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

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Highlights

- Vehicle Automation and Communication Systems (VACS) are reviewed.
- A VACS taxonomy is proposed from a motorway traffic management perspective.
- VACS are classified regarding enabled/foreseen functions and level of autonomy.
- VACS are analysed regarding relevance for future motorway traffic management.
- VACS-related future challenges are outlined and discussed.

Abstract

During the last decade, there has been an enormous interdisciplinary effort by the automobile industry and numerous research institutions worldwide towards the development, testing and employment of a variety of Vehicle Automation and Communication Systems (VACS) with the main aims to improve road safety and driver convenience. Some VACS, however, have a direct impact on road efficiency as well and could therefore be exploited to relieve road networks from the significant congestion problems and their negative consequences for travel times, safety, fuel consumption, the environment and the quality of life in general. In other words, some of the available VACS could also be used as novel or innovative sensors, actuators and tools towards a new era of traffic management. This paper provides an overview of proposed and available VACS and discusses their perspectives from the motorway traffic management point of view. Classifications of the different systems in this respect are also provided, while SWOT (Strengths-Weaknesses-Opportunities-Threats) analyses are used to identify specific exploitation ways. Current trends and future perspectives of VACS within a motorway traffic management context are finally summarised.

Keywords: Vehicle automation and communication systems; motorway traffic management; SWOT analysis

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 in the next decades. 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, improving and easing the driving task. They are typically developed to benefit the individual vehicle, without a clear view or complete 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 (often neglected) necessity and continuously growing opportunities for accordingly adapted or utterly new traffic management actions and strategies.

This paper presents the results of a study aiming at addressing existing or envisaged VACS options, assess their relevance for motorway traffic management (MTM), and develop, for a most relevant subset of VACS, appropriate exploitation possibilities towards a more efficient motorway traffic flow. The study has been based on an extensive review of proposed, available or evolving VACS carried out by Diakaki et al. (2014)**.**

The paper is organised in five more sections. Section 2 discusses the emergence of VACS and the factors that boosted their rapid development and evolution observed in recent years. Section 3 presents an overview of VACS, and proposes a taxonomy from the perspective of their potential implications to motorway traffic flow. Section 4 focuses and further studies and analyses VACS that have been identified to have direct motorway traffic flow implications; while relevant SWOT (Strengths-Weaknesses-Opportunities-Threats) analyses are presented and discussed in Section 5 in an effort to identify specific ways of exploitation of their most promising features towards an efficient MTM. Section 6 finally, summarises current trends and future perspectives of VACS within a MTM context.

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. In 1902, the automobile 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", the first broadly affordable 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.

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

- Every year, there are 1.24 million road traffic deaths worldwide.
- 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 it has remained stable.

These facts, which have been derived through information on road safety from 182 countries, accounting for almost 99% of the world's population, indicate that the total number of road traffic deaths worldwide 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, 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 accounting for about three quarters of transport emissions in 2011.
- Global transport fuel demand is expected to grow by nearly 40% by 2035.

Motivated by such facts and statistics, an enormous continuing interdisciplinary effort has been applied 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 aiming at assisting, improving and easing the driving task. Although safety and driver convenience have been the main motivators behind their development, 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. their drivers and passengers. 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 exploit the emerging VACS capabilities in an effort to improve road efficiency and reduce congestion and the resulting negative impacts on environment, safety 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.

However, further research is necessary in order to fully exploit the MTM potential in a manner that is safe, understandable and acceptable to the driver and other stakeholders. In this context, it is important to work towards developing the foundations for a new era of future motorway traffic management research and practice. This new research effort 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. VACS taxonomy from a motorway traffic management perspective

Current literature reports on numerous VACS, some of which are indeed very similar in nature. Marketing and differentiation concerns, but also independent parallel developments often lead manufacturers and researchers to give different names to systems that are practically the same, at least from a functional point of view. In addition, several taxonomies have been proposed, serving different purposes and reflecting different VACS aspects (see e.g. Bishop, 2005; Gasser et al., 2012; iMobility Forum, 2013; NHTSA, 2013; Popescu-Zeletin et al., 2010; Shladover, 2012b; van Schijndel-de Nooij et al., 2011). This variety indicates 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 and interests. In this paper, a specific 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 direct implications on traffic flow; from VACS that serve purely safety and comfort purposes without any direct effects on traffic conditions. Obviously, only VACS of the first category may be useful for exploitation within a real-time traffic management context aiming at improving traffic efficiency via appropriate manipulation of the prevailing traffic conditions. This category is then further subdivided, to differentiate VACS that address motorway operations from VACS that address urban operations only.

Summarising the above considerations, an initial VACS taxonomy is proposed, which reflects the relevance of the corresponding systems for the motorway traffic flow efficiency and therefore for MTM (see also Figure 1):

- *VACS without direct 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.
- *VACS with direct traffic flow implications*: This category includes VACS, the operation of which modifies the common traffic flow characteristics, beyond any other safety and comfort features that they may also have. These VACS are further distinguished in:
    - *Urban traffic related VACS*, which address urban road operations only; and
    - *Motorway traffic related VACS*, which address, among others, motorway operations.

< insert Figure 1 here >

In general, most systems reported in the relevant literature belong to the first of the aforementioned VACS class, i.e. they are systems with no direct traffic flow implications; even VACS which were found to have direct 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, but also in the development of VACS specifically aimed for such a deployment.

The class of VACS without direct traffic flow implications 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, convenience- or safety-related VACS, which reduce the probability of traffic incidents or awkward driver manoeuvres, have an indirect (statistical) positive impact on traffic flow efficiency, as they reduce the instances and consequences of corresponding non-recurrent events. The relevant literature reports on numerous such systems, whose operation may be informative or assisting or even intervening; and the systems can be further classified based on their aimed functionalities in (see Figure 1):

- *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 active braking to minimise impacts. 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 actually have implications on traffic flow, the range and magnitude of which, however, have never been investigated, since they are deemed exclusively safety-oriented systems.
- *Lane-keeping assistance systems*: They assist the driver to maintain the position of the vehicle within the lane.
- *Vision assistance systems*: They assist the driver under hard visibility conditions (at night and/or at blind spot) to avoid potential hazards.
- *Speed monitoring systems*: They issue warnings for speeding at hazardous locations such as road curves.
- *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 respond to the warnings.
- *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 pedestrian detection, etc.
- *Other warning systems*: This last category includes systems aiming at warning the driver in hazardous situations not covered by the aforementioned cases, including presence of animals, approach of emergency vehicles, approach to non-moving vehicles or hazardous road surfaces or traffic jams, etc.

The urban traffic related VACS class includes systems that have direct implications on traffic flow, but address exclusively urban road traffic operations. The relevant literature reports on several such systems, which, based on their aimed functionalities, may be further classified in (see Figure 1):

- *Driving 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.
- *Intersection support systems*: This category includes VACS aiming at supporting the driving task in the vicinity of intersections.

The last, motorway traffic related VACS class includes systems that have direct implications for the motorway traffic flow, so that they are potentially suitable for deployment as MTM tools. The relevant literature reports on several such systems, which, based on their aimed functionalities, may be further classified in (see Figure 1):

- *Cruise systems*: This category includes systems that assist equipped vehicles to follow other vehicles in a safe and comfortable manner. Table 1 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”, settings or limits. Table 2 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 lists and briefly describes relevant systems.
- *Combined-functionality systems*: This category includes systems, which combine several functionalities and cannot be classified to only one of the previous three categories. Table 4 lists and briefly describes relevant systems.
- *Vehicle platooning systems*: This category involves a variety of options for forming more or less closely spaced vehicle platoons, aiming at more convenient, safe, fuel-efficient or traffic-efficient driving. Table 5 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 real-time en-route decisions. Table 6 describes briefly the options offered by such systems.

Diakaki et al. (2014) reports and briefly describes VACS without traffic flow implications, as well as urban road traffic related VACS. In addition, they provide a more comprehensive review of the VACS classified as motorway traffic related.

< insert Table 1 here >

< insert Table 2 here >

< insert Table 3 here >

< insert Table 4 here >

< insert Table 5 here >

< insert Table 6 here >

4. Classification and analysis of motorway traffic related VACS

4.1 Introduction

Motorways had been conceived as the type of infrastructure 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 local capacity reduction. They appear due to:

- Permanent attributes of the infrastructure, such as on- and off-ramps, lane drops and road curves, uphill and downhill road gradients, tunnels, bridges etc.;

- Temporary activities such as road-works and construction sites;
- Occasional incidents, i.e. unexpected 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.
- Specific traffic behaviour, such as weaving sections, over-spilling off-ramps, speed limits.

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 5-25% drop in the already lower bottleneck capacity (see, e.g., Papageorgiou et al., 2008; Treiber and Kesting, 2013). Also, traffic congestion extends backwards and covers network exits (e.g. off-ramps) or bifurcations, thus reducing the amount of exiting vehicles upstream of active bottlenecks and accelerating the pace of congestion increase (Papageorgiou and Kotsialos, 2002; Papageorgiou et al., 2003).

For bottleneck activation, it suffices to have an inflow around or above the level of its local capacity. Bottleneck activation is typically triggered by an individual driver attempting an abrupt driving action, given that the traffic load is sufficiently high. Individual drivers who accelerate or decelerate, change lane or overtake abruptly, may create such traffic flow perturbations. In case of low enough traffic loads, such perturbations are absorbed and do not grow or 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 breakdown appearances as well as the space-time extent and severity of the formed congestion may be reduced, and motorway traffic efficiency may be improved, via appropriate MTM actions:

- Stationary capacity (before breakdown) may be increased via shorter inter-vehicle gaps; improved lane usage; less unnecessary lane-changing; efficient merging and lane changing.
- Dynamic capacity (after breakdown) may be increased via improved acceleration at the congestion head.
- Flow control (at on-ramps or on the mainstream) may reduce and redistribute (in space and time) traffic congestion to mitigate its degrading consequences (blocking of exits, capacity drop).
- Speed harmonisation may help in avoiding sudden and/or unnecessary speed variations or lane-changing that may trigger bottleneck activation.
- Traffic redistribution may take place at local (lane distribution) or network (route guidance) levels; it enables utilisation of the available motorway capacity to the maximum possible extent.

To achieve this impact, MTM should be able to make control decisions regarding speeds (or even accelerations), headways, lane assignment and lane-change/merge manoeuvres of the vehicles, as well as to apply ramp metering and provide route guidance. To this end, efficient control algorithms and strategies are necessary. In addition, suitable actuators are 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 not only reflects their functional requirements and the degree of their interaction with the user, but also affects their deployment potential by a MTM system.

To identify the VACS that seem promising in this respect, the motorway traffic related VACS are examined and classified according to their enabled functions and level of autonomy. The aim is to identify those VACS that have a real potential to contribute to the current and future MTM needs.

4.2 VACS classification according to enabled functions

As mentioned previously, MTM should be able to make and impose control decisions regarding speeds, headways, lane assignment and lane change/merge manoeuvres, as well as ramp metering and route guidance. In this respect, we need to identify motorway traffic related VACS, which enable these functions, as well as any combinations of these functions.

To this end, the motorway traffic related VACS 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. It should be noted here that, further to their aimed by design purpose, the speed control systems may be used as mainline metering devices upstream of bottlenecks and merges (Carlson et al., 2011; Papageorgiou et al., 2008) and even as ramp metering actuators. The speed regulation systems AGD, CVSLS, FEA and ISA (see Table 2), and the combined-functionality system IRSA (see Table 4) are VACS that could be used as speed control systems.
- *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 gap) or space (space gap), must preserve safety under all circumstances. The cruise systems ACC, CACC, FSRA and LSACC (see Table 1), and the combined-functionality systems CFM, HP and IRSA (see Table 4) are VACS that could be used as headway control systems.
- *Lane change/merge control 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. The lane change/merge assistance systems CM and LCDAS (see Table 3), and the combined-functionality system CFM (see Table 4) are VACS that could be used as lane change/merge systems. This category may also include lane-change or keep-lane advice (for lane assignment actions).
- *Platooning systems*: This category includes systems that can be used to form vehicle platoons by enabling headway (gap) control in an autonomous and/or cooperative way. The cruise systems ACC, CACC, FSRA and LSACC (see Table 1), and the

combined-functionality systems CFM, HP and IRSA (see Table 4) are systems that could be used in this respect.

- *Route guidance systems*: This last category includes the navigation systems (see Table 6) that enable real-time (en-route) route guidance. By its nature, route guidance is only provided in an informative manner, since the vehicle driver may choose to follow or ignore the related recommendations.

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 speed control means.

4.3 VACS classification according to level of autonomy

As mentioned earlier, the level of autonomy of VACS is a significant factor from a MTM aspect, since it does not only reflect their functional requirements and the degree of their interaction with the user, but also affects their deployment potential by a MTM system.

The relevant literature provides VACS classification schemes developed by official bodies such as the National Highway Traffic Safety Administration of USA (NHTSA, 2013), the German Federal Highway Research Institute's project group "Legal consequences of an increase in vehicle automation" (Gasser et al., 2012), and the iMobility Forum of the European iMobility Support Action (iMobility Forum, 2013). These classification schemes are based on the degree of VACS automation as defined by the systems' ability to perform specific control functions relating to the driving task in an autonomous way, that is without human intervention.

Herein, however, a different taxonomy is developed, as the purpose is not to analyse the individual systems per se and/or their interaction with the driver, but to investigate their deployment potential towards more efficient motorway traffic flow. Obviously, such a deployment potential increases for systems that are able to communicate with an infrastructure-based MTM system so that this system can inform them about its control decisions and recommendations, and it is this aspect that defines the classification developed and adopted in this analysis.

To identify the VACS, which are relevant to MTM in the aforementioned sense, the motorway traffic related VACS are classified in the following categories, which reflect their level of autonomy in relation to the other vehicles and the infrastructure:

- *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 an infrastructure-based MTM system. The cruise systems ACC, FSRA and LSACC (see Table 1), the speed regulation systems AGD, FEA and ISA (see Table 2), the lane change/merge assistance system LCDAS (see Table 3), and the combined-functionality system HP (see Table 4) are VACS of this category.

- *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) communication 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 an infrastructure-based MTM system. The cruise system CACC (see Table 1), the lane change/merge assistance system CM (see Table 3), the combined-functionality systems CFM and IRSA (see Table 4), and the vehicle platooning system VPS (see Table 5) are VACS of this category.
    - *Vehicle to infrastructure (V2I) communication 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 an infrastructure-based 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. The speed regulation systems CVSLS and ISA (see Table 2), the lane change/merge assistance system CM (see Table 3), and the navigation system NAVS (see Table 6) are VACS of this category.
    - *Vehicle to both vehicle and infrastructure (V2X) communication systems*: This last category includes systems, which feature the characteristics of both the V2V and V2I systems categories. The combined-functionality systems CFM and IRSA (see Table 4), and the vehicle platooning system VPS (see Table 5) are VACS of this category.

The above classification is also 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.

5. Relevance assessment of motorway traffic related VACS from a traffic management perspective

5.1 Introductory concepts

Summarising the classification results of Sections 4.2 and 4.3, the classification matrix of Table 7 is obtained; Table 7 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 call for different traffic management architectures.

< insert Table 7 here >

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, their features 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 determine, which of the VACS, identified to affect motorway 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.

A SWOT analysis (Humphrey, 2005) is a structured planning method used to evaluate the strengths, weaknesses, opportunities and threats involved in a project or in a business venture. 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.

5.2 SWOT analysis of motorway traffic related VACS

The analysis in this section starts with the ACC system (see Table 1), which, according to the literature seems to be the most mature system from a market perspective. ACC is an autonomous system that carries on board all technology and logic necessary to maintain a user-defined gap from the preceding vehicle; while keeping the speed up to a user-defined limit. According to literature findings, 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 with possible benefits to traffic efficiency, motorway capacity and the environment (Alkim et al., 2007; Benmimoun et al., 2012, 2013; Bose and Ioannou, 1999, 2001, 2003; Davis, 2004, 2006, 2007; Fancher et al., 1998; Hallé and Chaib-draa, 2005; Kessler et al., 2012; Tapani, 2012; Viti et al., 2008; Zwaneveld and van Arem, 1997).

Due to its autonomous nature, ACC has the potential to offer the aforementioned services without the need of any external assistance. Thus, autonomy is 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 for, the speed and gap, which would be beneficial at a traffic flow level. As a matter of fact, when used with gaps lower than those of manually-driven vehicles, ACC can lead to capacity and throughput increases; but under conservative use, i.e. with gaps higher than those commonly used by manually-driven vehicles (as currently recommended by car manufacturers), it leads to a, possibly substantial, decrease of motorway capacity (Alkim et al., 2007; Fancher et al., 1998; VanderWerf et al., 2001, 2002; Yuan et al., 2009; Zwaneveld and van Arem, 1997). This weakness may possibly be mitigated if the ACC system includes autonomous traffic-adaptive capabilities, as e.g. 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 (Davis, 2004, 2006, 2007); 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 (Viti et al., 2008). Finally, simulation investigations of ACC indicate that the control laws currently employed may not guarantee traffic flow stability under all circumstances (Bose and Ioannou, 1999; Davis, 2004; Li and Shrivastava, 2002; Rajamani et al., 2005; Rajamani, 2012; Santhanakrishnan and Rajamani, 2003; Swaroop and Rajagopal, 1998; Swaroop and Rajagopal, 2001; Wang and Rajamani, 2004).

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

- V2I communication enables an infrastructure-based MTM system to provide advice and recommendations on gap, speed and other parameter settings that are beneficial at a traffic flow level. Navigation devices could be alternatively used in this respect. Intervention could also be enabled by some ISA systems (see Table 2) capable of imposing dynamic speed limits. Until, however, technology is mature enough to directly communicate advices and/or intervene in the driving task, traditional VMS 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 Table 1), with all its additional strengths of reducing start delay, journey times, and stops and stop-time per vehicle in the journey (Benz et al., 2003; SINTEF et al., 2004; van Driel and van Arem, 2008, 2010; van Driel, 2007), can also enhance the benefits gained by a common ACC. A FSRA (see Table 1) 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, may eventually ensure traffic flow stability under all traffic conditions.

Some of the ACC weaknesses may be mitigated or inversed with V2V communication, which will enable the preservation of much shorter, though still safe, gaps. Specifically, significant capacity increase may be achieved via deployment of CACC (see Table 1) and VPS (see Table 5), as reported in the relevant literature (Arnaout and Bowling, 2011, 2013; iMobility Forum, 2013; Shladover et al., 2010, 2011, 2012a; Tientrakool et al., 2011; van Arem et al., 2006; VanderWerf et al., 2001, 2002; Visser, 2005). In case of high penetration rates, however, even with common ACC systems operating under short gap settings, on-ramp flow merging problems may deteriorate even more (Davis, 2004, 2006, 2007). V2V and/or V2I communication should therefore be used to also assist and smooth the merging process. Related opportunities can be offered by the advances in the field of LCDAS (see Table 3). Although existing LCDAS are simply warning systems, manufacturers and researchers are making efforts to automating the whole merging process and developing related cooperative systems (Habenicht et al., 2011; Knake-Langhorst et al., 2013; Tideman et al., 2007; Tomar and Verma, 2012; Wan et al., 2011).

Another 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 first barrier in this effort is the cost of the system. As, however, technology, including not only the purely technical but also the utility, usability and safety aspects of ACC, will mature, demand may gradually increase, so as for the price to 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 convenience, 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 congestion-induced degradation of the motorway infrastructure with all the devastating consequences that such a deterioration of traffic conditions will have to the environment and the quality of life.

Table 8 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 (see Table 4) is a vehicle application with an operation and traffic flow implications similar to FSRA; its only additional strength being that it also supports the driver in the lateral control (steering) of the vehicle.

< insert Table 8 here >

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, which are analysed below.

To start with, ISA (see Table 2) is a system, which 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, to enable traffic homogenisation and mainstream metering (Carlson et al., 2011) and to decrease accident probability (Benmimoun et al., 2012; Carsten and Tate, 2000, 2005; Hogema et al., 2002; Kessler et al., 2012; Liu and Tate, 2004; Marchau et al., 2010; SWOV, 2010; Tampère et al., 1999; Varhelyi and Makinen, 2001; Vlassenroot et al., 2011a, 2011b). However, according to usage results, it can be frustrating, especially at low penetration rates, and lead to a potential decrease of average speeds and, consequently, to an increase of travel times (Carsten and Tate, 2000, 2005; Varhelyi and Makinen, 2001).

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, according to relevant FOT findings (Carsten and Tate, 2000, 2005; SWOV, 2010), 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. At the same time, similarly to ACC, technology maturity may lead to demand increase, thus allowing the reduction of the relevant cost 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 (Carsten and Tate, 2000, 2005; SWOV, 2010). Table 9 summarises the SWOT analysis of ISA.

< insert Table 9 here >

Unlike ISA, LCDAS (see Table 3) 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 strength for 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 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 efficiency and user comfort (Habenicht et al., 2011; Knake-Langhorst et al., 2013; Tideman et al., 2007; Tomar and Verma, 2012; Wan et al., 2011).

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 Table 3). 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 10 summarises the SWOT analysis of LCDAS.

< insert Table 10 here >

At this point, it should be mentioned that:

- the IRSA system (see Table 4) may be viewed as a FSRA combined with ISA and CM, while
- the CFM system (see Table 4) may be viewed as a combination of CACC and CM.

Thus, 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, they may be threatened, just like their component systems, by user acceptance, related cost and potential delay of MTM adaptation to their evolution.

Beyond the previously analysed systems, two more systems exist, which offer the potential of speed control, FEA and CVSLS. FEA (see Table 2) 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 Table 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 these latter systems have been also found to have positive effects on fuel consumption and the environment (see also "Strengths" in Tables 8 and 9). The penetration and spread of ISA systems is expected to put aside also CVSLS (see Table 2), as this latter system comprises basically an advisory ISA system operating with dynamic speed limits, which are provided at specific network locations.

The last VACS identified as particularly relevant to motorway traffic is NAVS (see Table 6). Unlike all previously discussed systems, the major strength of the NAVS 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, the use of NAVS under high penetration rates may lead to oscillations and fail to improve the traffic conditions (Jahn et al., 2005; Buscena et al., 2009). Research in this field is still ongoing (Buscena et al., 2009; Delling and Wagner, 2009; Delling et al., 2009; Flinsenberg, 2004; Jahn et al., 2005; Kaparias and Bell, 2009, 2010; Kaparias et al., 2007; Lee and Yang, 2012; Schultes, 2008), likewise in other related fields, such as positioning and communication systems, aesthetics, contextual optimisation, etc. (Belzowski and Ekstrom, 2013; Eby and Kostyniuk, 1999; Lavien et al., 2011; Lee et al., 2008; Ma and Kaber, 2007; May et al., 2005; McNally et al., 2003; Nagaki, 2012). The real-time capabilities and accuracy of NAVSs are still below the user-desired levels, which may hinder their spread and penetration as trustful routing devices. 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 11 summarises the SWOT analysis of NAVS.

< insert Table 11 here >

Considering the functions that have been identified as being of main interest from a MTM perspective (see Section 4), as well as the results of the above SWOT analyses, it seems that the most promising VACS are the cruise system ACC (see Table 1), the speed regulation system ISA (see Table 2), the lane change/merge assistance system LCDAS (see Table 3), and the navigation system NAVS (see Table 6). 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, 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 increasing 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.

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

Motivated mainly from safety and convenience 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, improving 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. In addition, FOTs of VACS, which mainly concern:

- technical 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 (Alkim et al., 2007; Viti et al., 2008). 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.

As far as the traffic flow implications of VACS are concerned, studies, performed mainly via simulation, suggest that, beyond any 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 simulation studies 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 analyses presented herein indicate 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, where, when and as 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 still widely acceptable motorway traffic management strategies, exploiting the mix of the current and evolving VACS capabilities.

The review and analyses presented herein also indicate that both VACS evolution and related research and development 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.

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List of Tables

Table 1. Cruise systems

System	Description	Sources of info
Adaptive Cruise Control (ACC)	Automatically adjusts the speed to maintain a desired time-gap of the vehicle to the one in front; if there is no vehicle in front, it maintains a maximum vehicle speed; activated by setting the desired maximum speed and time gap to the vehicle in front; operates at relatively high speed levels; carries on board all technology and logic necessary for its operation	Alkim et al., 2007; Benmimoun et al., 2012, 2013; Bishop, 2005; Bose and Ioannou, 1999, 2001, 2003; Davis, 2004, 2006, 2007; Fancher et al., 1998; General Motors Corporation, 2005; Ioannou and Zhang, 2005; Ioannou et al., 2007; Jiang and Wu, 2006; Kessler et al., 2012; Kesting et al., 2007a, 2007b, 2008, 2010; Li and Shrivastava, 2002; Pueboobpaphan and van Arem, 2010; Rajamani et al., 2005; Rajamani, 2012; Santhanakrishnan and Rajamani, 2003; Swaroop and Rajagopal, 1998; Swaroop and Rajagopal, 2001; Tapani, 2012; University of Michigan and General Motors Corporation, 2005a, 2005b; VanderWerf et al., 2001, 2002; Visser, 2005; Viti et al., 2008; Wang and Rajamani, 2004; Xiao and Gao, 2010; Yi and Horowitz, 2006; Yuan et al., 2009; Zhang and Ioannou, 2004; Zwaneveld and van Arem, 1997; http://www.eurofot-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; and maintain smaller inter-vehicle gaps	Arnaout and Bowling, 2011, 2013; Bishop, 2005; Visser, 2005; Maihöfer et al., 2004; Popescu-Zeletin et al., 2010; Shladover et al., 2010, 2011; VanderWerf et al., 2001, 2002
Full Speed Range Adaptive Cruise Control (FSRA)	Evolution of the Adaptive Cruise Control, which operates in all speed ranges	Alkim et al., 2007; Bishop, 2005; Ehmanns and Spannheimer, 2004; Hoeger et al., 2011; iMobility Forum, 2013; Minderhoud, 1999; Shladover, 2012a; Viti et al., 2008
Low Speed Adaptive Cruise Control (LSACC)	Evolution of the Adaptive Cruise Control, which operates in slow, congested traffic, i.e. at low speed levels, to follow the vehicle immediately ahead	Benz et al., 2003; Bishop, 2005; Minderhoud, 1999; SINTEF et al., 2004; van Driel and van Arem, 2008, 2010; van Driel, 2007

Table 2. Speed regulation systems

System	Description	Sources of info
Active Green Driving (AGD)	A suitably designed (within the HAVEit European project) human-machine interface used to coach the driver with the aim to reduce the fuel consumption and pollution; carries on board all technology and logic necessary for its operation	Hoeger et al., 2011
Cooperative Variable Speed Limit System (CVSLS)	Extension of the conventional Variable Speed Limit (VSL) system that employs vehicle-to-infrastructure communication to communicate to vehicles upstream of the VSL gantry location individual speed limits determined according to 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; carries on board all technology and logic necessary for its operation	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; ranges from purely advisory to completely mandatory types; vehicle-to-infrastructure communication is necessary to perform its functions in full extent; in an elementary form, it may operate autonomously or in cooperation with similarly equipped vehicles	Benmimoun et al., 2012; Biding and Lind, 2002; Bishop, 2005; Blum et al., 2012; Boriboonsomsin et al., 2008; Carsten and Tate, 2000, 2005; Doecke and Woolley, 2010; Hegeman, 2002; Hoeger et al., 2011; Hogema et al., 2002; iMobility Forum, 2013; Kessler et al., 2012; Liu and Tate, 2004; Marchau et al., 2010; SWOV, 2010; Tampère et al., 1999; van Driel, 2007; Varhelyi and Makinen, 2001; Vlassenroot et al., 2011a, 2011b

Table 3. Lane change/merge assistance systems

System	Description	Sources of info
Cooperative Merging (CM)	Combines automated longitudinal control with vehicle to vehicle or infrastructure communication to assist the driver in lane changing manoeuvres by creating and maintaining an appropriate gap in the target lane	Popescu-Zeletin et al., 2010; Tampère et al., 1999
Lane Change Decision Aid System (LCDAS)	Autonomous system, which supports lane change and merge vehicle manoeuvres, mainly to avoid potential collisions; ranges from warning to more active systems, which support the driver all the way from the lane-change intention until placement in the target lane; cooperation with similarly equipped vehicles has been suggested to enhance its capabilities	Bartels et al., 2012; Godbole et al., 1997; Habenicht et al., 2011; Jula et al., 1999, 2000; Knake-Langhorst et al., 2013; Popescu-Zeletin et al., 2010; Smith et al., 2003; Tideman et al., 2007; Tomar and Verma, 2012; Visvikis et al., 2008; Wan et al., 2011

Table 4. Combined-functionality 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 assist lane changing manoeuvres by creating and maintaining an appropriate gap in the target lane; cooperation with similarly equipped vehicles and/or the infrastructure is therefore necessary	Tampère et al., 1999
Highway Pilot (HP)	Autonomous vehicle application, which supports 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	Hoeger et al., 2011; iMobility Forum, 2013
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; it can be viewed as a combination of ISA with a cooperative or conventional FSRA extended with the CM concept; ranges from purely advisory to completely mandatory types and requires vehicle to vehicle and infrastructure communication to perform its functions	van Arem et al., 2007; Wilmink et al., 2006

Table 5. Vehicle platooning systems

System	Description	Sources of info
Vehicle Platooning Systems (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; combination of vehicle to both vehicle and infrastructure communication has been used to form and maintain platoons, although vehicle to vehicle communication only suffices in this respect	Alam et al., 2010; Alam, 2011; Bergenheim et al., 2012a, 2012b; Bishop, 2005; Bonnet, 2003; Brännström, 2013; Davila, 2013; Ehmanns and Spannheimer, 2004; Hallé and Chaib-draa; 2005; Hedrick et al., 2001; iMobility Forum, 2013; Kavathekar, 2012; Kianfar, 2013; Lee and Kim, 2002; Michael et al., 1998; PATH, 1997; SARTRE, 2013; Shladover, 2012a; Tientrakool et al., 2011; Tsugawa, 2014; van Arem et al., 2006

Table 6. Navigation systems

System	Description	Sources of info
Navigation Systems (NAVS)	Aims at providing personalised location and route guidance information in order to assist and advice the driver in planning or efficiently executing a journey; vehicle to infrastructure cooperation is necessary to receive the necessary location and route guidance information, as well as for the establishment of a “probe car” system	Belzowski and Ekstrom, 2013; Buscena et al., 2009; Delling and Wagner, 2009; Delling et al., 2009; Eby and Kostyniuk, 1999; Flinsenberg, 2004; Jahn et al., 2005; Kaparias and Bell, 2009, 2010; Kaparias et al., 2007; Lavien et al., 2011; Lee and Yang, 2012; Lee et al., 2008; Ma and Kaber, 2007; May et al., 2005; McNally et al., 2003; Nagaki, 2012; Pang et al., 2002; Schultes, 2008; Skog and Händel, 2012

Table 7. 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

AGD: Active Green Driving (see Table 2)
ACC: Adaptive Cruise Control (see Table 1)
CACC: Cooperative Adaptive Cruise Control (see Table 1)
CFM: Cooperative Following and Merging (see Table 4)
CM: Cooperative Following (see Table 3)
CVSLS: Cooperative Variable Speed limit System (see Table 2)
FEA: Fuel Efficiency Advisor (see Table 2)
FSRA: Full Speed Range Adaptive Cruise Control (see Table 1)
HP: Highway Pilot (see Table 4)
IRSA: Integrated Full-Speed Range Speed Assistant (see Table 4)
ISA: Intelligent Speed Adaptation (see Table 2)
LCDAS: Lane Change Decision Aid System (see Table 3)
LSACC: Low Speed Adaptive Cruise Control (see Table 1)
NAVS: Navigation Systems (see Table 6)
VPS: Vehicle Platooning Systems (see Table 5)

Table 8. SWOT analysis of ACC (Adaptive Cruise Control)

Strengths	**Weaknesses**
- Autonomy in that all necessary technology and intelligence 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

Table 9. SWOT analysis of ISA (Intelligent Speed Adaptation)

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

Table 10. SWOT analysis of LCDAS (Lane Change Decision Aid System)

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

Table 11. SWOT analysis of NAVS (Navigations Systems)

Strengths	Weaknesses
- Can contribute to the maximisation of network infrastructure utilisation	- Employed routing algorithms ignore their own impact on traffic, thus may fail to mitigate congestion problems under high penetration rates
Opportunities	**Threats**
- Continuous research on practical and efficient routing algorithm	- User acceptance in terms of purchase intention - User trust - MTM delayed adaptation

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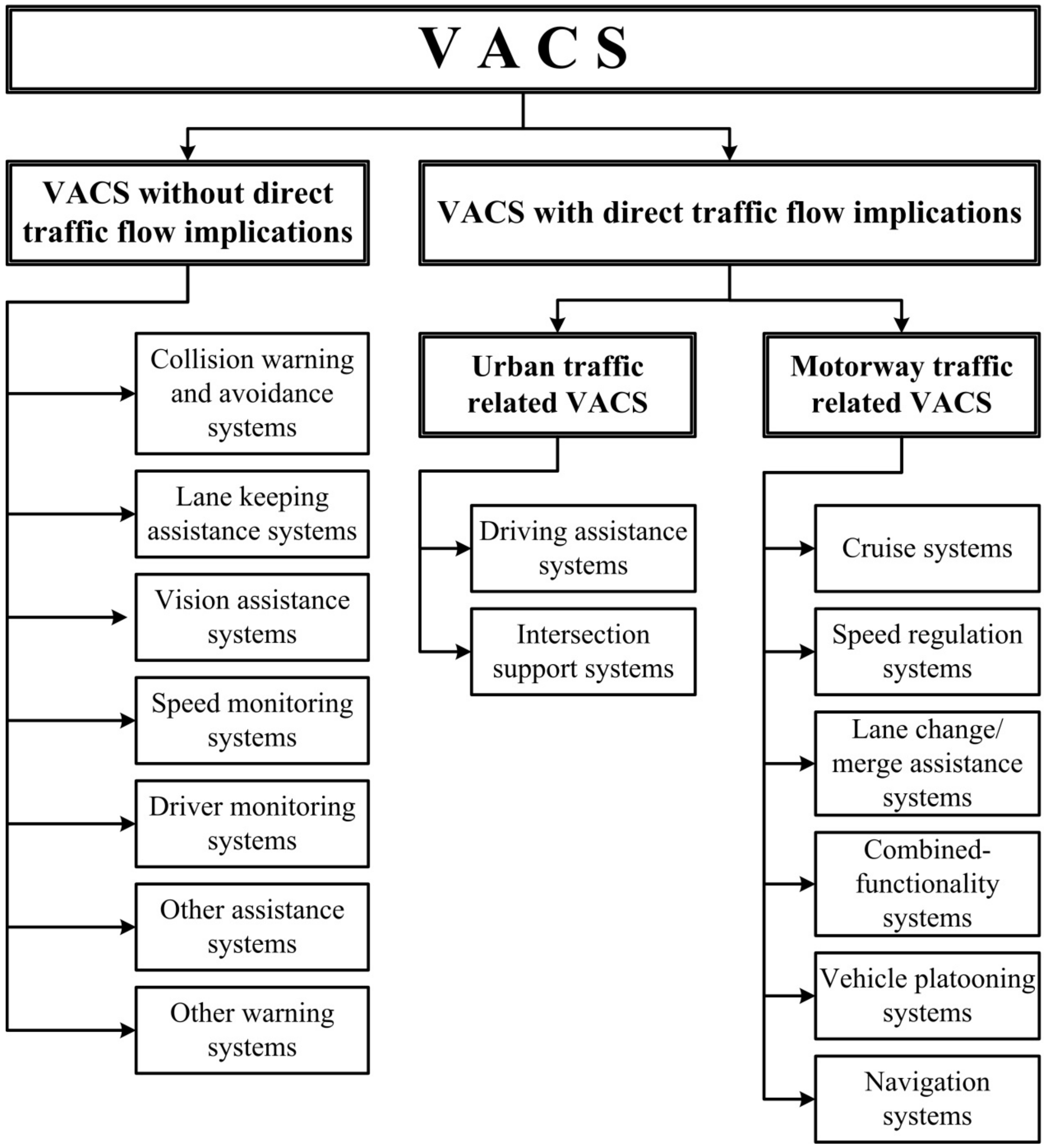

Figure 1. VACS taxonomy from a motorway traffic management perspective