladover SE, Lu X-Y, Nowakowski C, Su D (2011). Development and Evaluation of Selected Mobility Applications for VII. Report No CA11-2138 prepared for the California Department of Transportation, Division of Research and Innovation, Sacramento, USA. http://www.dot.ca.gov/newtech/researchreports/reports/2011/task_2138-tsm.pdf [accessed 12.04.2013]

SINTEF, TRG, STRATEC (2004). STARDUST: Evaluation of Scenarios to Deployment of ADAS/AVG Systems in Urban Contexts. Deliverable 10 of the STARDUST (Contract Number: EVK4-CT-2000-00024) FP5 project. http://trg1.civil.soton.ac.uk/stardust/d10.pdf [accessed 20.09.2013]

Skog I, Händel P (2012). State-of-the-Art In-Car Navigation: An overview. In Eskandarian A (Ed), Handbook of Intelligent Vehicles, Springer-Verlag London Ltd., 435-462.

Smith DL, Glassco R, Chang J, Cohen D (2003). Feasibility of modelling lane-change performance. NHTSA paper 2003-01-0280, Washington DC, USA. http://nhthqnlas187.nhtsa.dot.gov/DOT/NHTSA/NRD/Multimedia/PDFs/Crash%20Avoidance/2003/SAE2003-01-0280.pdf [accessed 14.11.2013]

Suppachai H, Silawatchananai C, Parnichkun M, Wuthishuwong C (2009). Double loop controller design for the vehicle's heading control. Proceedings of the IEEE International Conference on Robotics and Biomimetics (ROBIO), 989-994.

Swaroop D, Rajagopal KR (1998). Intelligent Cruise Control Systems and Traffic Flow Stability. California PATH Research Report UCB-ITS-PRR-98-36. California PATH Program, University of California, State of California Business, Transportation, and Housing Agency, Department of Transportation and United States Department of Transportation, Federal Highway Administration. http://www.path.berkeley.edu/PATH/Publications/PDF/PRR/98/PRR-98-36.pdf [accessed 27.04.2013]

SWOV (2010). Intelligent Speed Assistance (ISA). SWOV Fact sheet, Institute of Road Safety Research, Leidschendam, The Netherlands. http://www.swov.nl/rapport/Factsheets/UK/FS_ISA_UK.pdf [accessed 09.04.2013]

Tampère CMJ, Hogema JH, van Katwijk RT, van Arem B (1999). Exploration of the impact of Intelligent Speed Adaptation and Co-operative Following and Merging on Highways using MIXIC. TNO-report Inro/NK2003 prepared for the Transport Research Centre (AVV) of the Dutch Ministry of Transport, Public Works and Water Management, The Netherlands. http://www.utwente.nl/ctw/aida/research/publications/tampere_et_al.pdf [accessed 09.04.2013]

Tapani A (2012): Vehicle trajectory effects of Adaptive Cruise Control. Journal of Intelligent Transportation Systems: Technology, Planning, and Operations 16(1), 36-44.

Tideman M, van der Voort MC, van Arem B, Tillema F (2007). A Review of lateral driver support systems. Proceedings of the 2007 IEEE Intelligent Transportation Systems Conference, Seattle, WA, USA, 992-999. http://doc.utwente.nl/60592/1/Tideman07review.pdf [accessed 07.11.2013]

Tientrakool P, Ho Y-C, Maxemchuk N (2011). Highway capacity benefits from using vehicle-to-vehicle communication and sensors for collision avoidance. Proceedings of the IEEE Vehicular Technology Conference (VTC Fall), San Francisco, CA, 1-5.

Tomar RS, Verma S (2012). Safety of lane change maneuver through a priori prediction of trajectory using neural networks. Network Protocols and Algorithms 4(1), 4-21.

TRB (2000). Highway Capacity Manual 2000. Transportation Research Board, National Research Council, Washington, D.C., USA. http://sjnavarro.files.wordpress.com/2008/08/highway_capacital_manual.pdf [accessed 14.08.2013]

Treiber M, Kesting A (2013). Traffic Flow Dynamics: Data, Models and Simulation. Springer-Verlag Berlin Heidelberg.

Tsugawa S (2014). An automated truck platoon within the Energy ITS Project. Featured Article, IEEE ITS Society Newsletter 16(1), 11-14. http://sites.ieee.org/itss/files/2014/01/v16n1January2014.pdf [accessed 20.01.2014]

University of Michigan and General Motors Corporation (2005a). Automotive Collision Avoidance System Field Operational Test Report: Methodology and Results. Report No DOT HS 809 900 prepared for the National Highway Traffic Safety Administration U.S. Department of Transportation, Washington, USA. http://deepblue.lib.umich.edu/bitstream/handle/2027.42/49539/99798.pdf?sequence=1 [accessed 04.04.2013]

University of Michigan and General Motors Corporation (2005b). Automotive Collision Avoidance System Field Operational Test Methodology and Results Appendices. Report No DOT HS 809 901 prepared for the National Highway Traffic Safety Administration, U.S. Department of Transportation, Washington, USA. http://www.nhtsa.gov/DOT/NHTSA/NRD/Multimedia/PDFs/Crash%20Avoidance/2005/809901All.pdf [accessed 02.04.2013]

van Arem B, Driever H, Feenstra Ph, Ploeg J, Klunder G, Wilmink I, Zoutendijk A, Papp Z, Netten B (2007). Design and Evaluation of an Integrated Full-Range Speed Assistant. TNO report 2007-D-R0280/B, Delft, The Netherlands. http://rijkswaterstaat.nl/rws/corporate/Wegen%20naar%20de%20toekomst/rijassistent%20-%20design%20and%20evaluation%20of%20an%20integrated%20full%20range%20speed%20assistant.pdf [accessed 05.11.2013]

van Arem B, van Driel CJG, Visser R (2006). The Impact of Cooperative Adaptive Cruise Control on Traffic-Flow Characteristics. IEEE Transactions on Intelligent Transportation Systems 7(4), 429-436.

van Driel CJG (2007). Driver Support in Congestion: An Assessment of User Needs and Impacts on Driver and Traffic Flow. CTIT Ph.D. thesis Series No. 07-106, TRAIL Thesis Series T2007/10, The Netherlands TRAIL Research School. http://doc.utwente.nl/58037/1/thesis_van_Driel.pdf [accessed 03.04.2013]

van Driel CJG, van Arem B (2008). Traffic flow impacts of a congestion assistant. Annual Meeting of the Transporation Research Board, Washington DC, USA. http://www.utwente.nl/ctw/aida/research/publications/CvD-TRB08.pdf [accessed 04.04.2013] van Driel CJG, van Arem B (2010). The impact of a congestion assistant on traffic flow efficiency and safety in congested traffic caused by a lane drop. Journal of Intelligent Transportation Systems: Technology, Planning, and Operations 14(4), 197-208.

van Schijndel-de Nooij M, Krosse B, van den Broek T, Maas S, van Nunen E, Zwijnenberg H, Schieben A, Mosebach H, Ford N, McDonald M, Jeffery D, Piao J, Sanchez J (2011). Definition of Necessary Vehicle and Infrastructure Systems for Automated Driving. Final Study Report prepared by the SMART 2010/0064 project for: European Commission DG Information Society and Media. http://ec.europa.eu/information_society/activities/esafety/doc/studies/automated/reportfinal.pdf [accessed 09.04.2013]

VanderWerf J, Shladover S, Kourjanskaia N, Miller M, Krishnan H (2001). Modeling effects of driver control assistance systems on traffic. Transportation Research Record 1748, Paper No. 01-3475, 167-174.

VanderWerf J, Shladover S, Miller M A, Kourjanskaia N (2002). Effects of adaptive cruise control systems on highway traffic flow capacity. Transportation Research Record 1800, Paper No. 02-3665, 78-84.

Varhelyi A, Makinen T (2001). The effects of in-car speed limiters: Field studies. Transportation Research C 9(3), 191-211.

Visser R (2005). Co-operative Driving on Highways - An Assessment of the Impact of the Advanced Driver Assistance System 'Co-operative Adaptive Cruise Control' on Traffic Flow Using Microscopic Traffic Simulation. MSc Thesis, University of Twente, The Netherlands. http://www.utwente.nl/ctw/aida/education/Rapport_RV.pdf [accessed 02.04.2013]

Visvikis C, Smith TL, Pitcher M, Smith R (2008). Study on lane departure warning and lane change assistant systems. Project Report PRR 374, Transport Research Laboratory. http://ec.europa.eu/enterprise/sectors/automotive/files/projects/report_ldwlca_en.pdf [accessed 07.11.2013]

Viti F, Hoogendoorn SP, Alkim TP, Bootsma G (2008). Driving behavior adaptation under ACC: results from a large Field Operational Test in the Netherlands. Preprints of the Intelligent Vehicle Symposium, Eindhoven, The Netherlands, 745-750. https://www.mech.kuleuven.be/cib/verkeer/dwn/pub/PC2008E.pdf [accessed 09.04.2013]

Vlassenroot S, Marchau V, De Mol1 J, Brookhuis K, Witlox F (2011a). Potential for in-car speed assistance systems: results of a large-scale survey in Belgium and the Netherlands. IET Intelligent Transportation Systems 5(1), 80-89.

Vlassenroot S, van der Plas J-W, Brookhuis K, De Mol J, Marchau V, Witlox F (2011b). Easy going - Multilevel assessment of ISA. In Bekiaris E, Wiethoff M, Gaitanidou E (Eds) Infrastructure and Safety in a Collaborative World. Road Traffic Safety. Berlin-Heidelberg-New York, Springer Verlag, 215-232.

von Arnim A, Arief B, Fusée A (2008). Cooperative Road Sign and Traffic Light Using Near Infrared Identification and Zigbee Smartdust Technologies. Technical Report Series No. CS-TR-1082, Computing Science, Newcastle University. http://eprint.ncl.ac.uk/fulltext.aspx?url=161041%2f0A0EF11F-AFA8-4D30-84A2-2E054E07707C.pdf&pub_id=161041&ts=635113655591926587 [accessed 02.07.2013]

Wan L, Raksincharoensak P, Maeda K, Nagai M (2011). Lane change behaviour modelling for autonomous vehicles based on surroundings recognition. International Journal of Automotive Engineering 2, 7-12.

WHO (2013). Global Status Report on Road Safety 2013: Supporting a Decade of Action. World Health Organization, Geneva, Switzerland. http://www.who.int/violence_injury_prevention/road_safety_status/2013/en/ [accessed 06.10.2013]

Wilmink I, Klunder G, van Arem B (2006). The impact of integrated full-range speed assistance on traffic flow. Proceedings of the 13th ITS World Congress, London, UK. ftp://218.22.27.69/%E6%99%BA%E8%83%BD%E4%BA%A4%E9%80%9A%E5%A4%A7%E4%BC%9A%E8%B5%84%E6%96%99/13%E5%B1%8AITS%E4%B8%96%E7%95%8C%E5%A4%A7%E4%BC%9A/papers/1372.doc [accessed 04.04.2013]

Xiao L, Gao F (2010). A comprehensive review of the development of adaptive cruise control systems. Vehicle System Dynamics: International Journal of Vehicle Mechanics and Mobility, 48(10), 1167-1192.

Yi J, Horowitz R (2006). Macroscopic traffic flow propagation stability for adaptive cruise controlled vehicles. Transportation Research Part C: Emerging Technologies 14(2), 81-95.

Yuan Y-M, Jiang R, Hu M-B, Wu Q-S, Wang R (2009). Traffic flow characteristics in a mixed traffic system consisting of ACC vehicles and manual vehicles: A hybrid modelling approach. Physica A: Statistical Mechanics and its Applications 388(12), 2483-2491.

Zhang J, Ioannou P (2004). Integrated Roadway / Adaptive Cruise Control System: Safety, Performance, Environmental and Near Term Deployment Considerations. California PATH Research Report UCB-ITS-PRR-2004-32, California PATH Program, Institute of Transportation Studies, University of California, Berkeley. http://www.escholarship.org/uc/item/4749164x [accessed 12.07.2013]

Zwaneveld P J, van Arem B (1997). Traffic Effects of Automated Vehicle Guidance System. A Literature Survey. TNO Report INRO-VVG 1997-17 Delft, The Netherlands. http://www.utwente.nl/ctw/aida/research/publications/zwaneveld_arem.pdf [accessed 27.04.2013]