"Connect & drive" C&D C-ACC for reducing congestion dynamics

Document Version:
Accepted manuscript including changes made at the peer-review stage

Please check the document version of this publication:

• A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
• The final author version and the galley proof are versions of the publication after peer review.
• The final published version features the final layout of the paper including the volume, issue and page numbers.

[Link to publication](#)

"CONNECT & DRIVE"
C&D
C-ACC FOR REDUCING CONGESTION DYNAMICS

Norddin El Ghouti[1,3*]**, Alex Serrarens**[1]**, Dirk van Sambeek**[1] **Jeroen Ploeg**[2]
1. Small Advanced Mobility b.v. Horsten 1, 5612 AX, Eindhoven, The Netherlands
2. Business Unit Automotive, TNO Science and Industry, Helmond, The Netherlands
3. Department of Mechanical Engineering, Eindhoven University of Technology, Eindhoven, The Netherlands.[*]Corresponding author. Tel.: +31402473895, fax: +31402461418, email: n.elghouti@tue.nl

ABSTRACT

This paper concentrates on a recently started project ($Q4 - 2008$), entitled "Connect & Drive" (C&D) defined in The Netherlands and subsidized by government funding. This project combines Adaptive Cruise Control techniques, vehicle-to-vehicle and vehicle-to-infrastructure communication to dampen congestion dynamics. This is termed "Cooperative Adaptive Cruise Control" ($CACC$). The use of this Advanced Driver Assistant (ADA) system will result in currently unforeseeable benefits on emissions and congestions, particularly since they are mutually enforcing mechanisms. The paper describes the Connect & Drive definition, motivation for this definition and some preliminary expected results on congestion damping. Furthermore, the underlying research and development work that is currently ongoing in The Netherlands within the framework of the Connect & Drive project is also briefly addressed throughout the paper.

KEYWORDS

Cooperative Adaptive Cruise Control (CACC), Congestion Damping, Vehicle Testing

1 INTRODUCTION

The main societal and technical problems stemming from mobility are carbon dioxide emissions, noise, congestion, safety, continuous strive for performance increase, sustainability, availability of fuels and energy sources, availability of space and reachability. The above mentioned problems are divers in nature and often result in conflicting solutions. Hence, Connect & Drive project is about finding some innovative solutions for mitigating shock waves and thereby damp the traffic congestions within the framework of this conflicting context. Actually, conventional ACC systems are the first generation of driver control assistance systems having the potential to

influence traffic flow characteristics, though with limited benefits [7, 8]. The new generation of Communication-equipped vehicles which rely on wireless communication to cooperatively control their speed and/or acceleration is believed to bear the potential for coping with the many challenges and bottlenecks encountered in everyday traffic flow [1, 9]. Furthermore, such systems will pave the way for realizing a fully intelligent traffic system, thus scoring gains in terms of traffic throughput, safety and efficiency. In the C&D project this system is dubbed TACS, which stands for Tribrid Adaptive Cruising System, and comprises the following interactive subsystems

1. The conventional Adaptive Cruise Control system, ACC

2. The higher-capability Cooperative ACC systems, C-ACC

3. The human in the loop Cooperative Cruising Control systems, CCC

In fact, in such new control assistance systems the speed and/or acceleration adjustments shall be made either fully automatic in case of the C-ACC equipped vehicles, or only some advises for cooperative driving will be provided through an adequate HMI in the case of CCC-equipped vehicles, leaving the freedom to the driver to take or not the required cooperative control action. Hence, the motivation behind this work is an attempt to address the longer-term advances in ACC capabilities, especially focusing on higher-capability C(A)CC systems (i.e. supporting both C-ACC and CCC capabilities) as well as the first-generation autonomous ACC. However, it must be noted that C-ACC equipped vehicles are not restricted to communicate with only the preceding vehicle [3], but refers to communication based ACC systems in general (i.e. covering communication links with more than just the preceding vehicle).

The C&D project is a consortium R&D program of the companies Small Advanced Mobility, Centric Tsolve, Fourtress, Twente Institute of Wireless Mobility, TNO Automotive, Eindhoven University of Technology, University of Twente and Delft University of technology. All consortium members are situated in the Netherlands or have a Dutch representation. The Connect & Drive development program aims both at increasing the cutting edge knowledge in navigation technology as well as being the front runner in the international arena for highly specialized automotive industries in the Netherlands. It must be noted that the C&D project focuses on two types of project activities, i.e. "prototype" and "end-product". The term "prototype" is used to label all the activities associated with the prototype implementation and demonstration, whereas the term "end-product" represents all the research and investigation activities, excluding any prototype implementation and demonstration activities.

The following sections of this paper will mainly emphasize the motivations behind the C&D project and its scope, followed by a brief description of the underlying research and development work that is currently ongoing in The Netherlands within the framework of this project, thereafter by means of simulations some preliminary expected results on congestion damping will be reported and commented. Finally a conclusion will be drawn together with some perspectives on the future activities.

2 MOTIVATION, DEFINITION AND SCOPE OF THE C&D

Human drivers are not able to anticipate and control adequately within a dense string of vehicles in order to prevent traffic jams and congested areas, due to the fact that traffic string dynamics are too complex and driver perception and anticipation capabilities decrease at increasing vehicle density. A solution aiming at an increased throughput or metering of traffic during daytime could be the use of Adaptive Cruise Control systems to reduce inter-vehicle distance spacing; hence, the use of Advanced Driver Assistance Systems and Automated Vehicle Guidance Systems for increased driver-traffic involvement and increased automation of traffic dynamics. These solutions are originally intended for increasing inter-vehicle safety and through collision avoidance and warning systems they are also very effective for smoothing the traffic dynamics and thus increased traffic efficiency and comfort, [5]. In the C&D Project, the consortium aims at finding solutions for individual mobility whereas other projects are focusing on public mobility [1, 6]. The combination of forward looking sensor, information technology, inter-vehicle control and refined powertrain control will ultimately lead to the capability to actively manipulate the vehicle drive cycle. Real time control of the drive cycle can be regarded as the last far-reaching instrument for reduction of the traffic congestion. In this context, the C&D project is defined to focus on finding some innovative and adequate solutions for damping the traffic congestions by exploiting the synergies of cooperative driving.

For the study and investigation, a prerequisite is the derivation of a set of use cases, which shall aim at covering the need to settle some vehicle-following logic for each operational mode, such as human driving, autonomous adaptive cruise control ACC [2, 3], cooperative adaptive cruise control C-ACC and the human in the loop cooperative version CCC, both with and without a cooperating preceding vehicle. Accordingly, the scope of the C&D project can be briefly summarized in the following three major items

1. C&D deals with connected platoon of vehicles undergoing traffic disturbances. The emphasis is on creating the platoon (i.e. initial condition errors and connectivity), changing the platoon (i.e. set-point variations) and driving in a platoon (i.e. disturbance rejection)

2. In C&D two possible solutions for Shock Wave mitigation are considered. The first is the automatic control of engine and brake using the higher capability C-ACC and the second is the human-in-the-loop control of engine and brake power using CCC based information system

3. In C&D the impact on traffic flow dynamics shall be investigated in terms of performance, robustness and possible gains of the TACS system as a function of the penetration level

Where a connected platoon is defined as a group of at least two TACS-equipped vehicles which by means of wireless communication cooperatively coordinate their driving patterns and a set-point is a target value that a given TACS-control algorithm tries to achieve. A shock wave is a continuous and often increasing ripple of traffic flow disturbances, on a road that is a major cause of traffic jams, which might be triggered by a single decelerating vehicle.

3   UNDERLYING RESEARCH AND DEVELOPMENT WORK IN C&D

The underlying research and development work that is currently ongoing in The Netherlands within the framework of the Connect & Drive project includes as primary milestone the derivation of a set of use cases which is the backbone of the system requirements. Furthermore, these use cases are the necessary prerequisites to evaluating the system, for both limited and large-scale interactions occurring when varying proportions of enhanced ACC equipped vehicles are mixed with conventionally driven vehicles in a limited-access highway operating environment. Important to notice is that for the study and investigation, the project makes a clear distinction between the prototype and the end-product. For the prototype only a reduced set of use cases will be considered for demonstration and testing purposes. However, for the sake of research and investigation a complete set of use cases will be considered, with the aim of laying the ground for a generic solution which will hopefully pave the way for a complete intelligent cooperative driving system. Besides, it must be noted that the main objective of the C&D project is to mitigate shock wave due to any disturbances, for instance occurring when driving in a platoon increasing in size at cut-in or merging, or decreasing in size at cut-out or exit, or finally oscillating at constant size like acceleration, deceleration, sudden brakes and incidents. Consequently, all the use cases reflecting these particular situations are defined at an abstract level. Further to notice is that this project puts an emphasis on the possibility of shock wave mitigation in at least two ways. The first involves the use of an automatic control of drive and brake power (i.e. C-ACC) and the second involves the human-in-the-loop control variant of drive and brake power (i.e. CCC). Based on system requirements, in terms of functionalities and specifications, a major milestone is the derivation of an adequate enhanced ACC system design and architecture, which is the backbone of the C&D project, together with the required wireless control solutions. Ergo, the intention is to provide an enhanced adaptive cruising system, which bears the potential for coping with the many challenges and bottlenecks encountered in everyday's traffic flow. Such system will pave the way for realizing a fully intelligent traffic system, thus scoring gains in terms of traffic throughput, safety and efficiency. In the C&D project the enhanced ACC system is dubbed TACS, and shall comprise the conventional ACC, the higher-capability C-ACC and finally the human in the loop CCC system, where it must be noted that the major goal of this undertaking is an attempt to address the longer-term advances in ACC capabilities, especially focusing on the higher-capability cooperative C-ACC and CCC systems as well as the first-generation autonomous ACC. Hence, by appropriate design and system architecture, all the different subsystems shall be covered in the C(A)CC functional blocks shown in figure 1, where based on the functional decomposition and the information at hand the system should be tailored to provide only one function at a time.

For the TACS system, the required C(A)CC functionalities shall be mainly designed and then implemented in order to support a large set of use cases aimed at the end-product, but with special focus on the reduced set for the prototype which shall eventually be demonstrated on the real highway system, during the timeframe of the C&D project. Furthermore, it must be noted that the long term objective of this undertaking is to provide a design and implementation framework able to support or rather cover a complete set of use cases aimed at the end-product, but given

4

the timing constraints of the C&D project the implementation shall proceed according to some prescribed priorities, meaning the highest priority use cases first. Consequently, to achieve the above stated objectives some control and communication strategies must be put in place in order to support the design and implementation of an operational TACS system covering at least (but not limited to) the prototype use cases for demonstration purposes. However, during the crucial phase of the system design and architecture selection one should bear in mind that a successful operation of any C(A)CC functionality shall depend on how accurate the distance between vehicles can be measured and how fast the set of data can be exchanged between vehicles, either directly or via the road side unit (RSU). Therefore, special care should be paid to selecting the appropriate wireless communication system technology, together with a suitable positioning system technology and also selecting an appropriate processing and control algorithm which provides the ability to cope with the impairments of the communication medium, the inherent uncertainties of the onboard instrumentations (sensors and actuators), the huge complexity of the control tasks and also but not the least provide some fault detection and isolation or tolerant and maybe even correction mechanism.
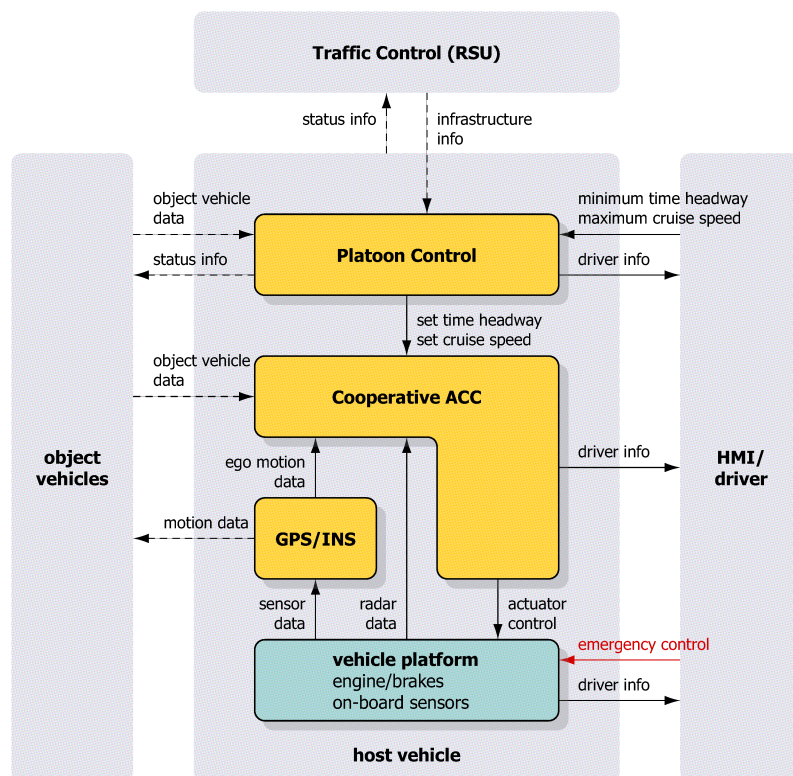

Figure 1: Functional decomposition of the C(A)CC cooperative wireless control scheme, where information flow is depicted in solid for wired connections and dashed for wireless links

5

4 OBJECTIVES AND PRELIMINARY CONTRIBUTIONS OF C&D

Basically, the Connect & Drive project aims mainly at actively controlling the dynamics in vehicle strings in order to mitigate jamming. To achieve this, it relies on the use of radar forward-looking sensors in combination with vehicle-to-vehicle and vehicle-to-infrastructure communication technology, where special attention is paid to the benefits and added value of the C-ACC system.

4.1 Testing facility

In practice, the simulation results shall be tested in real life circumstances using about 20 equipped vehicles. Therefore, before entering on outdoor vehicle string tests, the development consortium uses the world's first active safety testing laboratory [4], VEHIL from TNO Automotive, shown in Figure 2.

Figure 2: VEhicle Hardware In the Loop (VEHIL) Laboratory (TNO Automotive, Helmond)

4.2 Simulations

Simulation activities constitute a vital part of this project and they are mainly aimed at testing the system in a virtual environment before resorting to actual experiment on the real system. Consequently, within the C&D framework a campaign of simulations are conducted aiming at improving the process of mitigating traffic jams by using C-ACC techniques. An interesting test case to consider is an experiment performed at the University of Nagoya, Japan, where they used about 20 vehicles driving on a circle and as such forming an infinite string of vehicles. However, for our experiments in harmony with the planned real testing scenarios, the C-ACC techniques are simulated and tested on a string of up to 20 vehicles, not necessarily forming a circle. For this purpose, a dynamic simulation tool is used to simulate the dynamic behavior of up to 20 longitudinal following vehicles.

In terms of ACC terminology; traffic jams especially those generated by shock waves are by nature closely related to the string stability of the platoon, which is directly dependent on the observed time headway between the involved vehicles. Therefore, mitigating shock waves boils down to achieving a string stable platoon while minimizing the headway distance which is directly related to traffic throughput. In our experiments, the main objective is to investigate and compare the ability and performance of both ACC and the C-ACC when applied as means to mitigate shock waves. To this end, the following testing procedure and conditions are applied through the experiments, where it is decided to vary the time headway between vehicles and observe the effect on the string stability behavior of the platoon at varying speed, following the prescribed speed profile imposed to the platoon members by the leading vehicle, see figure 3.
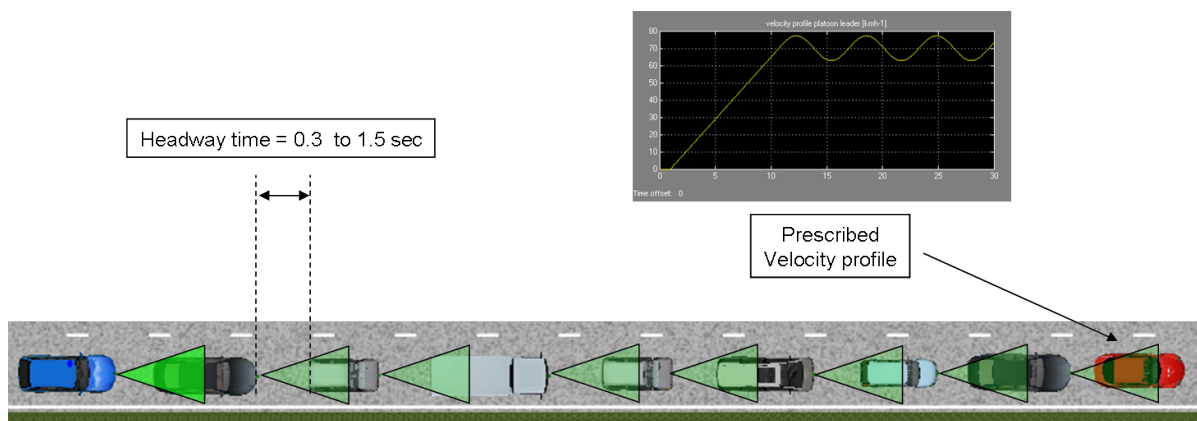

Figure 3: Setup conditions for simulating a platoon string stability behavior

The following figures 4 and 5 report on the behavior of a string of vehicles when ACC is applied in each of its platoon members, where it can be noticed that the string is stable when the time headway is set to 1.5 second, see figure 4.
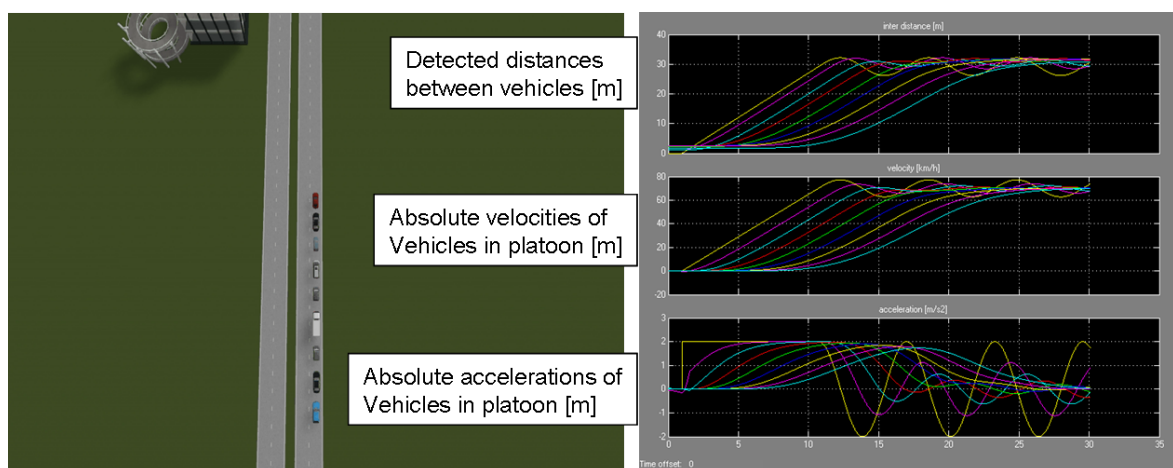

Figure 4: String stable behavior under ACC control constrained with time headway of 1.5 second

7

However, the platoon becomes string instable when the time headway reaches the value of 0.3 second, see figure 5.
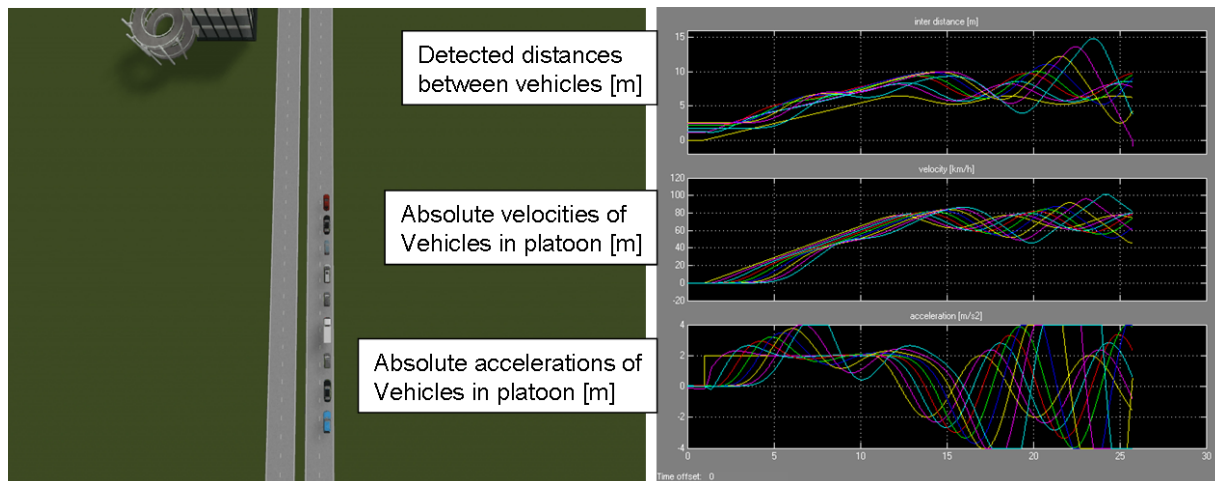

Figure 5: String instable behavior under ACC control constrained with time headway of 0.3 second

In contrast, the figure 6 clearly shows that the performance of the string at 0.3 second time headway remains stable when the C-ACC is applied in each member of the platoon, which is a good indication of its superior performance.
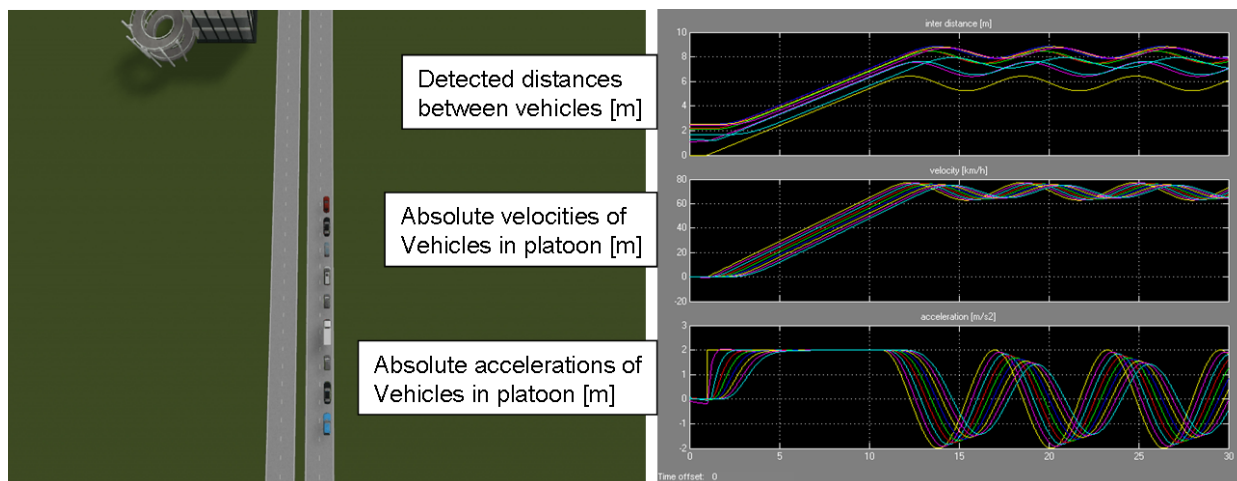

Figure 6: String stable behavior under C-ACC control constrained with time headway of 0.3 second

N.B, The applied speed profile, see figure 3, reaches a maximum average value of 70 km/h, which implies that at this speed the time headway of 1.5 and 0.3 second translates to a gap distance of 30 meter and 6 meter, respectively.

5 CONCLUSIONS AND FUTURE WORK

This article described the definition and motivation behind the C&D project, together with the underlying and currently ongoing work supporting the stated objectives of this project. Special attention is paid to emphasizing the scope, objective and the basic requirements of the C&D project, which are the necessary prerequisites for realizing and then testing an enhanced adaptive cruising system. This system, which bears the potential for coping with the many challenges and bottlenecks encountered in everyday's traffic flow, is believed to pave the way for realizing a fully intelligent traffic system, thus scoring gains in terms of traffic throughput, safety and efficiency. Through simulation it is shown that significant improvements can be achieved in the utilization of the infrastructure when using cooperative adaptive cruise control. A Dutch development consortium is currently working towards the demonstration of these improvements in real-life indoor and outdoor experiments using 10 to 20 vehicles. If these experiments also provide the indicated improvements large operational field tests will be carried out in cooperation with the Dutch Ministry of Traffic & Water Affairs.

REFERENCES

[1] R. Visser B. van Arem, C. J. G. van Driel. The impact of cooperative adaptive cruise control on traffic-flow characteristics. IEEE Transactions on Intelligent Transportation Systems, December 2006.

[2] J. K. Hedrick D. Swaroop. Constant spacing strategies for platooning in automated highway systems. Transactions of the ASME, Vol. 121, September 1999.

[3] J. Ploeg R. van de Molengraft M. Steinbuch G. L. J. Naus, R. Vugts. Towards on-the-road implementation of cooperative adaptive cruise control. 16th World Congress & Exhibition on Intelligent Transport Systems and Services (ITS World 2009), Stockholm, Sweden, September 2009.

[4] O. Gietelink J. Ploeg, B. de Schutter and M. Verhaegen. Development of advanced driver assistance systems with vehicle hardware-in-the-loop simulations. vehicle system dynamics. Vehicle System Dynamics, Vol. 44, No. 7, pp. 569590, 2006 July.

[5] M. A. Miller J. VanderWerf, S. Shladover. Conceptual development and performance assessment for the deployment staging of advanced vehicle control and safety systems. This paper is posted at the eScholarship Repository, University of California. http://repositories.cdlib.org/its/path/reports/UCB-ITS-PRR-2004-22, 2004.

[6] B. van Arem P. J. Zwaneveld. Traffic effects of automated vehicle guidance systems. TNO Inro, Delft, The Netherlands, Report INRO-VVG 1997-17, 1997.

[7] M.A. Miller N. Kourjanskaia H. Krishnan S. Shladover, J. VanderWerf. Development and performance evaluation of avcss deployment sequences to advance from today's driving environment to full automation. California Partners for Advanced Transit and Highways (PATH). Research Reports: Paper UCB-ITS-PRR-2001-18, August 2001.

[8] H. Simon. Automated highway systems: Platoons of vehicles viewed as a multiagent system. URL: www.theses.ulaval.ca/2005/22729/22729.pdf, 2005.

[9] S. Tsugawa. A cooperative driving system with automated vehicles and inter-vehicle communications in demo 2000. IEEE Intelligent Transportation Systems Conference Proceedings - Oakland (CA) USA, August 2001.