ITS FOR SUSTAINABLE MOBILITY: TOOLS FOR
DESIGNING AND EVALUATING CO-OPERATIVE
ROAD-VEHICLE SYSTEMS

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ABSTRACT

Intelligent co-operative road-vehicle systems, in which intelligent road-side equipment co-operates with intelligent vehicles, have great potential to improve traffic flow safety, efficiency, reliability and quality of the environment. But what concepts for these systems are both realistic and beneficial? This paper presents the objectives, approach and first results of TNO’s R&D program SUMMITS (SUstainable Mobility Methodologies using Intelligent Transport Systems), set up to deal with these issues. This paper will focus on the comprehensive set of integrated tools for the design and evaluation of intelligent road-vehicle systems that is being developed within SUMMITS.

INTRODUCTION

Volumes of traffic are rising, especially road traffic, and as a result problems caused by road transport (congestion and unreliability of the road network, negative impact on local environment and public health, CO2 emissions and fatalities, injuries and material damage caused by accidents) are growing bigger and bigger. Although vehicles are cleaner, safer and more recyclable than before, societal costs by road transport is still by far too high. Much is being expected from the deployment of ICT in transport, also called Intelligent Transport Systems (ITS) (1), (2). ICT is already widely being deployed to make both roads and vehicles smarter. Roadside traffic management systems are used to generate safe, efficient and reliable traffic flow on the road network. Vehicles are being equipped with systems and services to help the driver reach his destination both safely and efficiently as well as comfortably. Drivers are well-informed about traffic conditions, both current and expected, and are able to respond to changing conditions. TNO envisages a system in which roads and vehicles can co-operate (see Figure 1). In contrast to more traditional roadside or vehicle approaches, such a system will be
able to offer substantial additional benefits in traffic flow safety, efficiency, reliability and quality of the environment.

![Figure 1: Co-operative intelligent road-vehicle system](image)

**CO-OPERATIVE ROAD-VEHICLE SYSTEMS**

Co-operative road-vehicle systems can be classified along several dimensions, as is illustrated in the following bullet list. Concerning the co-operation technology, it is assumed that this will be primarily addressed through telematic systems. The classification also indicates the degrees of freedom that exist in defining a co-operative road-vehicle system and also indicates the possible development sequences.

**Road infrastructure:**
- **hierarchical level:** network, link, intersection;
- **road type:** interurban-motorway, interurban-rural, urban;
- **road function:** long distance connections, orbital roads and roads in residential, business, industrial areas; dedicated lanes;
- **road design** (width, curvature, markings).

**Driver task (perception, interpretation, action):**
- trip planning, navigation, maneuver, longitudinal, lateral, collision avoidance.

**Degree of support:**
- **informing:** the driver is provided with information, through text, speech or audio;
- advisory: the driver is provided with tailor made advices through text, speech or audio
- **supporting:** there is an active system taking over certain tasks (active accelerator pedal, automatic braking, active steering), but these can be overruled by the driver;
- **automating;**
Co-operation model
- *mutually informing*: road users and operator exchange information but may adapt their actions separately;
- *negotiating*: there is a set of rules for the mutual exchange of goals, preferences, feasible actions and restrictions of road, allowing for an exchange of data.
- *compelling*: one actor is able to determine, restrict and enforce the others’ actions.

Figure 2: Road traffic system in 2015

Figure 2 illustrates the main communication elements which are expected to be available in 2015 between vehicles, traffic management centers, service providers and local traffic management systems. At the **road network level** there will be an increasing co-operation between traffic managers from different road operators and new instruments (e.g. e-Payment, Electronic Vehicle Identification) will become available. The road operator can communicate directly with the driver. The driver is supported in making decisions about navigation and destination by means of real-time traffic and travel info (but will still be in full control of his vehicle). This will lead to an improved road network level utilization in space and time in terms of traffic. At a **local level** scenario we observe an increasing support of the driving task at both the maneuver and the control level (e.g. longitudinal, lateral and collision avoidance). Vehicle-vehicle communication will enhance the self-organizing potential of traffic (e.g. clustering). There will also be an extension of current traffic management systems with two-way communication between vehicles and road-side systems. In 2015 we expect that there is **integration between the local and the network level**.
R&D PROGRAMME SUMMITS – KEY OBJECTIVES

Given the expected development and possibilities of co-operative road-vehicle systems TNO has set up an R&D program SUMMITS (acronym for SUstainable Mobility Methodologies using Intelligent Transport Systems). Key objectives of SUMMITS are:

- development of concepts and systems for the intelligent road-vehicle system in 2015
- development of a set of advanced integrated tools for design, testing and evaluation
- application of concepts, systems and tools in pilot projects, together with main stakeholders (government, traffic and automotive industry).

Within SUMMITS the focus is put on the following design, implementation and evaluation issues that need to be addressed when dealing with co-operative road-vehicle systems:

1. **design of functional concepts**, with specific attention to impacts on traffic safety, traffic efficiency and environmental aspects: how should we design a co-operative road-vehicle system in order to achieve substantial benefits in levels of traffic safety, traffic efficiency and environmental impacts?
2. **information exchange**: what information is exchanged? What requirements with respect to accuracy, authenticity, reliability, timing etc.? What language and technology?
3. **role of the driver**: how to sustain or improve driving performance on the basis of information from downstream? How to deal with transitions between normal and co-operative road-vehicle systems, how to deal with mixed traffic?
4. **reliability of systems**: how to design and implement fault-tolerant co-operative road-vehicle systems, dealing on a vehicle level with human driver in the loop, multiple possibly interfering subsystems. On a co-operative road-vehicle level system reliability is connected to information exchange issues and functional concepts.

INTEGRATED DESIGN AND EVALUATION TOOLS

An important activity within SUMMITS is the development of tools for developing, testing, and assessing concepts for intelligent road-vehicle systems in an early phase of the design process. These tools must enable the R&D issues (design of functional concepts, information exchange, role of the driver, system reliability) to be addressed and should incorporate traffic management, traffic processes, intelligent road, driver and intelligent vehicle.

This TNO development and evaluation platform is called IRVIN (Intelligent Road and Vehicle test INfrastructure) and is aimed at providing an integrated infrastructure of (hardware and software) tools for testing and evaluating methods for traffic management, parts of the intelligent road, the intelligent vehicle and the combination of both.

Based on the vision of the road traffic system as depicted in Figure 2, three different levels are
distinguished within SUMMITS. These are the network level, the maneuver (or cluster) level, and the level of the individual vehicle. At each of these levels, different concepts will be developed within SUMMITS. Some examples are given Table 1.

<table>
<thead>
<tr>
<th>Level</th>
<th>Example concepts</th>
<th>Description</th>
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<tbody>
<tr>
<td>Network</td>
<td>Traffic information and navigation services dedicated to the driver’s specific context</td>
<td>At this level network traffic is modeled. Road operators, road users, and traffic and travel service providers will be co-operating. The focus is on route navigation and the effects of the developed concepts on a network level.</td>
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<tr>
<td>Maneuver</td>
<td>Merging by using clusters of co-operating vehicles</td>
<td>This level is about the longitudinal and lateral movements of multiple cars and their interactions with each other and with road-side equipment. The focus is on vehicles operating in clusters.</td>
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<tr>
<td>Vehicle</td>
<td>Intelligent vehicle systems that communicate with the outside world</td>
<td>At this level the control systems of the individual vehicle and the basic interactions of the vehicle with its surroundings are considered (sensing, communicating). These surroundings include primarily the surrounding vehicles and road-side equipment.</td>
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Table 1: Examples of SUMMITS concepts at different levels of the road traffic system

At each level, tools are required for the design and evaluation of the concepts developed at that level. At TNO we have different tools for this at our disposal, aimed at traffic systems, vehicle control as well as driver behaviour. However, to design and evaluate co-operative road-vehicle systems effectively and efficiently, these tools need to be integrated to a certain extent. Based on the research issues of co-operative road-vehicle systems we have decided to set up the following couplings:

- **intelligent vehicle models, tools and facilities (ADVANCE, PRESCAN, VEHIL, Driving Simulator):** for development of in-vehicle systems (Global Chassis Control, X-by-wire, Advanced Driver Assistance, etc.) that are robust and fault-tolerant;

- **traffic models (PARAMICS, MIXIC) + intelligent vehicle model (ADVANCE) + Driving Simulator:** to assess the influence of the driver on control actions for traffic management (both from within the vehicle as from the roadside), with different vehicle control characteristics.

The first toolset is typically used for developing concepts on the vehicle level, and the second toolset for concepts on the network level. Both toolsets can be applied for analyses on the maneuver level, depending on the research question. Couplings can be either online and offline. A short description of the indicated tools is given below.

**PRESCAN** is a simulator that was developed for the pre-crash sensing and collision avoidance application domain. Components to PRESCAN experiments can be developed in various programming/modeling (Java, C, C++, MATLAB®, Simulink®, Stateflow®) languages. These
components form the PRESCAN libraries containing vehicle dynamic models, sensor models, relevant obstacle models, infrastructure, accident scenarios from accident statistics, decision algorithms for the deployment of safety devices, etc.

**ADVANCE** is a modular vehicle modeling and simulation environment within MATLAB®/Simulink®. The user can build and analyze vehicle models of different levels of complexity using a library of component models. The models comprise the vehicle chassis, tyres, and powertrain. ADVANCE vehicle models can be used for “offline” simulation on a PC, or code can be generated for specific real-time systems (in HIL and RCP applications). ADVANCE is specifically suited for vehicle control systems development as the MATLAB®/Simulink® environment ADVANCE has been built on, is the de-facto world standard in this field.

**VEHIL** To evaluate the functionality of intelligent vehicles, the vehicle's sensors and actuators have to be subjected to realistic driving conditions, such as high vehicle speeds and realistic tracking distances. Using VEHIL a vehicle can be tested in laboratory conditions, while realistic road conditions are being simulated. In this VEHIL test facility, the complete intelligent vehicle is placed on a chassis dynamometer, with each wheel supported by one of the 4 drums of the dynamometer. The vehicle is able to ride and brake as if on the road. The dynamometer simulates road behavior based on a simulation model of the test vehicle. Other road users are represented by so-called moving bases. These are highly dynamic automatic guided vehicles. A central controlling computer creates a virtual relative world for the test vehicle and co-ordinates the interaction between chassis dynamometer and moving bases. The computer also provides a visualization on a large computer screen, on which, for control purposes the realistic road behavior of the test vehicle is simulated. VEHIL is an intermediate step between simulation and full scale road tests.

**PARAMICS** is a microscopic traffic simulation model for both urban and motorway traffic. It can be used for simulating larger traffic networks. Within TNO it is primarily used for the analysis of alternative traffic management strategies. To enable this functionality, various traffic management measures have been added to the model. As the user is able to program any required measure, wide variation is possible from fixed cycles to the most complex dynamic algorithms. Classic examples of measures are traffic light installations, ramp metering installations, traffic signaling in the form of dynamic speed limits and lane closure signs, dynamic route information and road pricing. PARAMICS can be used as a virtual world for testing of new traffic management applications and the training of traffic operators. It is already used for that purpose by the Dutch Ministry of Transport and the institutes of TNO Traffic and Transport.

**MIXIC** is a microscopic simulation model for motorway traffic. MIXIC can be used to assess the impact of an Intelligent Traffic System on traffic flow on a single straight road segment. The core of MIXIC is formed by a detailed vehicle and driver model. These are based on extensive theoretical and experimental study results. Both vehicles and infrastructure can be equipped
with added intelligence (such as Adaptive Cruise Control and derivatives) that influences the
transportation system.

**Driving Simulator** The TNO Driving Simulator consists of a realistic vehicle mock-up (BMW 318 or as DAF truck cabin) on a 6-degrees-of-freedom motion platform, and a visual system. An advanced image generation system allows the ‘outside world’ of the TNO Driving Simulator (including up to 120 independently programmable vehicles) to be realized covering a total forward angle of view of 120° on a large cylindrical projection screen and the rear-view through three mirrors (left, inner, right). The test subject in the mock-up directly experiences the results of his driving actions on the direction and speed. The subject receives feedback via a 3D sound system and steering forces as these would actually occur. The vehicle dynamics are now being implemented in an ADVANCE vehicle model, see hereafter.

**Figure 3: General framework for the IRVIN toolbox**

The objective of IRVIN is to be a modular toolset that allows the user to combine any of these tools as required for the research question at hand. Figure 3 gives the general framework for the IRVIN toolbox. The basic idea is that for a given application a combination of sub-models can be chosen out of different families of sub-models such as traffic simulation models, vehicle...
models, and driver(model)s. This set-up must guarantee that, for example, the driver models that are used for different applications are interconnected at a content level and are based on the same knowledge and expertise. In general, the Intelligent Co-operative Road Vehicle Systems (ICRVS) concepts will contain advanced road-side and vehicle systems and advanced driver-assistance systems, and will make use of vehicle-vehicle and vehicle-roadside communication. In the evaluation environment it should be possible to model each of these aspects. Other aspects that need to be addressed are the impacts on traffic safety, traffic efficiency and environment. In other words, in addition to the elements depicted in Figure 3, IRVIN will be extended with communication models and indicators for safety, throughput and environment.

PRELIMINARY RESULTS

INTELLIGENT VEHICLE MODELS AND THE DRIVING SIMULATOR

In preparation for a SUMMITS Driving Simulator study later this year, a preliminary test has been conducted. A simple vehicle model is used with a fixed driving speed of 90 km/h, and a bicycle model to represent lateral vehicle dynamics. The vehicle model contains a Steer-by-Wire (SbW) system where:

- the SbW controller receives steering wheel angle as input
- the SbW algorithm produces a wheel angle set-point (or rack position set-point) that is realized by an ideal servo system
- the SbW produces a steering wheel torque set-point that is realized by the control loader in the Driving Simulator

The steering wheel torque (i.e., the set-point for the control loader) has 2 components: a damping (based on the steering wheel angular velocity) and a component proportional to the wheel angle (representing a steering wheel force resulting from the self-aligning torque). The latter is based on the philosophy that in order to serve the needs and expectations of the normal driver, a SbW controlled car should at least be able to match normal car steering systems. A ‘system error’ is simulated by putting a step on the steering wheel feedback torque, and after 10 seconds a step down again. The test is performed with the driver in the loop, trying to keep the vehicle driving straight. From Figure 4 it can be seen that within 0.4 s the driver has applied sufficient torque to return the steering wheel angle to 0 degrees. Further corrections are needed to return the vehicle to the centre of the lane. The effect of the removal of the error-torque, at t=20, seems larger in terms of steering wheel and yaw rate amplitudes. The result of this preliminary test shows that using the ADVANCE (Simulink®) vehicle model to run the Driving Simulator provides a powerful enhancement of the Driving Simulator functionality. X-by-Wire system developments can be evaluated with a driver in the loop in an early stage of the design process: the control system development environment is the same as the vehicle modeling
environment, and this environment can be coupled in real-time with the TNO Driving Simulator.

![Figure 4: Step up and down on torque, closed loop](image)

**TRAFFIC MODELS AND THE DRIVING SIMULATOR**

The tool couplings and tool developments realized in IRVIN must be so generic, modular, and flexible that one can easily select the tools and modify the type and amount of data transfer depending on the research question at hand.

![Figure 5: SUMMITS test network for testing, assessing, and evaluating the functionality of candidate co-operative road-vehicle systems](image)

As it is envisaged that in 2015 the driver is still in control of his/her vehicle, it is important that the toolset includes the possibility to investigate the influence of the driver on the performance
of the road traffic system. In that sense, a coupling of Traffic simulation models such as PARAMICS or MIXIC and the Driving Simulator is crucial. In IRVIN the coupling between PARAMICS and the TNO Driving Simulator is two-fold, one for importing the PARAMICS road world into the driving simulator (for efficiency reasons this would be very useful in joint projects), and the other for actually driving around in real-time (in the Driving simulator) in the PARAMICS traffic environment. At a basic level, both elements have been implemented using the general approach and interfacing structure of HLA (High Level Architecture) for the SUMMITS test network depicted in Figure 5. Whereas an initial attempt had tried to import the PARAMICS road world into the visual database of the Driving Simulator, a better solution appeared to be to import one separate road data model into both PARAMICS and the Driving Simulator. The coupling will be ready for use in the last quarter of 2004.

REFERENCES

(1) “Information and Communications Technologies for Safe and Intelligent Vehicles”. Available at http://europa.eu.int/information_society/programmes/esafety/index_en.htm