A Methodology for the Estimation of Traffic and Related Impacts of Advanced Driver Assistance Systems

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Abstract

The objective of this paper is to present a methodology for the estimation of the impact of Advanced Driver Assistance Systems (ADAS) on network efficiency and the environment. The methodology proposes a set of traffic and emissions simulation models, both microscopic and macroscopic. Issues relevant to the models are discussed, and the inputs to the methodology are presented, along with its expected outputs. An indicative application of the methodology is performed, where the traffic impact of the Adaptive Cruise Control (ACC) system is tested in an urban network. The simulation results indicate that the impact of the introduction of Adaptive Cruise Control can be significant in the improvement of the traffic parameters for high system penetration levels and peak period traffic conditions.

Key-words: advanced driver assistance systems, traffic efficiency, simulation, traffic models, adaptive cruise control

INTRODUCTION

The deployment of Advanced Driver Assistance Systems (ADAS) is expected to influence traffic conditions. A large variety of ADA systems are being developed by system and car manufacturers, as well as scientists worldwide (Brand et al, 1997; Davison et al, 1997; Heijer et al, 2000). Depending on their basic characteristics or utility, ADA systems can be categorised in several ways, including tactical versus operational driver support. Tactical level driver support is related to the execution of manoeuvres such as car-following and overtaking, while operational level driver support is related to lateral steering assistance and appropriate speed determination and maintenance (Heijer et al, 2000).

As such systems become increasingly popular, and their penetration levels increase, the traffic dynamics are expected to change accordingly. These changes will be reflected to a variety of measures, including but certainly not limited to traffic capacity of links, mean driving speed, fuel consumption, and pollutant emissions (SWOV, 2003).

Meanwhile, the continuous increase in car use (*demand*) in combination with the physical and financial limitations associated with the expansion of the road networks (*supply*) has led to large periods of congestion in most urban networks. These problems are well known and sufficiently documented (Bhargab et al, 1999; NRC, 1995).

Apart from infrastructure-related solutions to these capacity issues (which are both costly and -often- not feasible) and solutions improving/increasing the capacity of public transportation, potential benefits can be reaped from the widespread use of Advanced Driver Assistance systems. These systems can conceivably have a positive impact in several fields that are linked to the improvement of traffic conditions and the reduction of fuel consumption (Penttinen et al, 2000). With the insightful use of ADAS, passenger car trips can be carried out in a more efficient way or can be shifted to more efficient modes of transport. This can be achieved, for example, through better real-time information for influencing pre-trip choices, as well as offering in-vehicle information on passenger cars and on-trip information on public transport vehicles. Furthermore, better vehicle control and speed adaptation, as well as more efficient, fuel-saving driving style (by improved use of accelerator and gear shift) can be achieved by the use of ADA systems.

Another topic that is inherently associated with any new technology introduced in vehicles is that of traffic safety. The negative impacts of traffic accidents include fatalities, injuries, material damages, and disruption of traffic. The introduction of ADA systems could alleviate the consequences of road accidents, both in terms of frequency as well as intensity (Naniopoulos, 2000; Sala et al, 2000).

Acceptance and widespread use of Advanced Driver Assistance Systems, like that of any other emerging technology, can significantly gain from experimental and laboratory assessment of its expected impact prior to its full implementation. Experimental studies have been performed, using either actual ADAS-equipped vehicles, or properly configured driving simulators for the assessment of the impact of the introduction of ADAS in driver behaviour and workload. Braban-Ledoux et al (2000) propose a set of microscopic indicators for characterising driver behaviour and describe a methodology for the assessment of Dynamic Speed Adaptation on driver behaviour. Duynstee et al (2000) present the preliminary results of a research aiming at estimating the effects of Intelligent Speed Adaptation on driving behaviour, based on experimental results. Ishida et al (2000) present experimental results of an evaluation of ADAS impacts on driver's workload that they performed, using an equipped vehicle. Regan et al (2000) present an experimental trial and evaluation of an integrated suite of eight in-vehicle intelligent transport systems, focused on safety and behavioural aspects. 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. An analysis of Adaptive Cruise Control impact on the fuel consumption of equipped vehicles is presented in Neunzig et al (2000). However, none of the above research efforts has addressed in a specific way the impacts that ADA systems and driver behaviour changes due to their application may have on network traffic conditions.

The objective of this paper is to describe a methodology which can assess the traffic and environmental impacts of Advanced Driver Assistance Systems equipped vehicles at local scale and at network level. This is achieved with the use of microscopic and macroscopic traffic and environmental models, which allow the comparison of the network efficiency and environmental characteristics without and with the presence of ADAS equipped vehicles. Preliminary results obtained through an application of the proposed methodology are also presented.

The proposed methodology for the estimation of the impacts of ADAS follows. The modelling system is first presented, and the required inputs and expected outputs are described, followed by an indicative application of the methodology. Finally, conclusions are drawn and directions for further research are identified.

METHODOLOGY

In brief the procedure proposed for the quantification and evaluation of the ADA systems impacts adopts already developed microscopic models, which when fed with the appropriate input parameters calculate the impacts of the existence of ADAS equipped vehicles. This output, expressed in the form of suitable parameter values, is used in turn as input in existing macroscopic models, which calculate the ADAS impacts on a network level. The required set of models as well as their high level interrelation are presented in Figure 1.

The Modelling System

The proposed model methodology does not assume the use of particular models. On the contrary, in terms of flexibility, the proposed methodology allows the use of any set of models -microscopic and macroscopic- that comply with its modelling principles. As long as these models use the prescribed inputs and produce the required outputs, they can be considered for use within the proposed model system.

The microscopic traffic model uses several input parameters, required to accurately describe the individual vehicle's behaviour under certain traffic conditions. To achieve this task the model uses as input the functional characteristics of the ADA system considered, parameters describing the driving style of the driver, the ADAS penetration level, the traffic composition, and the prevailing level of service. The model then produces among others the capacity and headway information which correspond to the case that is being modelled and which are used as input in the macroscopic traffic model, and speed profiles that are used as input in the microscopic environmental model.

The macroscopic traffic model uses as input the traffic parameter values produced by the microscopic traffic model along with the prevailing level of service, the ADAS penetration levels, and the traffic demand, and produces average speeds and delays for each link and for the whole network considered. These outputs can be used to estimate the ADAS impacts directly, or to calculate the generalized cost for use in more sophisticated analyses e.g. in multi-criteria or cost-benefit analysis.

The microscopic environmental model receives traffic impact data (speed profiles) as input from the microscopic traffic model along with information concerning the ADAS penetration levels, level of service, traffic composition and vehicle fuel consumption and emission characteristics required for the analytical calculation of the emissions (CO, CO_2, NOx, and others; expressed in milligrams per vehicle, vehicle-kilometre or vehicle-hour) and the fuel consumption (expressed in litres per vehicle-kilometre).

The macroscopic environmental model accepts mean speeds as input from the macroscopic traffic model and emissions and fuel consumption information from the microscopic environmental model and produces among others total emission factors on a network level allowing for the identification of the percentage change of each pollutant. Other inputs used by the macroscopic environmental model include level of service, ADAS penetration levels, and traffic composition.

For the assessment of the impact due to the use of Advanced Driver Assistance Systems, the models are first run for a fleet without ADAS, as a base-case scenario. The models are then run for the selected scenarios concerning the ADA systems considered. Therefore, ceteris paribus any changes in the network efficiency and environmental conditions identified through this procedure may be attributed to the introduction of these systems.

It should be of course noted that the term ADAS covers a wide and diverse research and application area (Heijer et al, 2000). In order to ensure the reliability of the results obtained through the model set the specific characteristics of the ADA system considered should be taken into account. This dictates the need for a degree of flexibility in the modelling, mainly in the microscopic model.

For reasons pertaining to the level of maturity and magnitude of expected benefits, the structure of the model set developed for this work reflects mainly the needs of the analysis concerning non-lateral ADA systems. Indicative systems belonging to this category are the Adaptive Cruise Control (ACC), which adjusts vehicle speed to maintain a safe separation between vehicles (Hayward et al, 2000; Oei, 1998a) and the Variable Speed Limiter (VSL) which can range from external speed recommendations to an automatic speed reduction function (Oei, 1998b; Davison et al, 1997). An indicative system in this category, with a lower level of maturity refers to platooning, a situation where each vehicle travels keeping a constant headway from the preceding one, either through external speed control or through electronic speed control by the vehicle itself (Brand et al, 1997).

It should be noted that the model set is flexible enough in terms of the specific models used so that any other ADA system can be considered either by adapting the model parameters to the specific system characteristics or, in extreme cases, even by using more suitable traffic or environmental models on the microscopic level. Such cases may include road and lane departure collision avoidance systems, which are lateral control systems providing warning and control assistance to the driver through lane or road edge tracking and through determination of the safe travel speed on the basis of road geometry in front of the vehicle (Tijerina et al, 1996) or lane change and merge collision avoidance systems, providing various levels of support for detecting and warning the driver of vehicles and objects in adjacent lanes (Ryu et al, 1999).

Key Input Parameters

The identification of the impact of an ADA system requires the application of the model set to a number of scenarios. For each scenario different values are assigned to those parameters that are expected to have an influence on the impact of the ADAS considered. The scenario selection process is a very difficult procedure, since all different dimensions for each such parameter have to be captured, without covering irrelevant -with respect to the task- cases. The final number of scenarios has of course to be kept on a realistic level.

The key parameters that are considered in the modelling methodology for the estimation of the impact of ADAS equipped vehicles in the network efficiency and the environment are described below.

ADAS penetration levels During the evolutionary stage from a virtually ADAS-free traffic composition to a uniform fleet of ADAS-equipped vehicles, the penetration of ADAS-equipped vehicles is expected to increase steadily. ADA systems are expected to have considerably different impact on the traffic and environmental conditions, as their market penetration increases. Examination of a specific ADA system requires impact analysis for different penetration levels covering in a representative way the whole reasonable value range. Thus, for example, for VSL and ACC three penetration levels might be considered:

low (10%), medium (50%) and high (90%); however when it comes to platooning only one level of penetration (high) should be considered, as platooning can only function in conditions where all or most of the vehicles are suitably equipped.

Level of service One of the parameters that is expected to influence the impact of ADAS in traffic is the prevailing traffic conditions. The level of service of the particular network (or link) that is examined is selected as a way to refer to these conditions. A convenient way to quantify the various alternative traffic conditions in terms of level of service is the volume over capacity ratio (v/c) for uninterrupted flow or the mean delay for signalised junctions. Alternatively, the mean speed can be used, which reflects directly in any case the above indices.

ADAS functional characteristics For the consideration of an Advanced Driver Assistance system in the models, its technical and functional characteristics are required. The technical characteristics, which have been identified as the necessary parameters for the description of each system refer to the:

- Minimum and maximum speed of ADAS equipped vehicles;
- Acceleration and deceleration rate range of ADAS equipped vehicles; and
- Minimum headways accepted by ADAS equipped vehicles giving way at priority junctions or traffic signals, for merging turns, for entry at roundabouts, as well as lane change.

Travel behaviour characteristics They refer to the parameters required to describe the driving characteristics that influence the traffic conditions in the network. These parameters include:

- Gap acceptance, nosing and merging thresholds; and
- Lane changing pattern.

For the vehicles not equipped with the ADA system considered, acceleration and deceleration profiles of the drivers are also required.

Vehicle consumption/emission characteristics Vehicle engines are characterized by performance curves, on the basis of which the fuel consumption and the emissions production at each level of operation can be determined, taking into account the specific operating conditions, such as vehicle speed, selected transmission gear, and revolutions per minute (r.p.m.). The combination of this input with the speed profiles, produced by the microscopic traffic model, enables the microscopic environmental model to estimate the fuel consumption and emissions of the simulated vehicles.

Traffic demand and composition For the calculation of the link flows the macroscopic network efficiency model assigns to the network the demand, as expressed by the origin-destination matrix used. As far as traffic composition is concerned this is directly input in the microscopic models while for the macroscopic traffic model it is deduced for each link through the assignment of a different demand matrix for each vehicle type to the network considered.

Network parameters Simulation results are expected to depend on the structure and characteristics of the network considered. A number of network parameters can be identified and examined with respect to the way they influence the impact of ADA systems. Examples of such network characteristics include merge situations (e.g. from 2 to 1 lanes or from 3 to 2 lanes, etc.) with both left and right lanes being merged, on- and off-ramps (on 2, 3 and 4-lane roads), as well as combinations of the above. A number of other parameters may significantly affect the results of the simulations and should therefore be examined, e.g. the number of lanes per link, the existence of traffic lights and/or their cycle lengths, the junctions configuration, etc.

Model Outputs

A large amount of information is output by the proposed modelling methodology, which compares the simulated traffic and environmental information, with and without ADAS equipped vehicles in traffic.

In terms of impact type, the outputs of the proposed modelling methodology can be separated in two main categories. The first category includes traffic indicators, which describe the impact of ADAS on traffic conditions. At the microscopic level, capacity values and headways distributions are used for the description of traffic conditions, while at the macroscopic level network average speeds and delays are output.

The second category covers emissions and fuel consumption, which describe the environmental impacts of ADAS. At the microscopic level, emissions and fuel consumption for individual vehicles are output, while at the macroscopic level, emission factors and percent change per pollutant are calculated per network link and for the whole network.

INDICATIVE METHODOLOGY APPLICATION

In this section, an indicative application of the model set and the corresponding preliminary results are presented in order to exhibit the feasibility of the developed modelling methodology and the validity of its steps. Within the scope of this paper, the traffic efficiency part of the methodology is validated, using a specific ADA system, in particular Adaptive Cruise Control (ACC).

As already explained, the Adaptive Cruise Control (ACC) system senses the presence and relative velocity of moving vehicles ahead of the equipped vehicle and adjusts its speed to maintain a safe separation between vehicles. Vehicle speed is adjusted either by allowing the vehicle to coast or by transmission downshifting (Hayward et al, 2000; Oei, 1998a);

The microscopic simulation model SIMONE (Hoogendoorn, 2000), which has been developed at the Delft University of Technology, was used for the traffic impact analysis at the microscopic level. The macroscopic traffic simulation model used for the network impact analysis was SATURN (Hall et al, 1980; Van Vliet, 1982).

Microscopic Traffic Simulation

The microscopic results discussed in this section quantify the impact of an Adaptive Cruise Control system on traffic parameters of a road section. The ACC system design determines the potential changes in the average headway per lane. Important ACC design variables are, for example, the supported speed range, the supported acceleration level, the reactivation method, and the headway setting. The employed car-following algorithm and sensor characteristics are also important for changes in the traffic flow quality (Hoogendoorn, 2000).

The experimental setup used was a two-lane road section situated a few hundred meters downstream of a ramp merging. The ACC penetration levels considered are 0% (base case scenario), 10%, 25%, 50% and 100%.

The analysis distinguished between passenger cars and trucks. These two user-classes were different with respect to the parameter settings for speed-choice, vehicle parameters (length, maximum speed, acceleration and braking capabilities), car-following characteristics and lane-changing behaviour. The percentage of trucks in the total traffic was equal to 10%. Furthermore, trucks were mainly using the right roadway lane.

The capacity of the road section considered for the different Adaptive Cruise Control penetration levels - relative to the capacity for the no-ADAS base case- is presented in Figure 3. These simulation results indicate that capacity increases monotonically with increasing ACC penetration.

Headway information was also obtained from several detectors. For each penetration level simulated, headways corresponding to vehicles travelling under saturation flow conditions were considered and the average value of these "minimum" headways was calculated. The upper and lower limits of these average minimum headway values are shown in Figure 4 for each penetration level. The headways are presented as a percentage of the headway obtained for the no-ADAS scenario. The values that were used as input in the macroscopic model are the weighted average of the above data. These values are graphically represented for the various ADAS penetration levels in Figure 5.

Macroscopic Network Efficiency Simulation

As already mentioned, the well-established simulation model SATURN was used for the macroscopic simulation. The greater area of Athens, Greece, was selected as the study area for the macroscopic simulation. Athens is a city of approximately 4 million people and 1500km^2, with considerable traffic congestion problems during long periods of the day. The corresponding urban network selected consists of 1.330 links and 285 origin destination zones.

The parameter selected to capture the impact of ADAS-equipped vehicles on the traffic conditions was the mean speed of the simulated traffic. Headway information from the microscopic model was used in order to prepare the macroscopic model inputs that would reflect the impact of the ACC system for the various penetration level scenarios. The ratio of mean minimum headway for a specific penetration scenario to that of the base case (zero ADAS penetration) was used to reflect the passenger car equivalent (PCE) of vehicles equipped with ADA systems. This information was fed each time in the traffic demand matrices leading thus to different assigned flows for each link and hence to different prevailing travel speeds. For all scenarios considered, the morning peak traffic conditions were simulated.

The estimated, by use of the macroscopic simulation model, network mean speeds for the various Adaptive Cruise Control penetration levels are presented in Figure 5. The simulation results indicate that the impact on the improvement of the traffic conditions due to the introduction of Adaptive Cruise Control can be significant for high ACC penetration levels and peak period traffic conditions.

A more detailed consideration of Figure 5 indicates that mean network speed increases as the ACC penetration level increases. However, the rate of increase is not constant along the entire penetration level range. The rate of increase of the mean network speed appears to be substantial for ACC penetration increases below 25%. For ACC penetration increases between 25% and 50% the impact on mean speed increase is lower but yet considerable. For penetration levels exceeding 50% the increase of speed due to penetration increases is not easily traceable.

It must be noted, however, that for such a large road network a series of techniques for the transferability of microscopic modelling results were adopted, such as the grouping of the network road links in categories of road type resembling - from a traffic point of view - as much as possible to those road types used in the microscopic modelling. Consequently, the above results should be seen rather as a general trend and an example application of the proposed methodology than as exact quantification of ACC impact on traffic conditions. Certainly, further microscopic simulations are necessary in order to provide the required input for a wider spectrum of types of roads found in a large urban network.

CONCLUSIONS

ADA systems are based on a combination of diverse, advanced technologies aimed at improving the operations of vehicles in many dimensions. The gradual introduction of ADAS in vehicles is expected to have an impact on traffic conditions, as well as on traffic safety and the environment. In this paper, a methodology is proposed for the estimation of the impact of ADAS on traffic and environmental conditions.

The proposed methodology attempts to describe a complex phenomenon. In order to accurately capture the traffic and related impacts of Advanced Driver Assistance Systems, the methodology integrates several degrees of analysis. Very detailed models are used in order to examine the impact of ADAS at the microscopic level. Their findings are incorporated in the inputs of macroscopic models in order to examine the ADAS impact on a network level. Thus a model set is proposed for the evaluation of the ADA systems' impacts. The input required for this set is the system penetration level, the level of service of the network elements, the system functional characteristics, the driver behaviour parameters, the traffic demand and composition and the vehicle consumption/emission characteristics.

A microscopic traffic model produces among others capacity information and headway curves, which are used by the macroscopic traffic model, and speed profiles that are used by the environmental models. A microscopic environmental model calculates emissions and fuel consumption per vehicle, information required in the macroscopic environmental model. A macroscopic traffic model produces information on average speed for each link and the whole network considered while a macroscopic environmental model calculates emission factors and changes in pollutants per link and on a network basis.

The validity of the proposed methodology was tested through an indicative application. This application addressed the problem of estimating the traffic impacts due to the use of an Adaptive Cruise Control system. The methodology was shown to be realistic and flexible and produced interesting results. It was shown that the impact of the introduction of the Adaptive Cruise Control system on traffic conditions can be significant for high ACC penetration levels and peak period traffic conditions. It is obvious that the above result is only preliminary and requires more analysis with respect to sensitivity to various parameters. However, the conclusion that under certain conditions the Advanced Driver Assistance System may influence traffic conditions considerably can already be drawn.

It must be noted that prospective users of this methodology should carefully assess the individual characteristics of the considered network and traffic conditions, so that they correspond as much as possible to traffic conditions examined in the microscopic modelling. It is clear that in this context more cases should be examined in the microscopic modelling and/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 set of models selected may be required for facing the specific requirements of these systems.

The proposed methodology can provide an estimate of traffic and related impacts due to the introduction of ADA systems prior to their actual deployment. These results can be used in the assessment of the importance and urgency for implementation of each ADAS, and can therefore play an important role for their future exploitation. The methodology is a flexible one and as such it can be used to examine the sensitivity of the impact of ADAS with respect to several parameters, such as traffic conditions, level of ADAS penetration, etc. Furthermore, a number of dimensions that have not been considered explicitly in this work, such as different fleet compositions, can easily be incorporated in the methodology.

While the proposed methodology covers the traffic and environmental impacts of ADAS, it cannot directly capture other types of ADAS impacts, such as those related to safety. It would be interesting to consider the latter in an integrated evaluation approach through cost-benefit or multi-criteria analysis in order to obtain an assessment of the overall impacts of Advanced Driver Assistance Systems.

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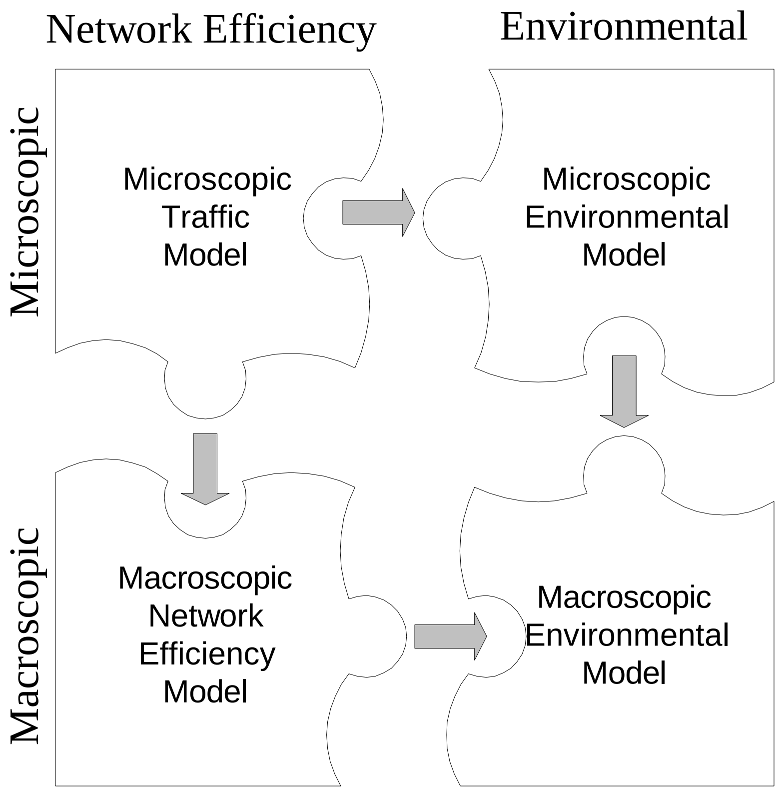
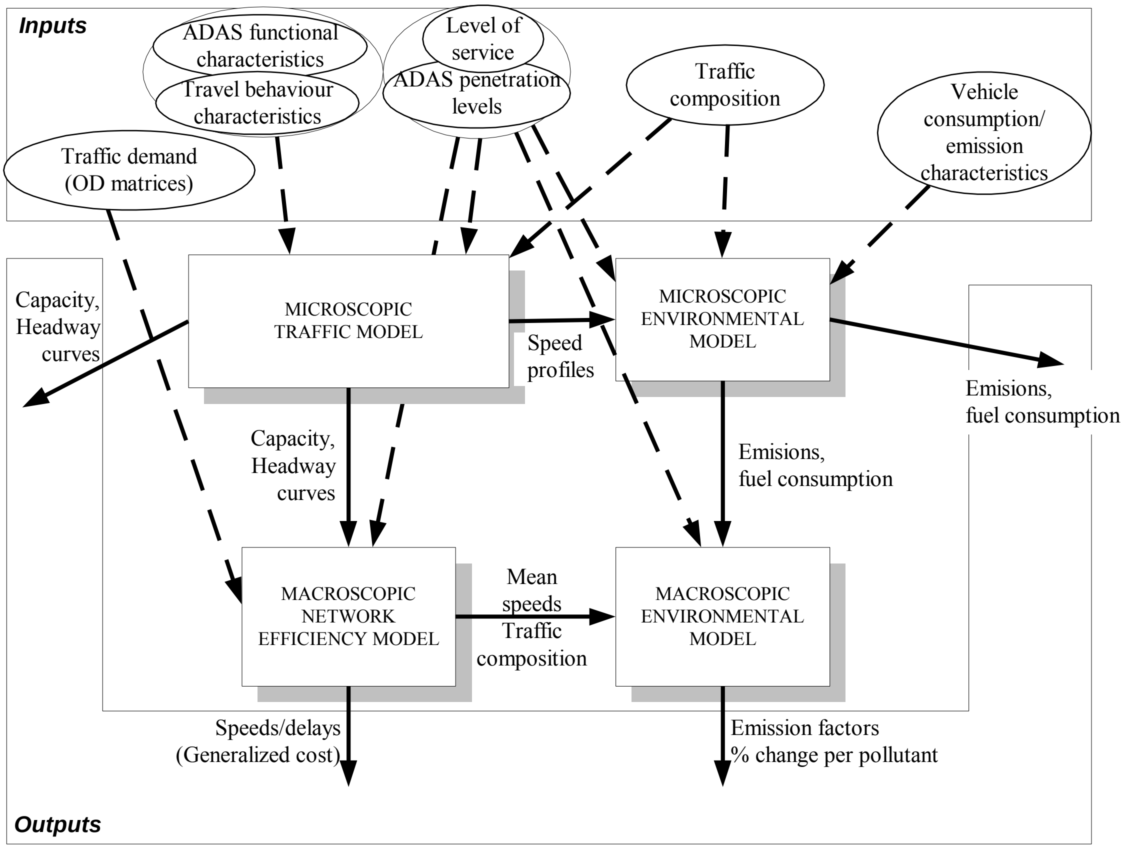
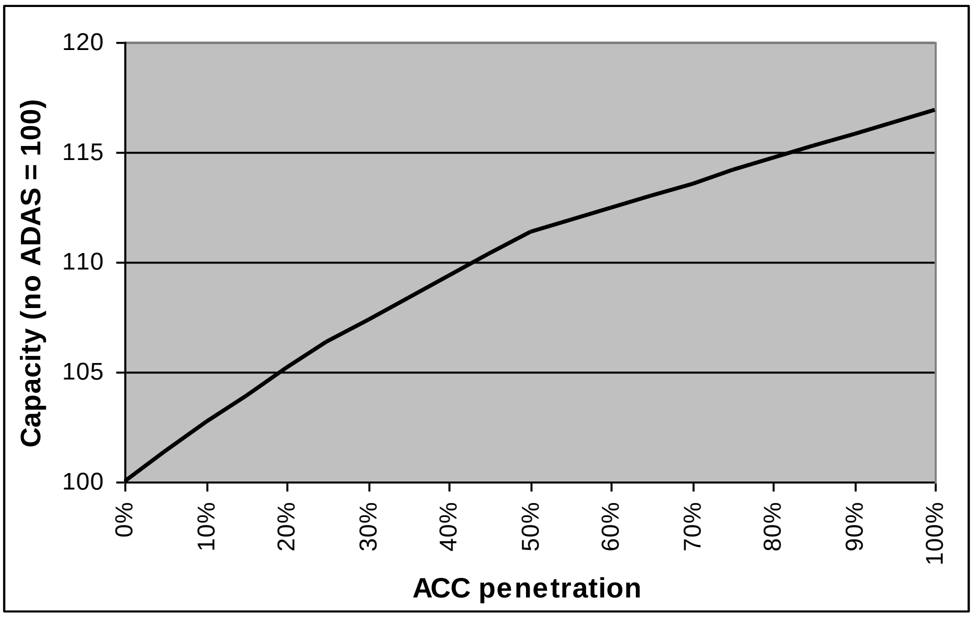
FIGURES



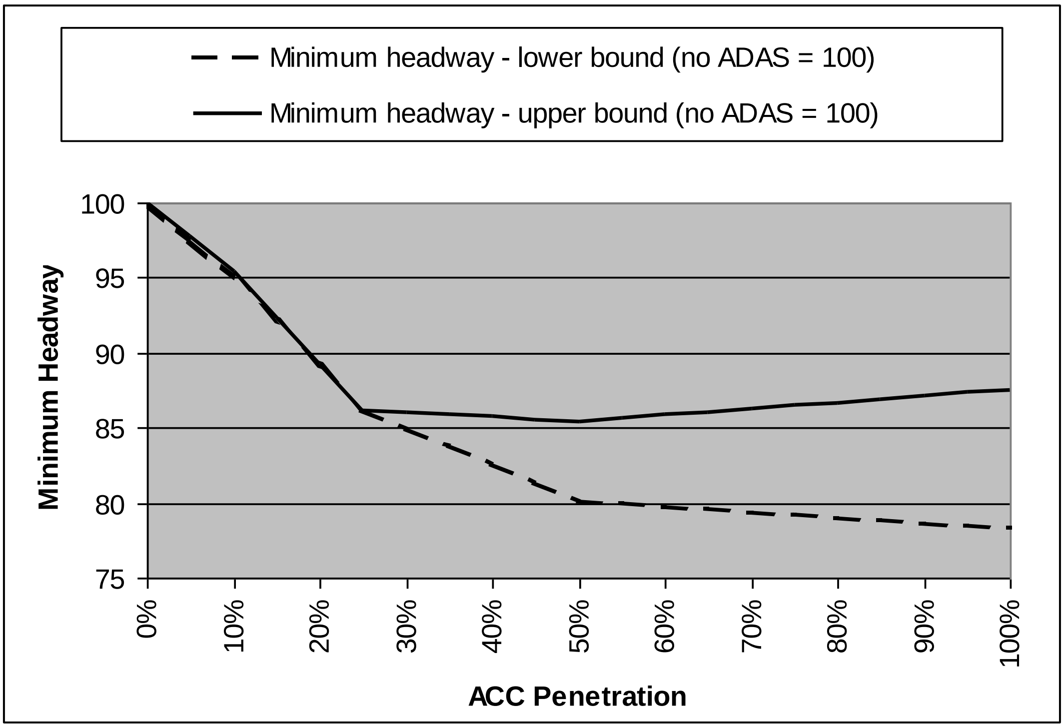
Golias et al, Figure 1. Methodology Diagram



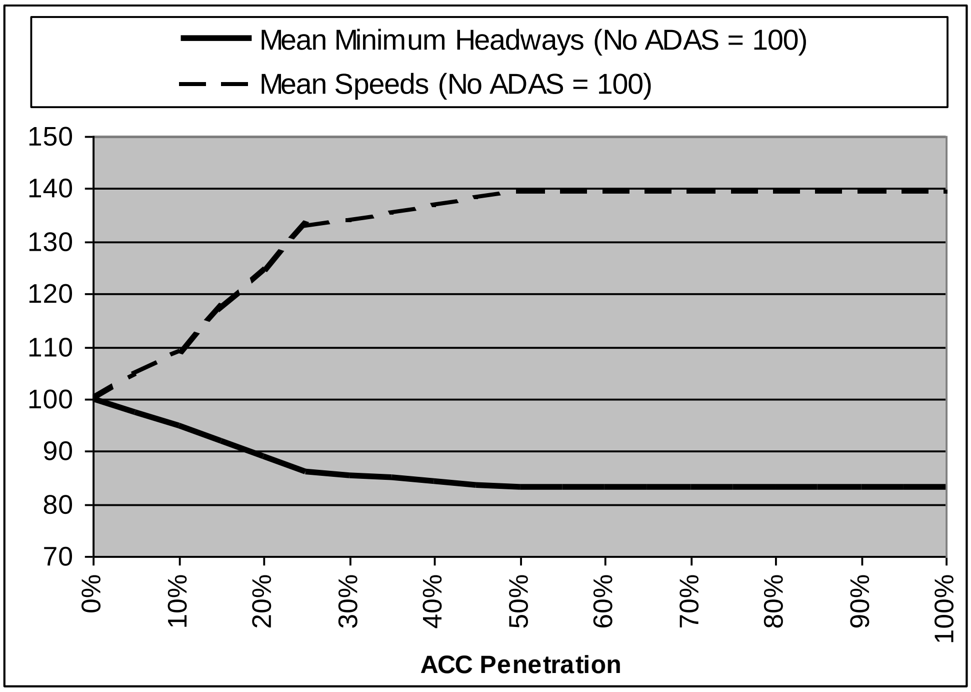
Golias et al, Figure 2. Inputs and Outputs of the Modelling Methodology



Golias et al, Figure 3. Capacity for Different ACC Penetration Levels.



Golias et al, Figure 4. Mean Minimum Headway Range for Different ACC Penetration Levels



Golias et al, Figure 5. Mean Minimum Headways and Network Mean Speeds with Respect to ACC Penetration

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