

MULTI-ASPECT DEVELOPMENT AND EVALUATION OF INTEGRATED FULL-RANGE SPEED ASSISTANCE

Bart van Arem, TNO, Delft, The Netherlands, +31 15 26 96770; bart.vanarem@tno.nl
Hans Driever, Philipus Feenstra, Gerdien Klunder, Hans Kostense, Zoltan Papp, Jeroen Ploeg, Isabel Wilmlink (TNO, the Netherlands)

ABSTRACT

Integrated full-Range Speed Assistance (IRSA) aims to assist drivers in their longitudinal driving task by providing speed advice or warnings and cruise control-like functionalities. This paper presents the development and evaluation of IRSA in four scenarios: Approaching a traffic jam, Approaching a reduced speed limit zone, Leaving the head of a queue and a cut-in situation. The results are obtained by application of an integrated tool-suite enabling a consistent assessment of technical functioning, human factors and traffic flow effects.

INTEGRATED FULL-RANGE SPEED ASSISTANCE

Speed is one of the key factors in road traffic. It is positively associated to the quality of travel: a high speed implies a short travel time. However, a high speed can also lead to high accident risk or high emission of exhaust gas and noise. The speed of a vehicle is traditionally controlled by the driver, who takes into account local traffic conditions as well as applicable speed limits. However, decisions by the driver are sensitive to judgment and operational errors. Many accidents are speed-related and partly due to human error. In cases of congestion, human drivers are typically poor controllers.

Advanced Driver Assistance (ADA) systems are systems that support a driver in his driving tasks. An example of an ADA system that is commercially available is the Adaptive Cruise Control (ACC) system: by extending a 'regular' cruise control system with a radar sensor, the vehicle can maintain a preset speed, but also adapt the speed to a slower predecessor. In addition to sensors on the vehicle, ADA systems can also use wireless communication systems to receive/send information from/to road-side systems and other vehicles.

In order to support the development of ADA systems, TNO has developed the SUMMITS Tool Suite. This is an integrated tool suite to assess issues regarding technical functioning, human factors and traffic flow in a consistent way. The IRSA system is a collection of functions to support a driver in maintaining an appropriate speed in a number of selected traffic conditions, such as approaching a traffic jam, cut-in situations and leaving the head of the queue at a traffic light.

This paper describes the overall approach and an impression of the results. It will discuss the research questions, the SUMMITS Tool Suite that was used as well as the meta-model and the traffic scenarios that were used for the Integrated Full-Range Speed Assistance system. In addition to that, it will discuss the results of the assessment of the system with respect to technical functioning, human factors and traffic flow effects. The paper ends with conclusions.

RESEARCH QUESTIONS

The following research questions were defined. First, to what extent can cooperative driving, achieved through vehicle to vehicle and vehicle to infrastructure communication, contribute to improved traffic and system safety, improved throughput, improved environmental aspects (gas emissions and noise) and improved driver comfort and safety perception. Second, what implementation issues exist, in the areas of robustness, stepwise introduction, structured

design methodologies and expected social benefits under different circumstances?

THE SUMMITS TOOL SUITE

The SUMMITS tool suite (1) consists of different tools that cover specific aspects of cooperative vehicle-infrastructure systems varying from traffic flow analysis to assessment of human factors and from dependable cooperative control architectures to fault tolerant hardware implementation, see Figure 1.

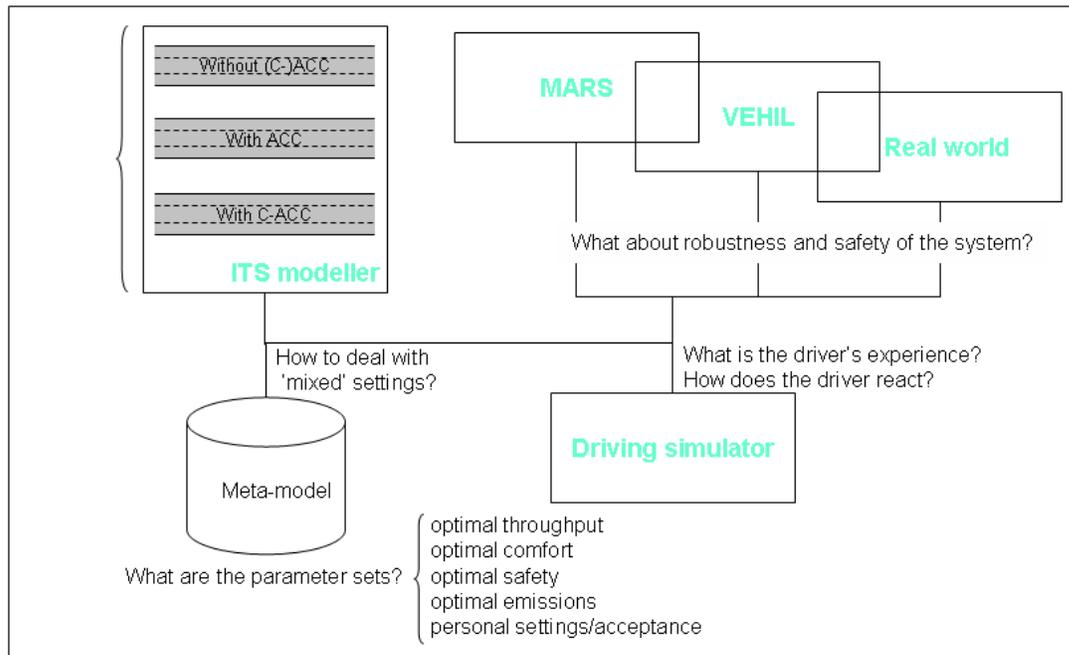


Figure 1: Multi-aspect development using the SUMMITS Tool Suite

The SUMMITS Tool Suite consists of driving simulators and instrumented vehicles, simulation environments for the design and evaluation of the next generation of intelligent vehicles (MARS, PreScan and the ITS Modeller) and TNO's Vehicle Hardware In the Loop (VEHIL) laboratory for testing and development of intelligent vehicle systems with moving bases. In order to ensure the consistency between the different tools, a common mathematical model of the IRSA system (the *meta-model*) was set up by a team of people with different backgrounds and expertise. They defined the IRSA system in such a way that all 'levels' could work with the same meta-model. In other words, the same IRSA system is assessed in the traffic flow simulation, the driving simulator, high-fidelity Hardware In the Loop (HIL) simulator or in an experiment on the road, albeit with different levels of detail in the algorithms.

THE IRSA META-MODEL

The cruise control function of IRSA was either an Adaptive Cruise Control (ACC, predecessor detected by radar, a Cooperative Adaptive Cruise Control (CACC, with a maximum of 3 predecessors detected also by vehicle-vehicle communication) or a CACC+ which was also capable of receiving messages from slowly driving vehicles further downstream. For the cooperative functions two variants were considered: the first based on the most restrictive acceleration with respect to each predecessor (CACC1), the second based on just the average speed of slower equipped predecessors (CACC2). For a detailed

description including the control rules, we refer to (2). Regarding the interaction of the system with the driver, both an informative and controlling variant were used.

SCENARIOS

The IRSA system was developed and tested for different traffic scenarios: a cut-in situation, approaching a traffic jam, approaching a reduced speed limit zone as well as leaving the queue of the queue at a traffic light. In this paper we focus on the scenario ‘Approaching a traffic jam. Vehicles broadcast messages containing their location and speed when their speed drops below a certain threshold, or when they have to brake hard. Figure 2 shows a sketch of how this functionality might work. The primary aim of this scenario is to increase traffic safety. By alerting drivers for slow traffic downstream, a driver will be better prepared for the braking manoeuvre. In the controlling mode, the IRSA system takes the speeds of the downstream traffic into account. A maximum broadcast distance of 300 m was used.

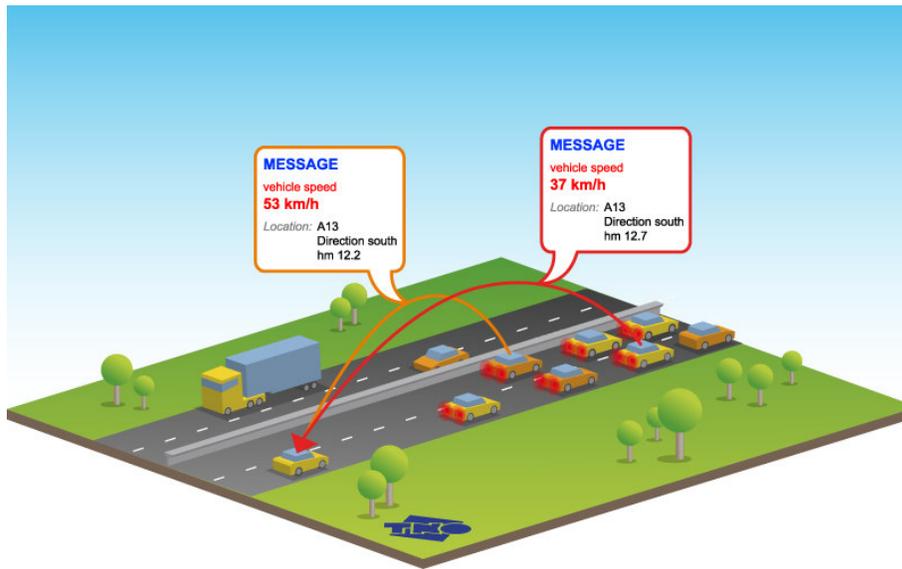


Figure 2: Approaching a traffic jam

TECHNICAL FUNCTIONING

The technical functioning was tested and evaluated on two levels. First model based fully simulated evaluation round was done using MARS, a high-fidelity model, to answer questions around sensor specification, robustness and cooperative safety (3). Second, final tests were carried out using the VEHIL hardware-in-the-loop facility as well as tests on a test track.

From the simulations, it was found that the results of the traffic jam approach scenario illustrate the differences in controller behavior best. The evaluation is based on the longitudinal acceleration and the spacing (actual distance between the vehicles). The simulation results of all controllers are presented in Figure 3.

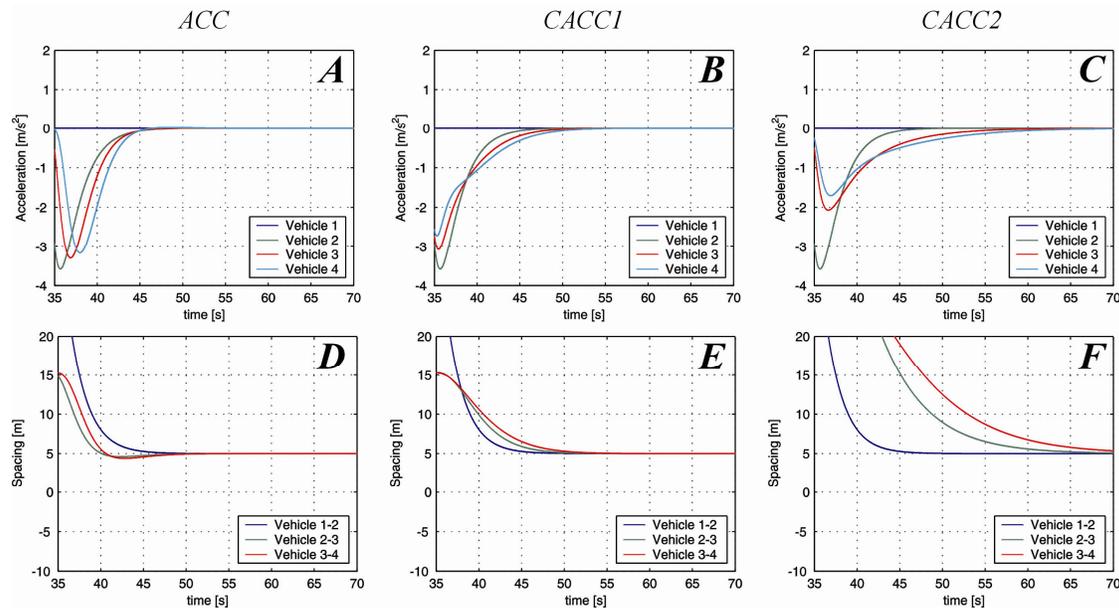


Figure 3. Simulation results of a traffic jam approach

After investigating these and other similar results, the following conclusions were drawn concerning the performance of the controllers:

- ACC
 - *Safety*: Although the scenario is handled well by the common ACC, it should be noted that the spacing, i.e. the measured actual distance between two subsequent vehicles, decreases rather fast and that even some undershoot occurs after $t = 40$ s. This indicates a critical safety level.
 - *String stability*: After $t = 40$ s, the spacing between vehicle 3 and 4 is just a little smaller than the one between vehicle 2 and 3. Given the fact that the desired spacing (not shown in the figure) is near constant throughout the platoon at this point of the simulation, it can be concluded that the spacing error slightly increases to the end of the platoon. The string is thus unstable, albeit very slightly.
 - *Comfort*: Although comfort is certainly not only dependent on acceleration, it can still be stated that acceleration levels smaller than -2 m/s^2 are in general not considered comfortable. As a result, the ACC behavior can be regarded uncomfortable.
- CACCI:
 - *Safety*: Compared to the ACC behavior, the spacing is now much larger during the greater part of the maneuver. Moreover, there is no undershoot anymore. As a consequence, this controller can be regarded safer than the ACC.
 - *String stability*: Because of the direct communication to all vehicles in the string, the vehicles react earlier on disturbances. This results in significantly increased string stability as can be seen in the increased spacing.
 - *Comfort*: compared to the ACC controller, the minimum acceleration is slightly larger, resulting in a moderate comfort improvement.
- CACC2:
 - *Safety*: Because the spacing is now very large, the controller can be regarded the safest.
 - *String stability*: With respect to both other controllers, a better damped response is shown. Consequently, the string stability is better.

- *Comfort*: The deceleration level is decreased compared to the previous controllers, indicating a significant improvement with respect to comfort. For vehicle 2 and 3, the deceleration is above -2 m/s^2 .

After successfully completing this phase the final tests of the technical functioning was carried out using the VEHIL hardware-in-the-loop facility as well as tests on a test track, see Figure 4.



Figure 4: Real-world test on a test track

During the real-world test, four vehicles were used. All vehicles were equipped with V-V communication. The first vehicle made a strong deceleration. The second vehicle was equipped with the ACC controller, the third and fourth vehicles were equipped with the CACC controllers. They were equipped with Lidar sensors which have a maximum detection range of 50 m. The tests showed that the CACC controller was able to decelerate in time in situations where the ACC algorithm could not decelerate in time and a steering action was needed to avoid a collision. The real-world pilot successfully demonstrated the add value of vehicle-vehicle communication compared with autonomous systems when approaching a traffic jam. Compared with the simulations, the difference between the ACC and both IRSA controllers was intensified by the limited detection range of the lidar. Because the object is detected in a later stage compared to the simulations, the deceleration levels of the vehicles equipped with ACC were much higher than the deceleration levels of both IRSA controlled vehicles.

HUMAN FACTORS

The behaviour of a driver in a vehicle with IRSA was studied in a driving simulator environment for a cut-in manoeuvre: A subject was driving on a 2-lane motorway with a speed limit of 100 km/h and instructed to stay in the right lane as much as possible. At a certain time instant another vehicle cuts in before the subject vehicle. The IRSA system had 3 variants to help the driver to achieve a stable car-following situation. The first variant gave a headway advice (advisory), the second variant used a counterforce on the accelerator pedal (intervening) and the third variant used an Adaptive Cruise Control function (controlling). The experiments were conducted in both light and busy traffic and for small and large time headway (THW) settings. Figure 5 shows the measured time headway of the subject vehicle during the cut-in situation.

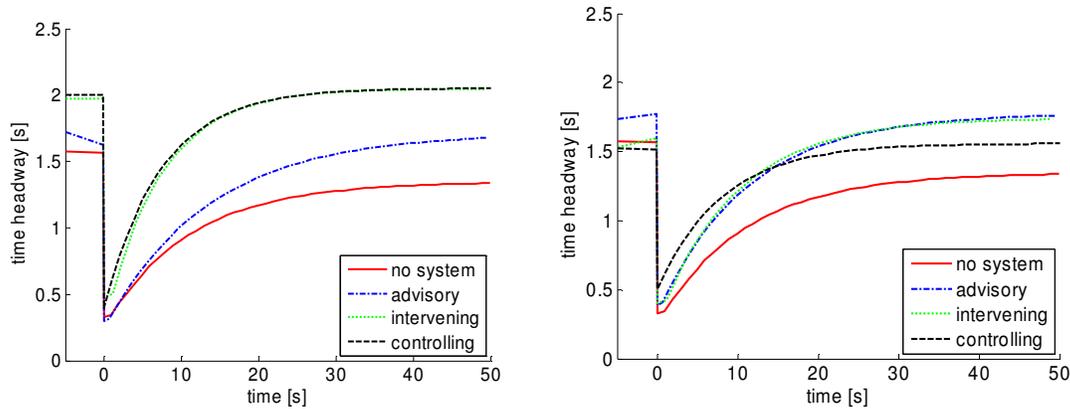


Figure 5 Measured time headway during the cut-in situation for busy traffic for high (left) and low (right) THW settings

Figure 5 shows that the time headway stabilizes fastest by using the Controlling mode of IRSA. The only exception was the Intervening system for busy traffic and high THW setting. Finally, the IRSA modes for busy traffic resemble the No system behaviour better for low THW setting than for high THW settings.

The subjects indicated after each run their opinion about the system by a questionnaire. The questionnaire consisted of nine questions. The answers were transformed into two variables, the usefulness and the satisfaction of the system, ranging from -2 to 2 using the Van der Laan methodology (4). Note that the judgments for Expectation represent the expectation of a subject before they had drove with an IRSA system, i.e., the subjects imagine that they had driven with a car-following assistant after they driven without a system. The results are shown in Figure 6. Statistical tests showed that the Controlling-mode was considered more satisfying than the Advisory-mode. A plausible reason for the low satisfying score of the Advisory mode could be the design, i.e., subjects were warned to early. No effects were found for the other conditions, e.g., the satisfaction compared to the time headway settings and traffic conditions.

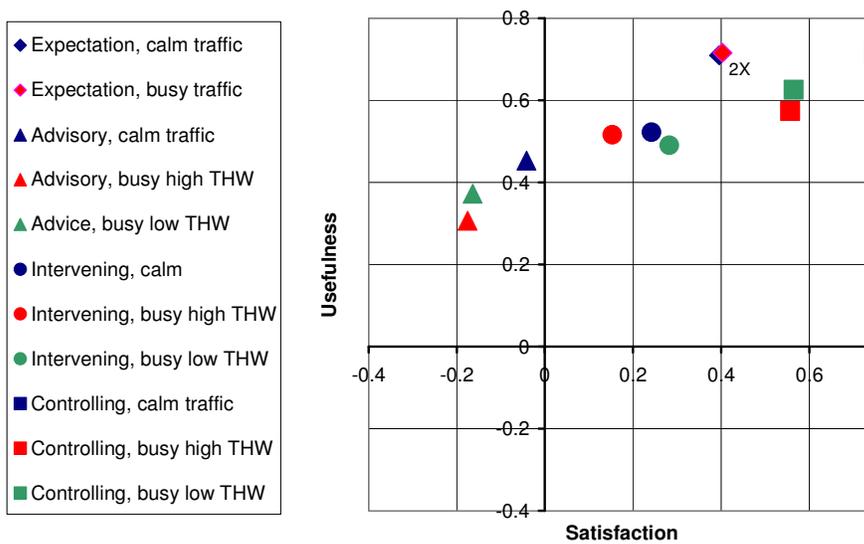


Figure 6: Van der Laan scale, Usefulness versus Satisfaction.

TRAFFIC FLOW EFFECTS

The traffic flow effects of IRSA were assessed using the ITS modeller (5), which is a modeling environment that can simulate intelligent transport systems. Several roadside and in-vehicle systems, as well as cooperative systems, have already been incorporated in the model. New systems can be modeled easily and added to the ITS modeller. The ITS modeller functions as a shell for several commercially available traffic simulation tools. In this case, it was used in combination with Paramics to model the traffic flow effects of IRSA in a traffic jam situation (6). Figure 7 shows the decrease of the total travel time and the standard deviation of the speed for all the cruise control variants. Also other indicators such as accelerations showed positive results. The CACC2 appears to perform better than CACC1. Adding information from slow vehicles further downstream (the + variants) appears to offer little additional benefit at high penetration rates.

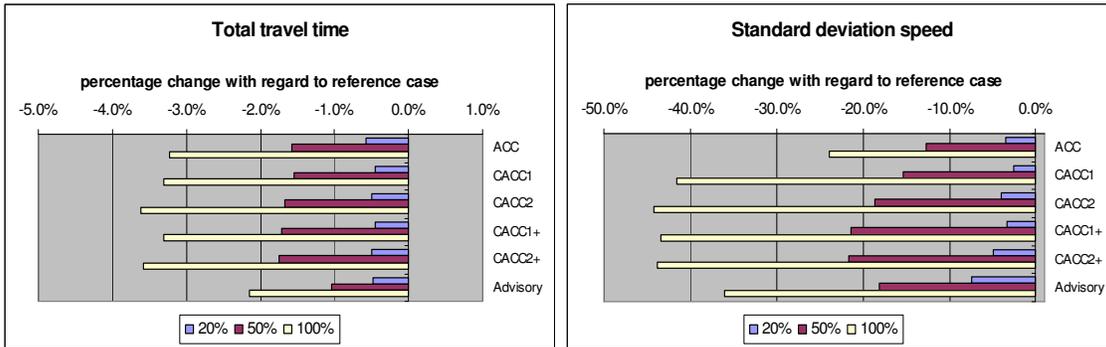


Figure 7 Changes in total travel time, and standard deviation of speed for different versions and penetration rates of IRSA in the Approaching a traffic jam scenario

Figure 8 focuses on the effects of IRSA in the Approaching a traffic jam scenario for CACC1+. It clearly shows the decrease of the delay, the increase of the average speed as well as the decrease of the standard deviation of the speed in the traffic jam. Also note that the effect increases with the penetration rate.

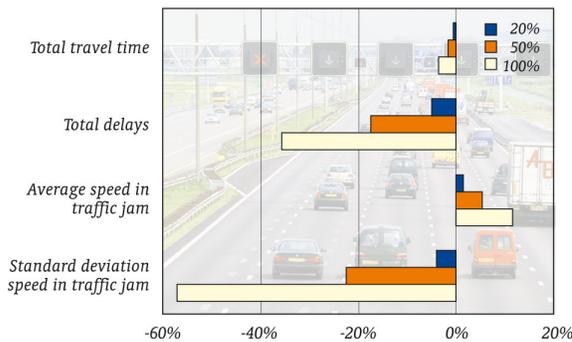


Figure 8 Effect of IRSA in the approaching a traffic jam scenario (CACC1+, % change with respect to no IRSA)

Simulation of other scenarios such as approaching a reduced speed limit zone revealed similar results. It was concluded that IRSA leads to a reduction of congestion, better traffic safety. Given the reduced standard deviation and increase of the speed in the traffic jam, also positive impact on energy consumption and exhaust of pollutant emissions is expected.

CONCLUSIONS

An Integrated Full Range Speed Assistant was designed and evaluated with respect to technical functioning, human factors and traffic flows impacts. In order to ensure consistency between these aspects the SUMMITS Tool Suite was developed, which included the use of a common meta-model for the IRSA system, covering different control variants and traffic flows scenarios. For a cut-in situation, a controlling variant appears to offer a good perspective on traffic flow stability as well user acceptance. For approaching a traffic jam, a cooperative cruise control system based on vehicle to vehicle communication resulted in a decrease of the travel time and speed variability. In the future the SUMMITS Tool Suite will be used in collaboration with the vehicle and traffic systems industry as well as road operators to optimize the comfort, safety and traffic performance of integrated road-vehicle systems as function of different control variants.

ACKNOWLEDGEMENT

The work reported in this paper was conducted as part of the SUMMITS program of the Netherlands Organization for Applied Scientific Research (TNO).

REFERENCES

- (1) Zoutendijk, A., H. Driever, I. Wilmink, J. Ploeg & P. Feenstra (2006), *TNO Toolbox to support the development and evaluation of cooperative vehicle infrastructure systems*, ITS World Congress, London, October 2006.
- (2) Arem, B. van, H. Driever, P. Feenstra, J. Ploeg, G. Klunder, I. Wilmink, A. Zoutendijk, Z. Papp, B. Netten (2007), Design and evaluation of an Integrated Full-Range Speed Assistant, TNO Report 2007-D-R0280/B, available on request at mobility@tno.nl.
- (3) Papp, Z., F. den Ouden, B. Netten, A. Zoutendijk, *Scalable HIL Simulator for Multi-Agent Systems Interacting in Physical Environments*. Proceedings of the 2006 IEEE Workshop on Distributed Intelligent Systems, Prague, Czech Republic, 15-16 June, 2006, pp. 177-182
- (4) Laan, J. van der, Heino, A., & De Waard, D. (1997). "A simple procedure for the assessment of acceptance of advanced transport telematics". *Transportation Research-C*, 5, 1-10.
- (5) Versteegt, E., G. Klunder & B. van Arem (2005), *Modelling cooperative roadside and in-vehicle Intelligent Transport Systems using the ITS modeller*. ITS World Congress, San Francisco: November, 2005.
- (6) Wilmink, I.R., G.A. Klunder & B. van Arem (2007), Traffic flow effects of Integrated Full-Range Speed Assistance, Proceedings of the 2007 IEEE Intelligent Vehicles Symposium, Istanbul, Turkey, June 13-15, 2007, pp. 1204-1210.