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Development of a methodology and tool to evaluate the impact of ICT measures on road transport emissions

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Abstract

The paper presents the main elements of a project entitled ICT-Emissions that aims at developing a novel methodology to evaluate the impact of ICT-related measures on mobility, vehicle energy consumption and CO_2 emissions of vehicle fleets at the local scale, in order to promote the wider application of the most appropriate ICT measures. The proposed methodology combines traffic and emission modelling at micro and macro scales. These will be linked with interfaces and submodules which will be specifically designed and developed. A number of sources are available to the consortium to obtain the necessary input data. Also, experimental campaigns are offered to fill in gaps of information in traffic and emission patterns. The application of the methodology will be demonstrated using commercially available software. However, the methodology is developed in such a way as to enable its implementation by a variety of emission and traffic models. Particular emphasis is given to (a) the correct estimation of driver behaviour, as a result of traffic-related ICT measures, (b) the coverage of a large number of current vehicle technologies, including ICT systems, and (c) near future technologies such as hybrid, plug-in hybrids, and electric vehicles. The innovative combination of traffic, driver, and emission models produces a versatile toolbox that can simulate the impact on energy and CO_2 of infrastructure measures (traffic management, dynamic traffic signs, etc.), driver assistance systems and ecosolutions (speed/cruise control, start/stop systems, etc.) or a combination of measures (cooperative systems).The methodology is validated by application in the Turin area and its capacity is further demonstrated by application in real world conditions in Madrid and Rome.

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1. Introduction

According to the Panorama of Transport (Eurostat, 2009), transport is the only sector in Europe for which greenhouse gas (GHG) emissions continue to increase, at an annual rate of ~1.5%. Road is the most significant transport mode, representing approximately 93% of total transport generated GHG emissions, which equals to ~18% of total GHG emissions in Europe. Therefore, large efforts are concentrated to reduce GHG emissions (primarily CO_2) from road transport. ICT technologies may have a significant role to play in this respect, as part on an integrated policy (EC, 2009), involving the introduction of fuel-efficient vehicle technologies, new fuels, and intermodal shifts. To name a few examples of road-traffic related ICT solutions that can potentially have a large impact on energy saving and CO_2 reduction, one may think of eco-driver assistance systems that inform the driver of energy efficient vehicle operation, dynamic traffic-light synchronization to enable 'green waves', etc.

However, the mechanisms by which such ICT solutions may impact CO_2 emissions are complex and, sometimes, diverse. Focussing on passenger transport, energy consumption and CO_2 emissions for a given demand (passenger-kilometres or pkm) will depend on the vehicle mix, the mean speed by which vehicles operate, and their speed variation. In an urban network CO_2 emissions generally drop with increasing mean speed (Ntziachristos and Samaras 2000; Van Beek et al., 2007) and decreasing speed dynamics. Drop of CO_2 emission with increasing mean speed may be counter-intuitive. For example, one may be tempted to use ICT technologies to remove reduced speed limits close to sensitive areas (schools, hospitals, etc.) at certain hours of the day. This may be seen as a measure to increase mean travelling speed, hence to reduce CO_2 emissions. However, this may increase speed dynamics with a negative effect on CO_2. At a second level, this may take several people out of public transport and into their cars, to benefit from the higher speed, increasing CO_2 emissions for the same transport demand.

The previous example shows that the full assessment of the impact of ICT measures on CO_2 emissions needs to at least take into account the following dimensions:

- How does the measure affect the driving pattern of single vehicles?
- How is the average driver's behaviour affected by the measure?
- How does the technology of different vehicles respond to the modified driving pattern?
- What kind of intermodal shifts, at fleet level, does the measure introduce?

2. Concept and objectives

The main concept of ICT-Emissions is to develop an integrated methodology that can be used to quantify the impact of ICT solutions on road transport CO_2 emissions. The methodology will provide answers to the previous list of questions by integrating results from traffic and emission models at the micro-scale (single vehicle, driving situation). Then the results will be extrapolated to the vehicle fleets (stock, total road transport) at a large urban agglomeration level using a macro traffic approach. The scientific and technical objectives of the specific research project are:

1. The development of a comprehensive methodology to assess the impacts of road transport ICT measures on CO_2 by taking into account the real-world driving and traffic behaviour in urban agglomerations.
2. The development of vehicle simulators to calculate the energy and CO_2 emissions of vehicles when operating in ICT regimes, also taking into account advanced vehicle technologies (start-stop, hybrids, plug-in hybrids, electric, etc.).
3. The simulation of the impact of various ICT measures by implementing commercial traffic models at

the micro and macro scales, and link them to vehicle simulators, following the methodology developed.
4. The validation of the methodology on existing real-world ICT applications in three cities.
5. The capitalisation in a database library of the impact of ICT measures on traffic, energy, and emissions.
6. The exploitation of the results via recommendations and implementation guidelines for use of best-practices in ICT measures that can lead to significant energy and CO_2 reductions from road transport.

Such a methodology can be used by transport planners, local authorities and automotive OEMs and suppliers, but also more generally, to quantify the impact of ICT measures on energy consumption and CO_2 emissions. The methodology is developed at two inter-linked levels: a micro-level where the impact of ICT measures is modelled at single-vehicle level. The micro-level is specifically developed for passenger cars. The micro-level takes into account the effect of ICT measures on driving pattern and driver behaviour. This is combined with an instantaneous emission model, taking into account the effect of different vehicle technologies, specifically designed to be coupled to the micro traffic model. Hence CO_2 emissions from passenger cars are calculated on the micro level. Then, results of this micro-simulation are extrapolated to the macro level, including all road transport modes. Total CO_2 emissions from road transport are then calculated by all vehicles using traffic situation and/or average speed specific emission factors for other road transport vehicles.

In this context, this methodology is expected to combine benefits from both micro and macro modelling. That is, it provides a micro modelling of passenger cars, the dominating energy consumer for passenger transport and the prime focus of most ICT measures. However, it combines the results of this detailed modelling with more aggregated level modelling (macro scale) to calculate emissions of all passenger road transport, in order to come up with the big picture. More importantly, it allows translation of a local ICT measure (e.g. street level) on CO_2 emissions of a wider area (e.g. urban level), with a representative level of detail at both the local and the wider level. The combination of approaches at different scales decreases computation time and the complexity of the approach. This makes it suitable not just for use by the developers but also by a wider audience, including less experienced authorities and road operators. Particular emphasis is given to the assessment of ICT for new vehicle technologies with increasing popularity in the coming years (i.e. hybrid, electric vehicles, etc.).

3. ICT Solutions to be considered

ICT-Emissions does not aim to develop a new complete traffic and emission model. Instead it aims at developing an integrated methodology and to demonstrate its application using commercial traffic and emission models. The intention is that the methodology can be used by stakeholders (city authorities, road operators) using their own tools and not force them to purchase yet a new suite of commercial software. At the same time, ICT-Emissions will develop some new modules and interfaces to link traffic and emission models. These are considered as an integral part of the methodology and will be made available for free. The methods and operations within these components will be described in detail so that they can be also implemented in commercial software.

In order to develop a methodology to assess the impact of different ICT measures, one needs first to identify the ICT solutions that can be possibly implemented to reduce CO_2 emissions from transport. In July 2008, the European Union and the Japanese Government established the EC-METI task force with the aim to achieve international agreement on reliable methodologies for evaluating the effectiveness of intelligent transport systems (ITS) in energy-saving and the reduction of CO_2 emissions. ITS are defined in Directive 2010/40/EC as “advanced applications which without embodying intelligence as such aim to provide innovative services relating to different modes of transport and traffic management and enable various users to be better informed and make safer, more coordinated and ‘smarter’ use of transport networks". Basically, ITS takes advantage of ICT solutions to enable more efficient and safer transport. EC-METI (2009) came up with a first technical report on ITS measures with the potential to reduce CO_2 in February 2009. This report concluded with the following list of solutions:

1. Traffic management and control systems ('green wave' strategy, traffic-adaptive urban control, ramp metering, dynamic speed limits etc.).
2. Demand and access management systems (cordon pricing, carbon credit, pay as you drive etc.).
3. Navigation and travel information systems ('green' enhanced on-board navigation, dynamic on-trip routing etc.).
4. Driver behaviour change and eco-driving (promotion and assistance of energy efficient driving).
5. Logistics and fleet management systems (relevant for freight, also public transport priority systems).

Areas 1 to 3 mostly aim at reducing congestion and decreasing total activity by which to decrease total CO_2. Area 4 mostly aims at the driver-vehicle relationship, enabling more efficient vehicle use and smoother driving. Finally, area 5 mostly targets freight transport and the logistics associated with it. For passenger transport one could look into fleet management for buses but the effect is expected relatively small due to the small contribution of buses to total road transport CO_2. In addition to these five main areas, the report identified two more areas with a CO_2 reduction potential, i.e.

- Safety systems, to avoid congestion due to accidents, and
- Co-operative systems, which combine two or more of the areas above.

Further to this, the European Commission funded the study "Impact of Information and Communication Technologies on Energy Efficiency in Road Transport" (Klunder et al., 2009). The study assessed ITS measures, vehicle technologies and other solutions based on ICT. The available measures were distinguished into three categories, i.e. eco-solutions, advanced driver assistance (ADA), and traffic management systems. In principle, these three categories are a different grouping of solutions also identified in the EC-METI report, with the inclusion of some newer and more vehicle-oriented ICT solutions such as "active gas pedal", start-stop systems, tyre-pressure indicator, etc.

In addition to identifying the different ICT solutions, the report also made an initial evaluation of the potential benefits of each ICT solutions at EU27 level. The evaluation took into account the impact of each measure at a micro level but also the ease of implementation, the expected penetration of each measure in reality as well as risk factors associated with its introduction (i.e. compliance of drivers with the measure) at a large scale. This first screening identified the following solutions of higher importance, in order of decreasing CO_2 reduction potential:

- Eco-driver coaching, that is eco-driving information on the vehicle linked to map information in order to take into account upcoming driving situations.
- Eco-driver assistance, which is similar to coaching but without map-enhanced possibilities.
- Pay-as-you-drive, which decreases demand and shifts passengers to public transport.
- Platooning, i.e. following the speed of the car in front to avoid unnecessary speed variation.
- Adaptive cruise-control, i.e. keeping a predetermined constant speed, regulated for the speed of the car in front.
- Dynamic traffic light synchronization, i.e. enabling a 'green wave'.
- Fuel-efficient route choice, i.e. navigation systems which optimize route on the basis of CO_2 emissions and fuel consumption.

It should be repeated that the report ordered the potential of ICT solutions taking into account also their expected penetration at EU27 scale. At local/regional level, the order could be different. For example, the same study reports examples where dynamic traffic signalling led to CO_2 improvements of more than 12.5%, while eco-drive coaching is assumed to lead to 5-10% CO_2 reduction. Therefore, depending on the particular application and the range considered, different measures may lead to various degrees of CO_2 reduction.

Despite the limitations of the two studies, they both offer a very good overview of available ICT measures and a good starting point on which to base the analysis. Both studies demonstrate that, for passenger transport, traffic management systems, on-board vehicle technologies and a combination of the two (cooperative systems) do offer significant CO_2 benefits. They affect the driving pattern of single vehicles and the driver behaviour. They bring a localized effect which then gradually leads to larger change of transport in the greater metropolitan area. In particular, new and upcoming vehicle technologies offer interesting interactions with ICT measures.

The approach developed in this work is expected to enable the modelling of ICT solutions at the micro level and project their impact on the macro level in terms of total CO_2 emissions. The work will address primarily the following ICT categories:

1. Traffic management and control systems
2. Access management systems
3. Navigation and travel information systems
4. Eco-driving
5. Advanced driver assistance systems
6. Accident avoidance (potential to model traffic with and without accident but not to model impact of safety systems on accident prevention)

4. Obstacles and shortcomings on ICT evaluation

The EC-METI study and the report by Klunder et al. (2009) reviewed both the traffic and the emission models that can be potentially used to simulate the impact of ICT measures on energy efficiency and CO_2 emissions from transport. Several models exist both for traffic and emission simulations. Traffic models range from micro models (single vehicle, driving pattern) to macro models (vehicle stock, mean travelling speed). Emission models range from instantaneous models that can be used to calculate emissions of single vehicles on a second by second basis, to average-speed and aggregated emission factor models (urban, rural, highway) with much less resolution. These models have been developed to fulfil different needs and may be used with various degrees of success to simulate ICT related measures.

It is important to identify the main shortcomings outlined by these studies as regards the use of existing traffic models for ICT evaluation, which basically defines the current state-of-the art:

1. Uncertainties in modelling of driver behaviour to traffic signals, driving advice, etc.
2. The development / simulation of realistic speed-time profiles at the micro level, also taking into account that a distribution rather than a single profile appears in real-world conditions.
3. The sensitivity by which models can address the impact of ICT measures.
4. Extrapolation of results from the micro to the macro scale, or in other words the interaction between individual vehicle behaviour and traffic flow.

With regard to emission and energy consumption models, the studies identified the following issues:

1. Models, in particular instantaneous ones, are often based on a limited number of vehicles which makes results specific to the particular vehicles.
2. Depending on their formulation, emission models seem to perform better in specific conditions and are not generally appropriate for a range of ICT solutions.
3. Lack of a validated link between driver behaviour and engine/vehicle response, which would be relevant for several ICT measures.

However, most importantly, the two studies identified the lack of a consolidated interface (appropriate scales and parameters) between traffic and emission models that could be used to reliably transfer information between the two. Hence, the application of the two models can currently be performed off-line, i.e. first the traffic model simulates the driving condition and this then has to be introduced in the emission model manually and by using assumptions for the parameters that are not common in the input-output files of the two models. Extensive lists of some relevant traffic and emission models which represent the current state of the art can be found in the EC-METI (2009) report and the study of Klunder et al. (2009). Since the overall approach tries to be versatile and not model-specific, the details of the available models are of secondary importance.

5. Methodology description

The ICT-Emissions project will attempt to establish the missing links between traffic and emission modelling at the micro and the macro scale. It will also develop an instantaneous emission model best suited to be linked to traffic micro-scale models. In this context, the following list outlines the main points of ICT-Emissions which define the progress beyond the state-of-the art:

1. Development of an integrated methodology for the assessment of ICT solutions on energy and CO_2 emissions, addressing the following items:
   a. Link of micro and macro traffic models for the assessment of ICT solutions impact
   b. Link/interfaces between emission and traffic models both at the micro and the macro levels.
   c. Consideration of driver behaviour through collection of data from dedicated monitoring campaigns and earlier projects and development of correction algorithms.
   d. Improvement in the links between vehicle behaviour and engine response, in particular modelling the impact of advanced driver assistance systems.
2. Parameterization of a number of ICT measures, including eco-solutions, advanced driver assistance systems and traffic management systems for simulation by traffic and emission models.
3. Collection and simulations of driving profiles with and without ICT interventions.
4. Collection of new experimental information to fill gaps and/or increase the size of the vehicle sample used for the development of emission factors in emission models.
5. Development of a vehicle engine/emission simulator to be linked to micro-scale models to calculate the impact of ICT measures on energy, CO_2 emissions, including new vehicle concepts (hybrids, range extenders and electric vehicles).
6. Validation of the model output both at the traffic simulation level but also at the emission modelling level, by executing two real-world experiments on the impact of ICT measures.
7. Guidelines, suggestions and modelled results for a number of cases to assess the impact of ICT measures in without the need for detailed modelling.
8. Demonstration of the impact of ICT measures in a number of cities.
9. Collection of guidelines, suggestions and of all measured and modelled outputs in a database that can provide a useful input in characterising the impact of various ICT solutions, without the need to run detailed modelling calculations.

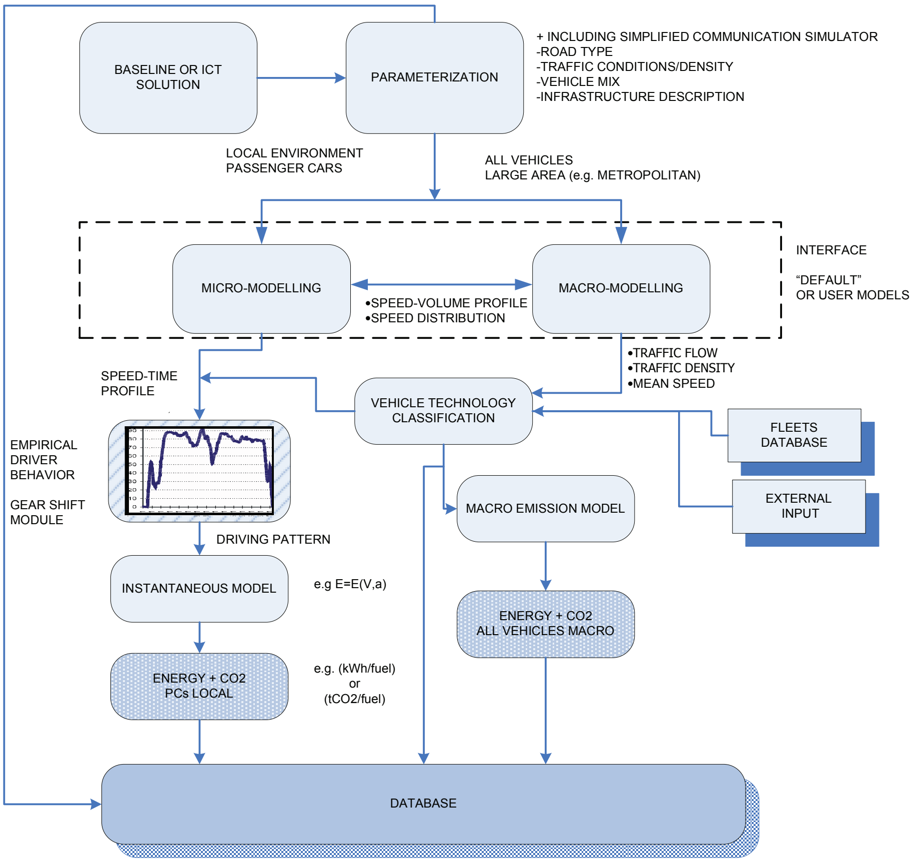

Fig. 1. Flow chart of the methodology outline.

In order to demonstrate how these targets can be achieved, Figure 1 provides a possible realisation of the methodology considered in this project. After a baseline or ICT solution is decided, this is parameterized, i.e. the road type, traffic conditions, vehicle mix, infrastructure description elements are defined in the parameterization module. These are necessary as input to the micro and macro simulators. A simplified communication simulator is also embedded in this module. This is not going to be an actual physical model, but basically an option to delay information between an event and the timing a driver is informed. The parameterization module provides output both for the micro modelling (passenger car characteristics at the micro level, and traffic density of other vehicle types, as well as output at the macro level i.e. driving conditions in a wider area). Then the micro and macro models are run by respecting an internal equilibrium between speed-volume profiles considered by the two models for the interface network links. The micro model then delivers a speed-time profile and the macro-model calculates traffic flows, density and mean speed over the wider area. The output of the two models is internally consistent. A vehicle classification module then intervenes which classifies vehicles in different types and emission classes. Information for this model may come either from the FLEETS database (Ntziachristos et al., 2008), or external input by the user, in case such information is available. For the macro case, all information is introduced in a macro emission model and total CO_2 emissions are calculated.

The speed-time profile from the micro model is input in a 'driver simulator module' (Figure 2). This module simulates the driver and uses empirical algorithms to filter the output of the micro model, i.e. remove jerk events, smooth-out speed transitions of high frequency, replace creeping speeds with idle, etc. Also, the driver simulator should predict gear shifting based on different driving attitude (e.g. smooth, normal, aggressive). This realistic driving profile will then be introduced to the instantaneous emission model to calculate detailed CO_2 for various technologies of passenger cars. All results, together with descriptors for the baseline or ICT solution considered, its parameterization, the driving pattern, and the vehicle mix considered will be introduced in a dedicated database that will become available as a deliverable of the project.

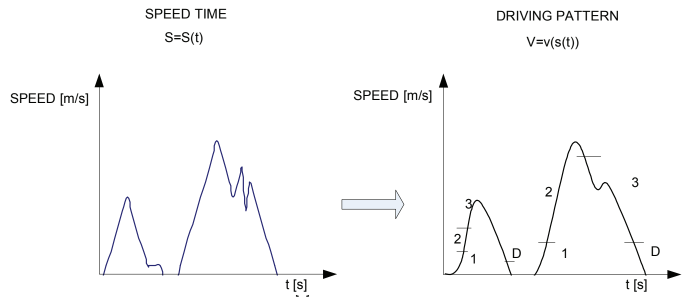

Fig. 2. Schematic of the operation of the driver simulator module.

The dashed line in Figure 1 designates the interface that will be delivered by the methodology. Inside the area defined by the dashed line, any micro and macro models can be used, provided they respect the traffic equilibrium criteria in the network links where the two models interface. In order to demonstrate the application of the methodology, the micro-scale VISSIM[†] and AIMSUN[‡] models and the macro-scale VISUM[§] and MT Model (C.S.S.T., 1997) will be used. The area outside the dashed line will consist of modules and interfaces either from the public domain or specifically designed in the framework of this project. For example, CEMOD (Kousoulidou et al., 2010) can be used as a public-domain instantaneous model within ICT-Emissions and a COPERT (Ntziachristos et al., 2010) or HBEFA[**] type of approach (with extensions from this project) can be used as a public domain macro-scale emission model. CRUISE[††] is an example of a commercial instantaneous model to be used for emission at the micro-scale.

A special case of particular attention is cooperative solutions, i.e. cases where traffic measures are combined with vehicle technology, such as ADAS, to bring combined benefits. In this case, a detailed modelling approach, taking into account the advanced capabilities at vehicle level will have to be taken into account. Such an application is shown in Fig 3. The "vehicle model" is a simulator of the advanced vehicle capabilities. Such a model consists of three sub-models:

- Sensor model: Dependent on the related ADAS a number of sensors will be simulated, providing the information required by the vehicle dynamics model and the ADAS models. This includes both:
  - Provisioning of local sensors information like distance sensors, traffic sign recognition, or speed

[†] http://www.ptvag.com/software/transportation-planning-traffic-engineering/software-system-solutions/vissim/
[‡] http://www.aimsun.com/site/
[§] http://www.ptvag.com/software/transportation-planning-traffic-engineering/software-system-solutions/visum/
[**] http://www.hbefa.net
[††] http://www.avl.com/cruise1

measurement based on the simulation data of the micro simulation.
- o Provisioning of information delivered by communication systems for Car2Car communication or mobile traffic information services like position and speed of surrounding cars, traffic flow data or traffic signal timing data.

- ❖ Vehicle dynamics model: This model determines the behaviour of the simulated driver/vehicle unit. Based on the input of the sensor models and the evaluated ADAS it determines the relevant dynamic driving parameters for the micro simulation.
- ❖ ADAS model: Each ADAS evaluated in this project requires a dedicated model providing the reaction of the driver/vehicle unit to the current traffic situation, e.g. acceleration, deceleration.

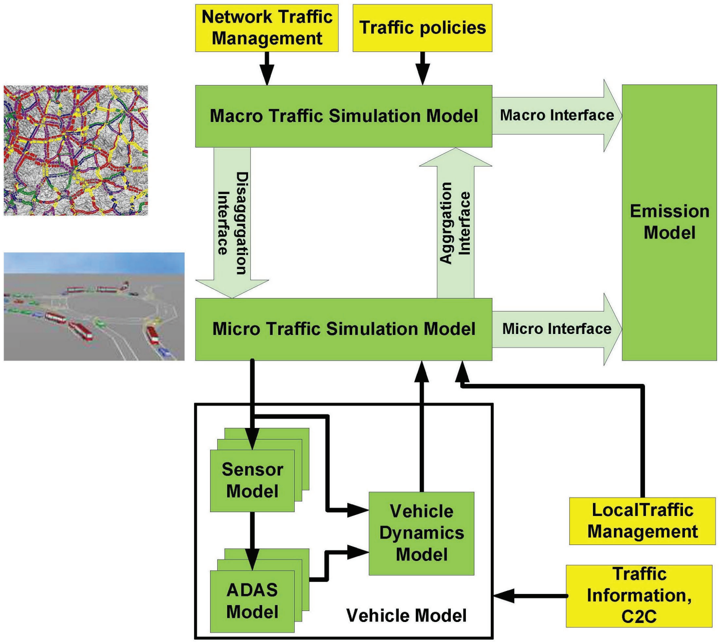

Fig. 3. Example of micro-macro simulation in the case of ADAS.

A number of parameters will have to be communicated on a second-by-second basis between the micro and the vehicle models. The micro model will communicate to the vehicle model the current speed of the vehicles in the micro-model, their acceleration, their position in relation to the ADAS vehicle(s), and the current target speed of the driver/vehicle unit of the ADAS vehicle(s). The maximum deceleration and acceleration levels of the ADAS vehicle(s) will be taken into account as boundary conditions. The vehicle model will then communicate back to the micro model the adapted target speed and acceleration of the ADAS vehicle(s). The vehicle model can be developed as part of the parameterization module. In this case a bi-directional link will be required between this and the micro model in Figure 1.

ADAS systems that will require such kind of approach include:

- ➢ Adaptive Cruise Control (ACC) only, i.e. only car sensor information.
- ➢ Real-time traffic signal timing information (TSTI) to drivers and reaction by driver.
- ➢ Informed ACC with TSTI, i.e. the ACC makes use of the traffic signal timing information to adapt automatically the travel speed for eco-driving.
- ➢ Informed ACC with Car2Car communication and/or accurate traffic flow information, i.e. the ACC

makes use of position, speed and acceleration data of surrounding cars to adapt automatically the travel speed for eco-driving.

- Informed ACC with Speed Limit Information, i.e. the ACC makes use of speed limitations to improve to adapt automatically the travel speed for eco-driving.

6. Summary

ICT-Emissions project aims at developing a novel methodology that can be used to quantify the CO_2 emissions of ICT solutions for road transport. The proposed methodology combines traffic and emission modelling at micro and macro scales. These will be linked with interfaces and submodules that will be specifically designed and developed. The methodology is developed in such a way as to enable its implementation by a variety of emission and traffic models. Particular emphasis is given to (a) the correct estimation of driver behaviour, as a result of traffic-related ICT measures, (b) the coverage of a large number of current vehicle technologies, including ICT systems, and (c) near future technologies such as hybrid, plug-in hybrids, and electric vehicles.

The innovative combination of traffic, driver, and emission models produces a versatile toolbox that can simulate the impact on energy and CO2 of infrastructure measures (traffic management, dynamic traffic signs, etc.), driver assistance systems and ecosolutions (speed/cruise control, start/stop systems, etc.) or a combination of measures (cooperative systems). The methodology is validated by application in the Turin area and its capacity is further demonstrated by application in real world conditions in Madrid and Rome. The main deliverables of the project will include (a) a vehicle energy/emission simulator for conventional and advanced passenger cars (b) a parameterization submodule (c) a driver simulator (d) a database with driving situations and structure for ICT impact evaluation and (e) an ICT-Emissions methodology handbook.

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