Impact of advanced driver assistance systems on urban traffic network conditions

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Abstract

This research deals with the investigation of the advanced driver assistance systems impact on urban traffic network conditions through the use of a traffic network simulation model. Information obtained through microscopic simulation was used as input to a network traffic simulation and assignment model (SATURN). SATURN was applied to the road network of the greater Athens area in an attempt to investigate the impact of two ADAS systems [variable speed limiter (VSL) and adaptive cruise control (ACC)] for different combinations of flow and market penetration levels. It was observed that the ADA systems' impact increases proportionally with the market penetration of these systems and that as traffic flow level increases, the average speed increase becomes smaller (when all other parameters remain unchanged). Furthermore, it appears that ACC offers better network efficiency results than VSL (up to twice as significant) and the benefits of a combined ACC and VSL system are only marginally better than the ACC system alone. The proposed methodology and the related findings can support system developers and policy makers in the process of further ADAS development and promotion.

Key-words: advanced driver assistance systems, traffic behaviour, traffic efficiency impact, traffic impact sensitivity.

1 Introduction

One of the most significant problems of modern cities is undoubtedly traffic congestion, a well-known and sufficiently documented issue (Bhargab et al, 1999; NRC, 1995). Several approaches have been adopted towards providing adequate solutions, or at least mitigating its impact in the everyday life of the citizens. Supply related solutions like the construction of new roads are not economical and do not really solve the problem as, by providing additional capacity, they often result in the generation of new demand. Similarly, demand related approaches, such as the improvement of the rider-ship of public transit modes, congestion pricing and flexible work-hours are difficult to implement or have low public acceptance.

One promising direction is the introduction of intelligent in-vehicle (or cooperative in-vehicle—infrastructure-based) systems that assist the driver in his/her various tasks. A large variety of such systems, collectively referred to as Advanced Driver Assistance Systems (ADAS) are being developed by various parties, including system developers, car manufacturers, and scientists worldwide (Brand et al, 1997; Davison et al, 1997; Heijer et al, 2000). Several attempts have been made to categorize these systems (Heijer et al, 2000). One of the key considerations in the design and development of ADA systems is the improvement of vehicles' traffic dynamics, thus improving the overall network efficiency. Other considerations include fuel consumption and related emission reduction, and safety improvements (Penttinen et al, 2000).

As ADA systems are a rapidly evolving area of research and development, it would be helpful to obtain intuition into the potential benefits from the implementation of these systems prior to their actual deployment. Research in the area has so far been mostly experimental, using either actual ADAS-equipped vehicles or properly configured driving simulators (Duynstee et al, 2000, Ishida et al, 2000, Regan et al, 2000).

A methodology for the assessment of Dynamic Speed Adaptation on driver behaviour has been proposed by Braban-Ledoux et al (2000), who also propose a set of microscopic indicators for characterising driver behaviour. A few simulation efforts have also been reported. For example, Misener et al (2000) describe the adaptation of a microscopic simulator, SmartAHS, for the evaluation of ADAS and present simulation results for an Adaptive Cruise Control and Stop and Go system. Furthermore, Neunzig et al (2000) present an analysis of the impact of Adaptive Cruise Control on the fuel consumption of equipped vehicles.

Given the relatively short history of advanced driver assistance systems their impact on traffic conditions started recently to be investigated, mainly at microscopic level (Hoogerndoorn et al. 2001, Stevens et al. 2001, Niittymäki et al. 2001) and the first results concerning specific types of road sections and traffic situations are available. However, no attempt is recorded for the identification of ADAS impact at network level as the low market penetration level of these systems makes very difficult the execution of any experiment in real conditions. In order to fill in this gap, the objective of this paper is the investigation of the advanced driver assistance systems impact on traffic network conditions through the use of a traffic network simulation model.

2 Methodology

For the achievement of this objective, information obtained through microscopic simulation was used as input to a network traffic simulation and assignment model for the investigation of the ADAS impact on traffic network conditions. For the purposes of this research the SATURN traffic simulation and assignment model was used, as it can deal with large networks as well as with congested situations and it allows for automatic iterations facilitating thus the execution of several runs (Hall et al, 1980; D. van Vliet, 1982). SATURN was applied to the road network of the greater Athens area (Figure 2). This research focussed on an urban road network as it is believed that the identification of ADAS effects at network level in complex situations with several links and nodes would present more interest.

The input data used by the SATURN simulation model concern traffic parameter values with and without ADA systems, produced by microscopic simulation as described in Section 3. In order to gain some intuition in the sensitivity and the prevailing trends of the ADAS impacts the scenarios considered for the SATURN simulation runs concern two ADAS systems (variable speed limiter and adaptive cruise control) and their combination, various flow levels and various market penetration levels as described in Section 4. A detailed description of the simulated ADA systems is outside the scope of the present paper. However, a brief description of these systems is presented below, aiming at providing the necessary context for better comprehension of the presented methodology.

Variable speed limiter (VSL or intelligent speed adaptation) describes a family of longitudinal control ADA systems. Several recent applications are classified under this area; some merely provide the drivers with applicable speed limit recommendations, taking into account the traffic and other conditions downstream, while others actually enable the system to automatically intervene and reduce the driving speed. Examples of such intervention techniques involve sending signals to an appropriate in-vehicle module, which in turn limits the speed, and accordingly managing signals to force vehicles to change their speed. A more complete coverage of VSL can be found, for example, in Davison et al (1997) and Oei (1998b).

Adaptive cruise control (ACC) is another longitudinal control system, albeit a more complicated one. Adaptive cruise control monitors the traffic around the equipped vehicle and adjusts its speed, as well as the separation with the preceding vehicles, accordingly. Vehicle speed is adjusted either by allowing the vehicle to coast or by transmission downshifting. Longitudinal control of ACC systems can range from normal cruise control to advanced cooperative intelligent cruise control, which are capable of detecting a vehicle ahead in the same lane travelling at any speed or fully stopped. ACC concepts and technologies are discussed, for example, in Martin (1993), Winner et al (1996), Oei (1998a), and Hayward et al (2000).

The outcome of the SATURN simulations revealed the trends of the impact of advanced driver assistance systems on the traffic network conditions, through the identification of the average speed change in the urban network examined. In Section 5, the respective diagrams are presented highlighting the sensitivity of the ADAS impact in relation to the scenarios considered. The discussion of the findings presented in Section 6 allows the extraction of basic conclusions on the ADAS impact trends and for the identification of key areas where further research is required.

3 Traffic parameters input

The key input to the SATURN traffic simulation and assignment model, that was used for capturing the network efficiency changes as a result of the introduction of the various ADA systems was the improved saturation flow for several penetration levels. More precisely, for each system and demand level considered, appropriate saturation flow values were used as input to the SATURN model.

It should be noted that the use of ADAS systems may also lead to better traffic stabilisation by eliminating shock-waves all along an urban link. However, for such a link the dominant parameter of interest is its capacity, which is determind by the junction capacity. As a consequence, the critical impact of ADAS in an urban network is expected to be adequately reflected in changes of junction capacity, which in the case of signalised junctions is realised through changes in saturation flows.

It is also mentioned that on the basis of the above arguments and the fact that VSL impact on free flow speed is expected to be negligible, as in central urban areas free flow speed is very close to the limit set in VSL systems, speed-density curves were not changed in the macroscopic simulation model.

The saturation flow values for the various scenarios considered within SATURN were obtained through microscopic simulation of the traffic dynamics of the considered ADA systems in an urban environment (Niittymäki et al., 2001), performed at the Helsinki Institute of Technology using the HUTSIM simulator (Kosonen et al., 1992, and Sane et al., 1996). HUTSIM is a well-calibrated microscopic simulation model with stochastic nature and it was designed especially for simulating traffic signal control, and a real signal controller is used as a part of the simulation system.

In the context of this research, HUTSIM has been used to simulate the impact of the introduction of ADAS equipped vehicles in a part of a main road in central Helsinki. A 770-metres long section of the street was modelled, which consists of four intersections and includes five traffic signals.

The maximum acceleration rate for ADAS equipped vehicles was set to 1.9m/s^2, while the maximum deceleration rate (again, for ADAS equipped vehicles) was set to 2.2m/s^2. Minimum gaps accepted by ADAS-equipped vehicles were set at 2,5 s to 4s, depending on the geometric characteristics. Minimum gaps for merging turns as well as for lane change were 2.1s. The headways maintained by ACC-equipped vehicles were given by a normal distribution with mean equal to 0.7s. Finally, ACC systems were assumed to cover all reasonable urban speed ranges, a fact which is expected to lead to increased saturation flow impact.

The saturation flow for several penetration scenarios for each system has been calculated by measuring for each signalised junction the minimum headways downstream the traffic lights. Based on the simulated minimum headways, the saturation flow as a function of the penetration level of each simulated ADA system was calculated.

In order to exploit the underlying trends captured by the provided information, while staying as independent from the actual numbers as possible, given that transferability of the results is not adequately investigated, the ratio of the saturation flow for each scenario over the saturation flow for the no-ADAS scenario was calculated. Based on the definition of capacity and saturation flows, it can be deduced that the obtained ratio of the saturation flows is equivalent to the similar ratio of the capacity under the two scenarios. The difference between capacity and saturation flow is that capacity corresponds to an hour of regular traffic, while saturation flow corresponds to an hour of green light. Therefore, for the same link/network (i.e. the same traffic light control strategy) the ratio of the capacity of a simulation scenario over the capacity of the reference scenario is equal to the ratio of the saturation flow for the same simulation scenario over the saturation flow of the reference scenario.

For the generalisation of the HUTSIM modelling results in the urban network examined it was assumed that the above ratios do not depend on the actual link capacity but only on the penetration level and therefore for each penetration level they are valid for all network links. This assumption is based on the results concerning the different links of the road section examined in the HUTSIM model. Therefore, it is considered to be a realistic assumption in the context of this study.

The ratios of saturation flows per ADA system and penetration level over saturation flow for the no-ADAS base case are presented in Table 1.

Table 1. Ratio of saturation flows per ADA system over saturation flow for the no-ADAS base case for various penetration levels (HUTSIM simulation output)

	Penetration level %				
ADA system	0	25	50	75	100
ACC	1,00	1,09	1,19	1,28	1,37
VSL	1,00	1,05	1,10	1,14	1,19
ACC+VSL	1,00	1,10	1,20	1,31	1,41

It is interesting to note from Table 1 that there is an increase in the saturation flow due to the introduction of any of the two systems or their combination. This is mainly explained by the fact that the use of VSL and ACC can lead to a more stable flow upstream and in the vicinity of the traffic signal, and thus to an increase of saturation flow (Pline 1992). This is easily understandable for the case of ACC. As far as VSL is concerned, its impact is related to the cases where vehicles join groups of other vehicles moving under saturation flow conditions and not to cases where vehicles are waiting for the start of the green period at the signalised junction. As a consequence, its impact on saturation flow is lower than that of ACC, which may have positive impacts in all cases. Furthermore, it is obvious that VSL impacts are also expected in low demand levels, as the cases related to these impacts are definitively present in such traffic conditions.

The information given in Table 1 was then used to obtain updated network files that reflected the existence of ADAS equipped vehicles in the network. Assuming uniform distribution of ADAS-equipped vehicles throughout the entire network, the capacity of all links in the network was uniformly adjusted to reflect the new capacity. In order to accomplish this task efficiently the necessary software utility was developed and the impact of the introduction of each ADA system was reflected at the modified traffic parameters of each network link used in the SATURN model.

4 Scenarios considered

A number of scenarios have been generated and used as the guide for the SATURN simulations. These scenarios are based on the combination of values for the following parameters:

- Type of ADAS;
- Penetration of ADAS; and
- Demand level.

More precisely, based on the list of systems that are most desirable to be implemented, and several parameters pertaining to the maturity and special characteristics of each system, two longitudinal control systems have been selected:

the variable speed limiter (VSL) and the adaptive cruise control (ACC). Furthermore, the combination of these two systems (ACC+VSL) was considered. Therefore, taking into account that the no-ADAS situation was taken as the base case, four alternative scenarios were considered in total.

Examination of a specific ADA system requires impact analysis for different market penetration levels covering in a representative way the whole reasonable value range. Thus, for ACC, VSL, as well as for their combination (ACC+VSL), four market penetration levels are considered: 25%, 50%, 75%, and 100%. These values provide an overall coverage of the full market penetration level range and can be used for a better understanding of the overall trends of a system impact. The no-ADAS base case is equivalent to a 0% penetration level for any system.

One of the parameters that are expected to influence the impact of ADAS in traffic is the prevailing traffic conditions. The traffic demand of the network considered is selected as a reflection of these conditions. In particular, the morning peak demand level, which reflects the usual peak traffic conditions was selected as the reference scenario. Based on an actual origin - destination (O-D) matrix for the used network and in order to gain some intuition in the sensitivity and the prevailing trends of the ADAS impacts with respect to the traffic demand, the following demand levels were simulated:

- 0.8 times the reference O-D matrix;
- The reference O-D matrix, corresponding to the morning peak; and
- 1.2 times the reference O-D matrix.

It should be mentioned that the third scenario is related to heavy traffic conditions approaching / reaching congestion at some main axes. For the preparation of the necessary O-D matrix input files, another software utility was developed and the demand level description files were used as an input to the SATURN simulation model.

The greater area of Athens, Greece, was selected as the study area. Athens is a city of approximately 4 million people and 1.500 km^2, with considerable traffic congestion problems during long periods of the day. The corresponding selected urban network consists of 1.330 links and 285 Origin - Destination zones. A well-calibrated network coding was used (Figure 1), which has been already used and tested in several other applications (NTUA 1999, NTUA 2000).

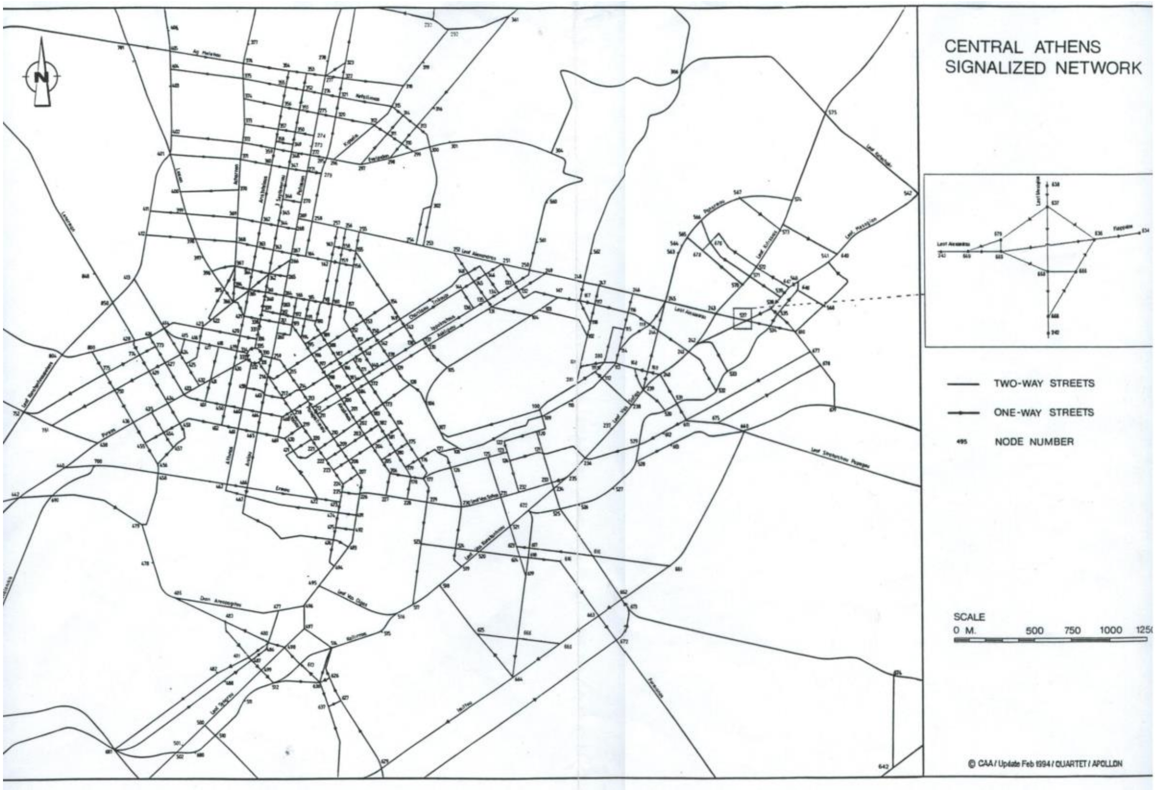

Figure 1. SATURN simulations network (Athens, Greece)

5 Sensitivity investigation

The parameter selected to capture the impact of ADAS-equipped vehicles on the traffic conditions was the mean speed of the simulated traffic. The model was run once for each simulation scenario. Using the no-ADAS scenario as the base case for each demand level, the observed difference in the average speed can be attributed to the impact of ADAS vehicles. Thus, it was possible to capture the impact of the various scenarios due to the existence of an advanced driver assistance system. The network-wide mean speeds obtained are the weighted average of link speeds for the entire network (weighted by vehicle-kilometers). There are no different speed values per vehicle category as an average value is obtained.

The results from the network efficiency simulations carried out by the SATURN model are presented in this Section. The collected simulation results are analysed and discussed from two viewpoints, one aiming at exhibiting the sensitivity of the impact of each system with respect to its penetration and the prevailing demand level, and one aiming at exhibiting the relative impact of the various systems under the same conditions.

Figure 2 shows the simulated network-wide average speed increase due to the introduction of the Adaptive Cruise Control for several penetration and demand levels. It is evident that for all demand levels the speed increases proportionally with the penetration level. Furthermore, this increase follows a fairly linear pattern, underlining the strong relation between the market penetration level of ACC and its impact on traffic conditions.

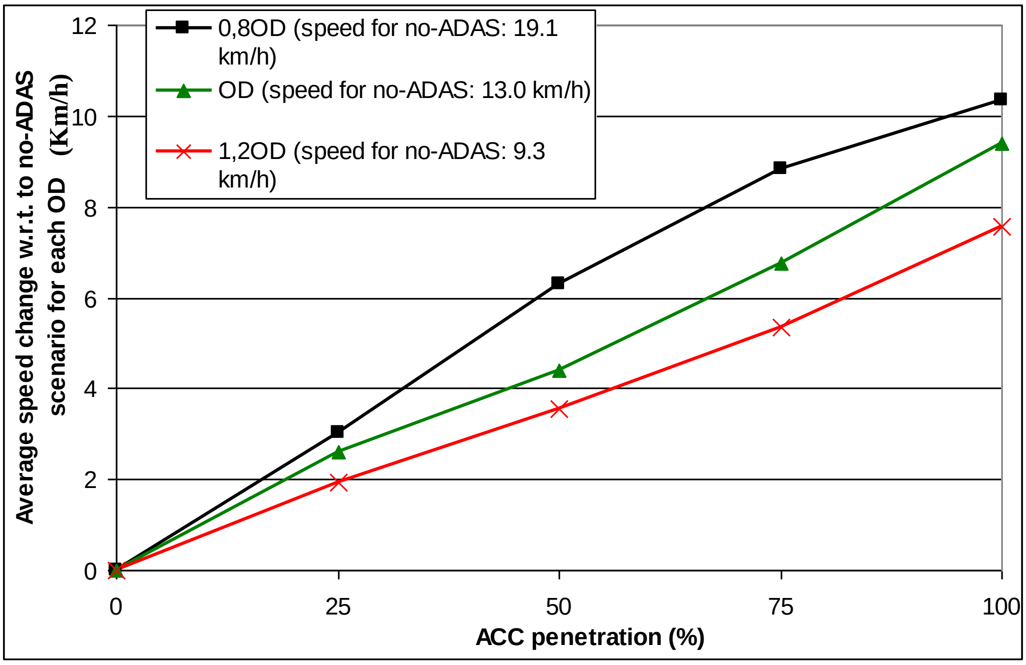

Figure 2. ACC network efficiency impact in absolute values

Another interesting result that can be extracted from Figure 2 is that the ADA system impact is less significant in absolute values in the higher demand levels. Nevertheless, the percent change of the speed is higher in the higher demand levels. This fact has to be evaluated with respect to the particular demand levels that were used in this simulation effort, which were fairly high. The reference OD matrix corresponds to the morning peak, and 1.2 times this demand leads to adverse traffic conditions in some axes.

ADAS impacts are presented with respect only to average speed and not to the different speed levels as these are indirectly taken into consideration in the different travel demand levels examined. It is also noted that the higher speeds found when VSL and ACC systems are used, are mainly explained by the fact that higher saturation flow levels result in link capacity increase and subsequent lower value of the ratio v/c. No actual impact on spill-back effects were observed from the use of the systems examined. However, it should be mentioned that as the model used is a simulation and assignment model at the same time, demand is assigned to the various links on the basis of the new link capacities, leading thus to a network spread through optimisation procedures of the capacity gains due to the use of ADA systems.

In Figure 3, the simulated network-wide average speed increase due to the introduction of the Variable Speed Limiter for the simulated penetration levels and demand levels is presented. Average speed increases proportionally to the penetration level for all the demand levels considered. The VSL impact on average speed follows similar pattern as the ACC impact, e.g. a fairly linear relation is observed. Even though the absolute values of the changes in speed are less significant in the higher demand levels, it appears that the ADAS impact on the percent change of the average speed is more significant for higher demand levels.

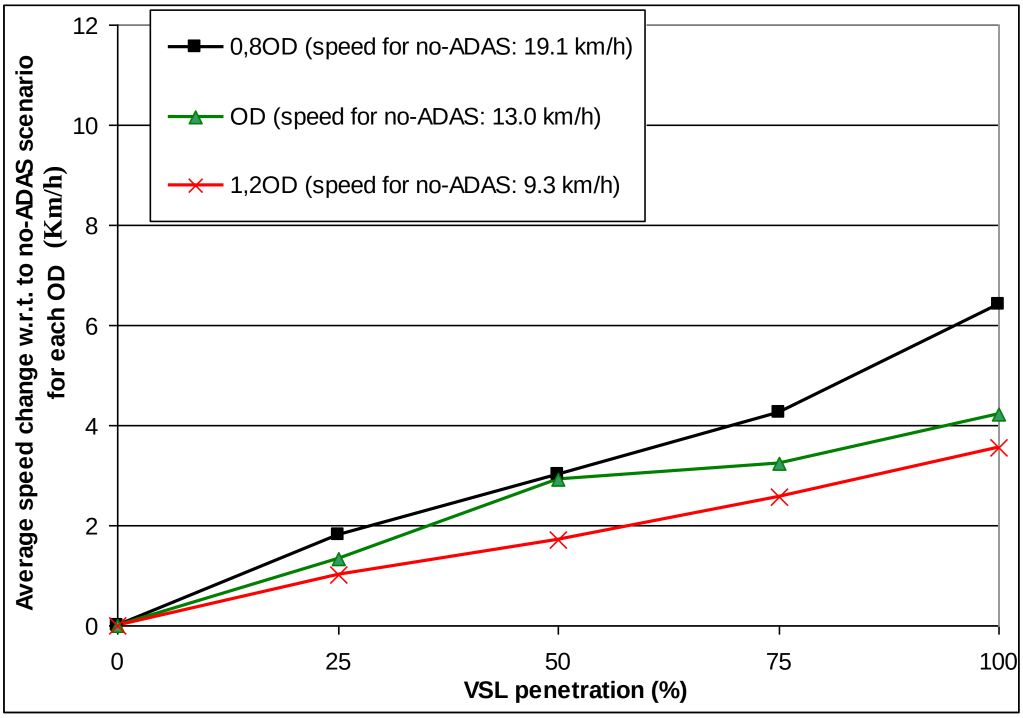

Figure 3. VSL network efficiency impacts

Figure 4 shows the simulated network-wide average speed increase due to the introduction of a system combining the characteristics of the Adaptive Cruise Control and the Variable Speed Limiter for the simulated penetration levels and demand levels. It is obvious that the average speed increase follows as expected patterns similar to those corresponding to the individual ACC and VSL impacts.

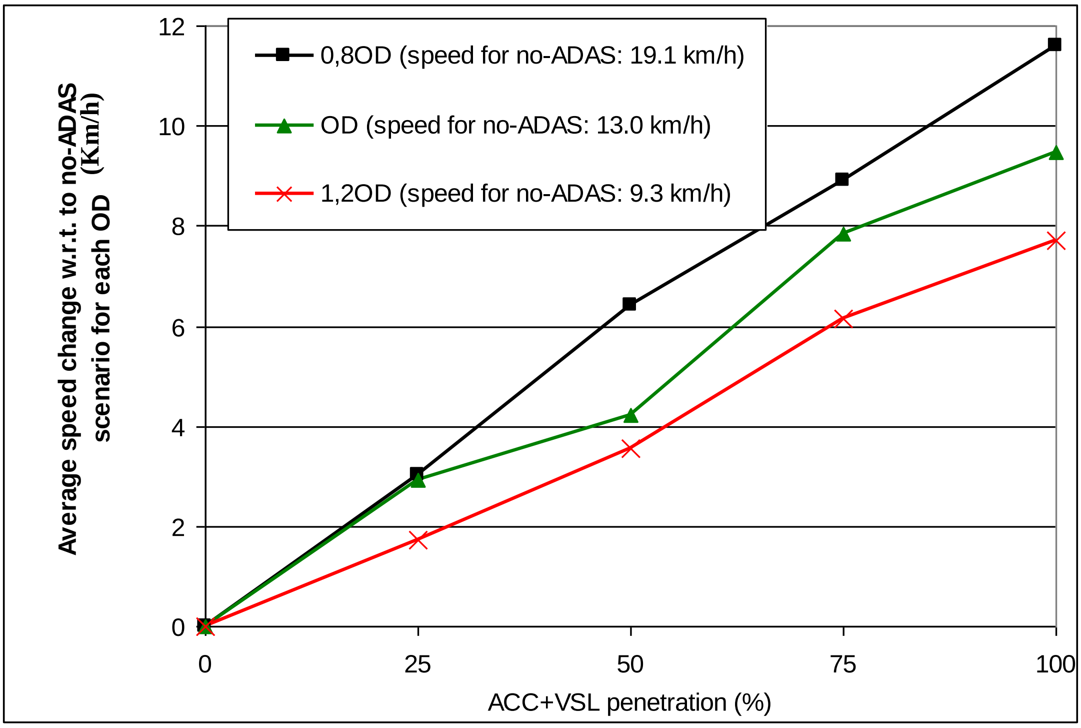

Figure 4. Combined ACC and VSL network efficiency impacts

Figure 5 visualises the simulated ADA systems' impacts from a different viewpoint. In particular, for the reference OD matrix, the simulated impacts of all three systems are compared. It can be seen that ACC provides significantly better performance in terms of average speed increase than VSL, approximately twice as significant in most penetration levels. Furthermore, the benefits of the combined ACC+VSL system seem to be only marginally higher than those of the ACC system alone. Thus, even though one can argue that a VSL system alone provides some benefits, the attractiveness of a combined ACC+VSL (at least in terms of network efficiency benefits) is not certain (since a -simpler and cheaper- ACC alone system would provide roughly the same positive traffic impacts).

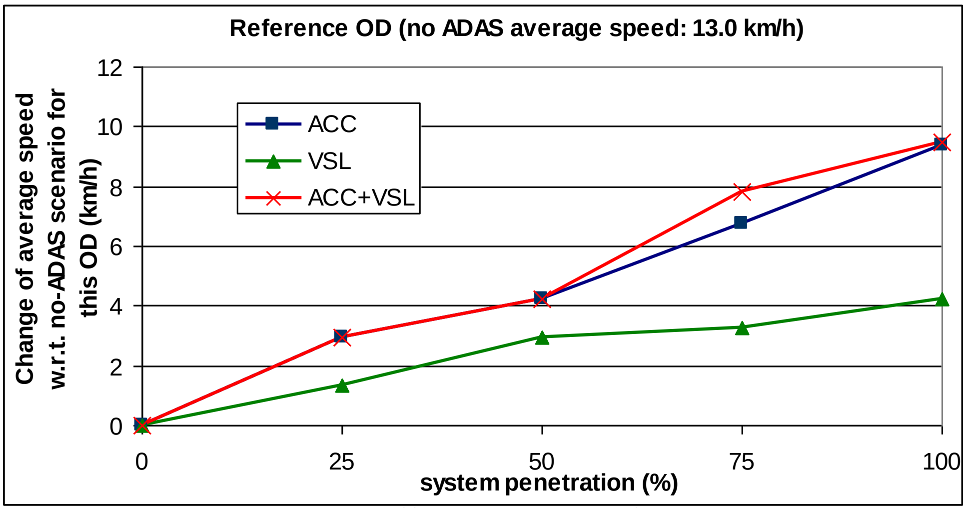

Figure 5. Network efficiency impact of all ADA systems

6 Discussion

The application of SATURN traffic simulation and assignment model to the Athens network for the various scenarios of traffic flow and market penetration level of the three advanced driver assistance systems considered allowed for the identification of basic trends of the impact of advanced ADAS on the traffic network conditions. More precisely, examining each system's impacts separately, it can be observed that the impact increases proportionally with the market penetration of these systems. The identification of the specific sensitivity of ADAS impact in relation to the ADAS market penetration provides interesting information to the system developers in their cost - benefit analyses.

Another dimension of analysis is the sensitivity of the simulated ADA system impacts with respect to the prevailing traffic conditions. In particular, as the traffic flow level increases, the average speed increase becomes smaller (when all other parameters remain unchanged). Additionally, when the simulated impacts of the three system configurations are compared, it can be deduced that ACC offers better network efficiency results than VSL (often twice as significant). It is also interesting to note that the benefits of a combined ACC and VSL system are only marginally better than the ACC system alone. This can be attributed to an important overlap in the expected impacts of the two system components.

The results obtained by the network traffic model may seem optimistic. It should be mentioned, however, that these results do not represent a permanent improvement in traffic conditions. On the contrary, like every traffic improvement, this speed increase will attract/generate an additional number of trips on the network. The increased demand will in turn result in a speed reduction, until an equilibrium has been achieved at or near the original average speed. Thus, it may be argued that the increase of the average speed does not reflect an improvement of the traffic conditions that will prevail but rather an increase in the capacity of the network after the introduction of the ADAS.

It is noted that the findings of this research represent an indicative quantification of the expected impacts of the considered ADA systems to the urban traffic conditions. Consequently, these results may constitute a useful input to the decision making process for the further development and promotion of ADA systems. However, they should be used with caution in situations where prevailing network and traffic conditions are different. Even though the proposed methodology, can be applied in other urban networks, it is clear that minor changes or partial methodology adaptations may be required to ensure applicability of the procedure and reliability of the results. Furthermore, when other ADA systems are considered, similar adaptation procedures concerning the input information from microscopic modelling may be required for facing the specific requirements of these systems.

The proposed methodological approach to the problem of estimating traffic network efficiency impacts of ADA systems can take into account possible system changes and it is applicable to any new ADA system development. Future research aiming to cover a larger spectrum of systems and networks (e.g. outside central urban areas, rural) is expected to further enlighten the sensitivity of impact of advanced driver assistance systems. Finally, in addition to the consideration of the traffic efficiency impact of ADAS, further research is needed towards the investigation of the related safety and environmental impacts of these systems. The co-evaluation of traffic, safety and environmental impact of ADAS through cost-benefit or multi-criteria analysis could be very beneficial to the industry and Government policy makers for the optimisation of the ADAS development and promotion process.

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