Traffic and Transport
Van Mourik Broekmanweg 6
P.O. Box 49
2600 AA Delft
The Netherlands

www.tno.nl

T +31 15 269 68 78
F +31 15 269 77 82
Trafficandtransport@tno.nl

TNO report

2007-D-R0280/B

Design and evaluation of an Integrated Full-Range Speed Assistant

Date	March 20, 2007
Author(s)	Bart van Arem Hans Driever Philippus Feenstra Jeroen Ploeg Gerdien Klunder Isabel Wilmink Allard Zoutendijk Zoltan Papp Bart Netten
Assignor	
Project number	034.65901
Classification report Title Abstract Report text Appendices	
Number of pages Number of appendices	66 (incl. appendices)

PREFACE

This report is the final report of the IRSA project of the SUMMITS research programme. The SUMMITS programme was conducted from 2003-2006 and financed by TNO. The IRSA project was managed by Hans Driever from 2004 to early 2006. From early 2006 until the completion the IRSA project was managed by Bart van Arem. The IRSA project was conducted by the following business units of TNO:

- BU Automotive, Core area Industry & Science
- BU Imaging systems, Core area Industry & Science
- BU Human Factors, Core area Defence & Security
- BU Mobility & Logistics, Core area Built Environment and Geosciences

The project managers would like to thank the many researchers that have contributed to the project in a stimulating, multidisciplinary way.

Bart van Arem
Hans Driever

ABSTRACT

In the SUMMITS-IRSA project, TNO has developed and demonstrated the SUMMITS Tool Suite, which is an integrated tool set to allow developers of Advanced Driver Assistance (ADA) systems to assess issues regarding technical functioning, human factors and traffic flow in a consistent way. The Integrated Full –Range Speed Assistant (IRSA) was selected as a case to guide and test the development of the tool suite. 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 situation and leaving the head of the queue at a traffic light. Consistent results were guaranteed by the use of a common mathematical description of the IRSA system (the meta-model), traffic scenarios and selective coupling of tools. Several control models were used, varying from a common Adaptive Cruise Control (ACC) algorithm, to algorithms that also use vehicle-vehicle communication with the three closest downstream IRSA equipped vehicles taking into account the time headways (CACC1) and average speed (CACC2).

EXECUTIVE SUMMARY

In the SUMMITS-IRSA project, TNO has developed and demonstrated the SUMMITS Tool Suite, which is an integrated tool set to allow developers of Advanced Driver Assistance (ADA) systems to assess issues regarding technical functioning, human factors and traffic flow in a consistent way. The Integrated Full –Range Speed Assistant (IRSA) was selected as a case to guide and test the development of the tool suite. 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 situation and leaving the head of the queue at a traffic light. Consistent results were guaranteed by the use of a common mathematical description of the IRSA system (the meta-model), traffic scenarios and selective coupling of tools. Several control models were used, varying from a common Adaptive Cruise Control (ACC) algorithm, to algorithms that also use vehicle-vehicle communication with the three closest downstream IRSA equipped vehicles taking into account the time headways (CACC1) and average speed (CACC2).

Simulations, hardware-in-the-loop experiments (VeHIL) and real-world experiments revealed that the IRSA system can be implemented and performs according to expectation: V –V communication indeed enhances the control of the vehicle, resulting in better safety and comfort. The CACC2 controller appeared to show the best performance.

The experiments with respect to robustness were especially useful when the development approaches the implementation phase, i.e. more and more “real world” influences should be taken into account. Sensor specification, evaluation of safety related features can be carried out in well controlled virtual environment, which reduces costs and time-to-market. The MARS environment was used to check and enhance the IRSA implementation at different levels of detail thus bridging the gap between ITS Modeller and VeHIL.

The driving simulator experiments focused on the cut-in situation, with the objective to see to which level the IRSA controller can help stabilize traffic flow. The experiments focused on an advisory, intervening and controlling system. It resulted in a clear preference for a controlling system, with the best stabilization properties as well as the best acceptance amongst drivers.

The traffic flow analyses using the ITS Modeller show that in general all IRSA functions contribute to a decrease in speed variation, with an increasing effect with an increasing penetration rate. In general safety indicator levels improved at unchanged traffic efficiency. Accordingly, also the negative impacts on the environment can be expected to improve. In addition, for the scenario approaching a traffic jam, a reduction of 30% in delays was obtained. The CACC2 controller showed the best performance.

The application of the SUMMUTS Tool Suite to the IRSA system has revealed that the tool suite is very useful for the assessment of ADA systems. The effort invested in the formulation of the meta-model and common scenarios, has paid off significantly. IN particular, this was the case when iterations in the model details and parameters were required; they could be studied extremely fast. The development of the common approach has also strengthened the multidisciplinary network of researchers in TNO.

The SUMMITS Tool Suite is now available to support the development and evaluation of autonomous and cooperative ADA systems and is already being used in projects for clients of TNO. The SUMMITS Tool Suite offers flexibility to efficiently study questions related to technical performance, robustness, traffic flow impacts and human factors.

The different tools within the SUMMITS Tool Suite will be further developed, to allow more detailed communication, sensor and driver modelling. It will also be extended to provide support to field operational tests.

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1 Introduction

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, operational errors and in many cases not all relevant information is available to the driver to make optimal/reasonable decisions. 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 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 information from road-side systems and other vehicles.

The scope of ADA systems that are commercially available is expanding slowly: in addition to Adaptive Cruise Control, systems such as Lane Departure Warning, Lane Keeping, Blind Spot Warning and Pre-crash Braking Assist are becoming available on an increasing number of brands and models. Other ADA systems, in particular those making use of wireless communication, are under development.

For the development of ADA systems, the following general sets of requirements need to be satisfied. First and most of all, it needs to be assured that the ADA systems operate correctly and dependably. ADA systems consist of a wide range of components for sensing, communication, processing and actuation. By dependability we mean that the ADA system should be able to tolerate certain failure modes (e.g. sensor degradation, communication failures, etc.), should be able to cope with unforeseen environmental and traffic conditions and should behave safely under any conditions (which may result in transparently transferring control to human driver). Second, ADA systems interact with a driver who is responsible for switching the system on and off and for the user settings. It is of vital importance that the ADA systems fit the needs of the user, are understandable, easy to use and will not lead to any negative compensating behaviour. Third, it needs to be assured that the ADA system will blend in smoothly in the traffic, and leads to improvements in traffic safety and efficiency and environmental impacts.

In order to support the development of ADA systems, TNO started the SUMMITS program with the objective to develop and demonstrate an integrated tool suite. The SUMMITS Tool Suite allows developers of ADA systems to assess issues regarding technical functioning, human factors and traffic flow in a consistent way.

The Integrated Full –Range Speed Assistant (IRSA) was selected as a case to guide and test the development of the SUMMITS Tool Suite. 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 situation and leaving the head of the queue at a traffic light.

The following overall research questions were defined in the SUMMITS-IRSA project:

- To what extent can cooperative driving, achieved through vehicle- vehicle (V-V) and vehicle-infrastructure (V-I) communication, contribute to
  - Improved traffic and system safety
  - Improved throughput
  - Improved environmental aspects (gas emissions and noise)
  - Improved driver comfort and safety perception
  - Added value to the existing ADA functionalities (ACC, Stop&Go, Forward Collision Warning, Lane Departure Warning).
- What implementation issues exist, in the areas of:
  - Robustness/graceful degradation
  - Stepwise introduction (from 0% to higher penetration levels)
  - Structured design methodologies
  - Expected societal benefits under different circumstances.

For the integration of the tools, the so-called Multi-Aspect Assessment Methodology was developed, see Figure 1.1.

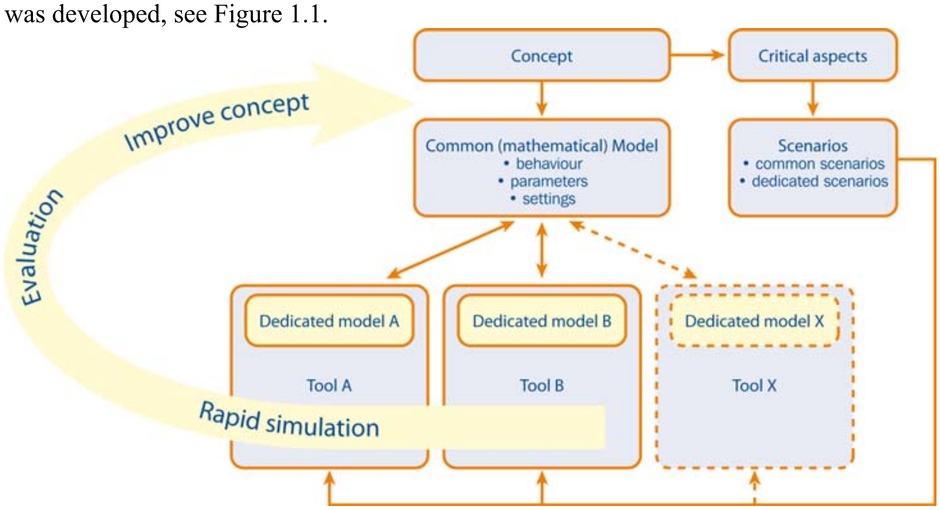

Figure 1.1: Multi-Aspect Assessment Methodology.

The methodology is based on the commonly used V-model, but adds an iterative aspect to the conceptual phase. It consists of the formulation of a common meta-model of the system to be developed. The meta-model is a high level description of the functional behaviour and the parameters that can be controlled. It serves as a common basis for the formulation of specific models to assess different aspects. Next, common scenarios are formulated in which the system needs to operate. Finally, for some cases it is advantageous to couple some of the test tools. By using this integrated methodology, it is possible to identify trade-offs in for instance system reliability, human factors and traffic efficiency. A more detailed description of the methodology can be found in Zoutendijk et al. (2006).

The application of the methodology is schematically depicted in Figure 1.2 for the development of a system for (Cooperative) Adaptive Cruise Control. The meta-model contains the common description of the system including the parameter settings. The ITS Modeller uses the meta-model to assess traffic flow impacts, MARS, VEHIL and real-world test vehicles (the ‘Real-world Pilot’) use the meta-model to assess robustness and safety of the system, while the driving simulator uses the meta-model to study the acceptance and response by drivers.

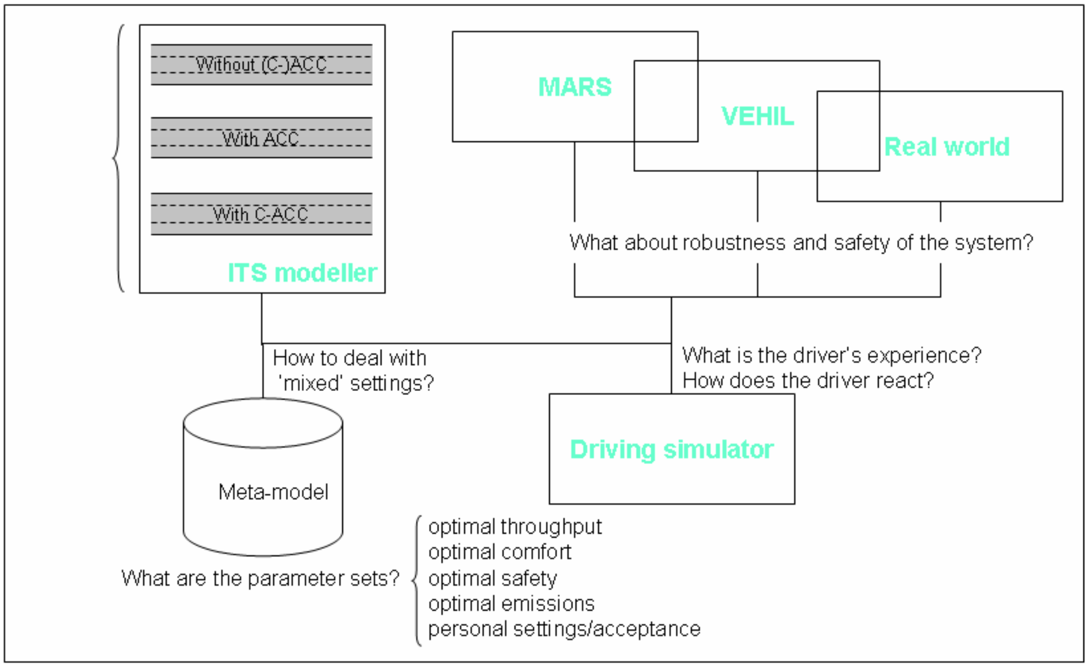

Figure 1.2: Example application of the Multi-Aspect Assessment Methodology

This report gives an overall overview of the results of the SUMMITS-IRSA project. In Chapter 2, we describe the meta-model and the common scenarios. Chapters 3 and 4 are devoted to system robustness and technical functioning of IRSA. Next, Chapters 5 and 6 will describe the impacts of IRSA on driver behaviour and traffic flow, respectively. Finally, a discussion of the approach and conclusion is presented in Chapter 7.

2 IRSA meta-model and scenarios

This chapter provides an overview of the main functions that were included in the meta-model of IRSA.

2.1 IRSA Modes

IRSA can be used in different ways, either as a pure advisory system, as a system that partly intervenes in the vehicle controls (e.g. by a haptic throttle), or as a controlling system that fully controls the longitudinal speed of the vehicle. The driver determines in which way he will use IRSA by selecting a mode of operation of the system. The possible modes of operation are:

Mode 0: IRSA off
Mode 1: IRSA advisory mode
Mode 2: IRSA intervening mode
Mode 3: IRSA controlling mode

In all modes, the IRSA system computes a desired acceleration, see Figure 2.1.

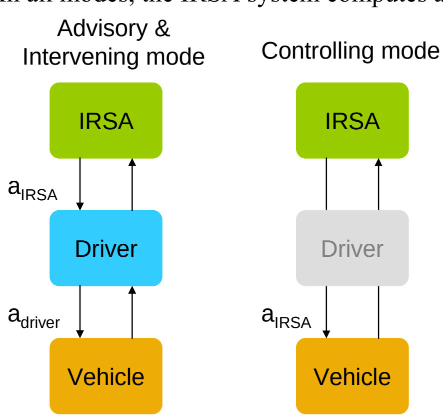

Figure 2.1: Relation between the advisory, intervening and controlling mode

In the advisory mode information about the desired acceleration by the IRSA system is presented to the driver in the form of audible or visual information. In the intervening mode, the information is passed on to the driver information in an active way, e.g. by a haptic gas pedal. The driver will react to these signals, and give a new desired acceleration to the vehicle by pushing the gas, brake or clutch pedals. In the controlling mode, the desired acceleration by the IRSA system is directly given to the vehicle.

Conceptually the major difference between the controlling mode and the advisory/intervening modes is that there is no driver that 'distorts' the optimal desired acceleration computed by the IRSA system in the controlling mode. Hence, in designing the IRSA system, the focus will be on the controlling mode.

2.2 IRSA functions

The IRSA system was assumed to consist of three main functions: speed assistance and/or warnings, adaptive cruise control and headway advice.

The speed advice and/or warnings IRSA presents to the driver are based on object warnings. Possible objects are:

- (reduced) speed limit zones;
- curved road segments;
- approaching a traffic jam
- leaving a traffic jam

The object warnings can be communicated via either infrastructure-vehicle (I-V) communication or vehicle-vehicle (V-V) communication.

In addition to the speed warnings and/or advice, another main functionality of IRSA will be the cruise control-like functionalities. These will be activated in the IRSA controlling mode. Depending on the situation the vehicle is in (with or without predecessor, V-V communication possible or not, etc.), a specific cruise control functionality will be activated. The different cruise control functions are depicted in given in Table 2.1.

Table 2.1: Cruise control functionalities

Conventional Cruise Control	No predecessor
Adaptive Cruise Control	Predecessor detected by radar, no V-V communication.
Cooperative Adaptive Cruise Control	Predecessor(s) detected by V-V communication (and possibly radar, for the direct predecessor).

The primary aim of the cruise control functionalities is to increase comfort. However, because the speed advice and warnings as described in the previous section are also taken into account by the cruise control, the system is expected to also contribute to improvements in traffic throughput and safety.

The third function is headway advice. A previous study by Visser (2005) showed that the platoon formation caused by introducing Cooperative Adaptive Cruise Control might seriously hamper merging processes at merging or weaving sections. To overcome these difficulties, and to prevent the introduction of unwanted effects by IRSA, one of the IRSA functionalities will be to give time headway advice near merging and weaving sections. This time headway advice will aim at increasing the gaps between vehicles, to create a smooth merging flow.

2.3 IRSA Algorithms

This section shortly describes the three control algorithms that have been developed: one concerning common ACC and two variants of IRSA; Gietelink (2005) provides a more detailed description. To this end, Figure 2.2 shows a schematic representation of a vehicle string consisting of n vehicles. The vehicles are all equipped with V-V communication and an object sensor that measures the relative motion of the predecessor. The figure also indicates the relative distance $x_{r,i}$ (the *headway*) between vehicle i and vehicle $i+1$. The longitudinal velocity of vehicle i is indicated as $v_{x,i}$. The relative velocity between these vehicles is $v_{xr,i} = v_{x,i+1} - v_{x,i}$. Further defined are the desired distance $x_{d,i}$, the headway separation error $e_{x,I} = x_{r,i} - x_{d,i}$, the desired velocity $v_{d,i}$, the relative speed error $e_{v,i} = v_{r,i} - v_{d,i}$ and the vehicle length $l_{v,i}$. These variables are used to explain the principle of the different control strategies.

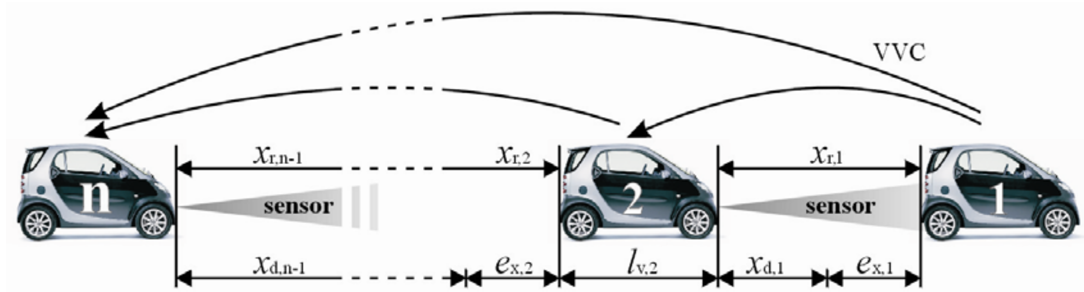

Figure 2.2 – Schematic representation of a vehicle string with V-V communication and object sensors

2.3.1 *ACC controller*

The ACC longitudinal controller of vehicle *i* only takes into account the relative motion of the direct predecessor *i*–1 that is measured by an environmental sensor, such as laser, radar, vision or a combination of those. The controller tries to maintain a pre-defined velocity set-point v_{cc}, unless a slower predecessor is detected ahead. In that case, vehicle *i* is controlled to follow vehicle *i*–1 with equal velocity at a desired distance $x_{d,i-1}$. In velocity control mode, the ACC operates as a conventional cruise control, where the desired acceleration a_d is given by a proportional controller:

$$a_d = k_{cc}(v_{cc} - v_x) \qquad k_{cc} > 0 \tag{2.1}$$

where k_{cc} is a constant gain. In distance control mode, a_d is generally given by proportional feedback control of the distance separation error and the relative speed error. Since the desired relative velocity $v_{d,}$ is obviously equal to zero, the relative speed error is equal to the relative speed between the vehicles. The desired acceleration is calculated with the following equation:

$$a_d = k_2 e_v + k_1 e_x, \quad k_1, k_2 > 0. \tag{2.2}$$

where the controller gains k_1 and k_2 are (non-linear) functions of ego-velocity v_x and distance error e_x. Equation (2.2) can be regarded as non-linear Proportional-Differential (PD) control of the distance separation error.

2.3.2 *IRSA controllers*

Because CACC uses inter-vehicle communication, the acceleration of the predecessor (which is difficult to estimate with an environmental sensor only) can be communicated to the following vehicle. With information on the acceleration a, as well as more reliable estimates for the range and range rate, the ACC control law (2.2) can be modified to:

$$a_d = k_3 a + k_2 e_v + k_1 e_x, \quad k_1, k_2, k_3 > 0. \tag{2.3}$$

where k_3 is a constant feedforward gain. The availability of an acceleration signal provides the opportunity to react faster to emergency braking.

The IRSA controller also takes into account vehicles that are outside the field of view of the object sensors. Because no direct relative motion measurement of these objects is available, this data has to be determined using absolute world positions (determined by fusion of GPS and on board sensors) that is communicated by the vehicles.

The CACC controller (2.3) only considers a single predecessor. Two methods have been developed to consider more vehicles in front, which is the aim of IRSA. They are referred to as CACC1 and CACC2. The acceleration of the predecessors is not taken into account in the IRSA controllers. The controllers are based on the ACC controller (2.2).

CACC1

The controller of vehicle n calculates the desired acceleration $a_{d,n,i}$ for each preceding vehicle i, according to the ACC control law (2.2). The desired distance of vehicle n to vehicle i is calculated using:

$$x_{d,n,i} = \left(l_{v,n-1} + x_{d,n-1}\right) + \ldots + \left(l_{v,i+1} + x_{d,n+1}\right) + x_{d,i} \tag{2.4}$$

The desired acceleration $a_{d,n}$ to be sent to vehicle n's lower-level acceleration controller is then calculated by taking the minimum value of all $a_{d,n,i}$ for n–1 preceding vehicles:

$$a_{d,n} = \min(a_{d,n,n-1}, \ldots, a_{d,n,1}) \tag{2.5}$$

This controller will only function in case all vehicles in the platoon are equipped with VVC. This is caused by the use of the desired distance part in the controller. For determining the desired distance to a predecessor (2.5), the motion data of all predecessors has to be known.

CACC2

The CACC2 controller consists of two parts that are added. The first part of the controller is the ACC control law (2.2) on the direct preceding vehicle. The second term consists of an error feedback of the average velocity of all remaining vehicles in front. This causes damping in the string. As a result, the desired acceleration $a_{d,n}$ of vehicle n becomes:

$$a_{d,n} = (k_2 e_{v,n-1} + k_1 e_{x,n-1}) + \left(\frac{k_2}{n-2}\sum_{i=1}^{n-2} e_{v,i}\right) \tag{2.6}$$

Even when not all vehicles in the platoon are equipped with V-V communication, this controller will function properly because the distance is not taken into account.

2.4 IRSA Scenarios

The IRSA scenarios were chosen to verify the behaviour and performance of the IRSA system with respect to different aspects (technical operation, robustness, human factors and traffic flows) and with respect to different roads (motorway, rural and urban).

The first scenario is approaching a reduced speed limit zone, as depicted in figure 2.3. The primary aim of the warnings received by the IRSA system is to calmly reduce the traffic speed to prevent the formation of shock waves due to abrupt braking manoeuvres. These warnings will make use of roadside beacons that broadcast messages containing the coordinates of the speed zone boundaries, and the speed limit itself. It was assumed that the warnings can be received 1250 m upstream from the start of the reduced speed limit zone.

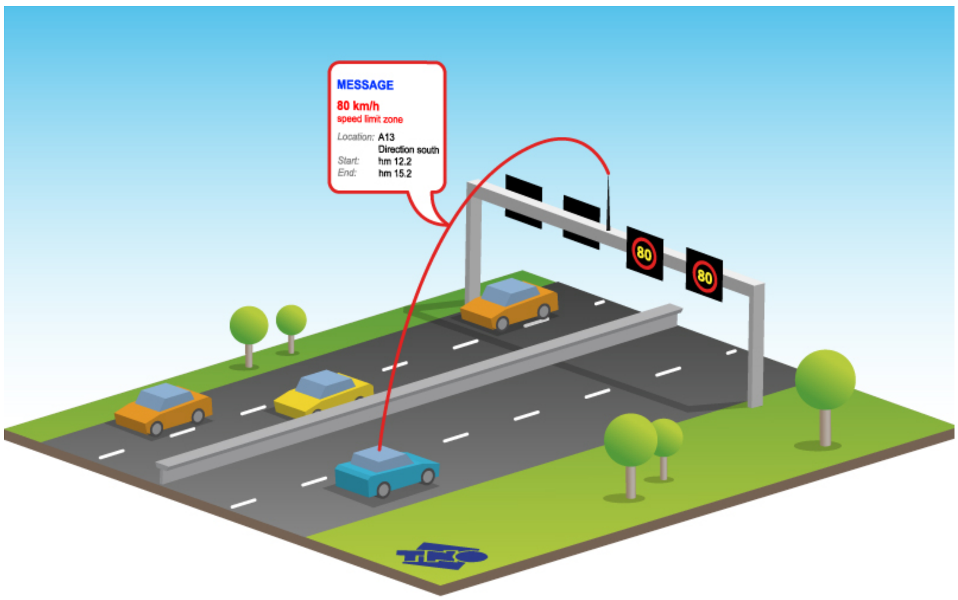

Figure 2.3: Approaching a reduced speed limit zone

The second scenario is 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 2.4 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 intro account. A maximum broadcast distance of 300 m was used.

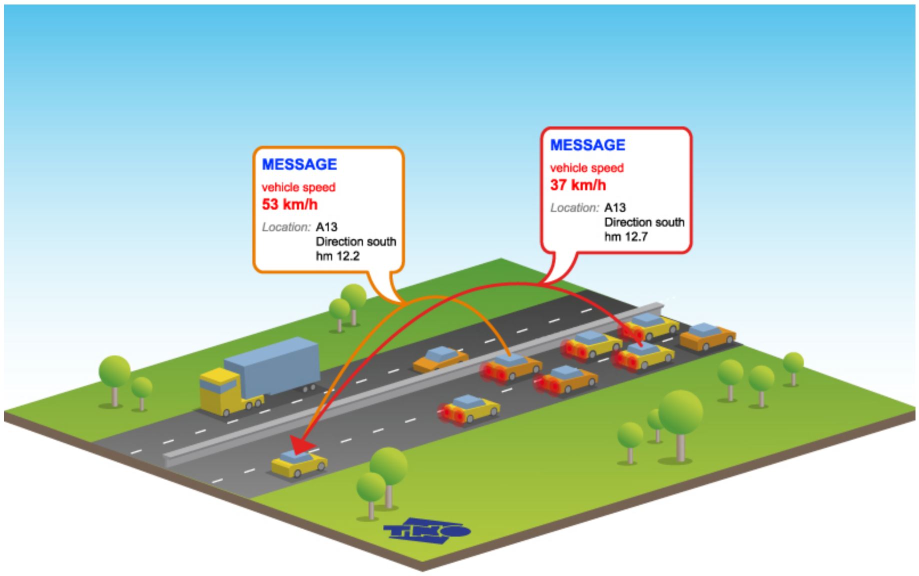

Figure 2.4: Approaching a traffic jam

The third scenario is leaving the head of a queue. Due to the presence of the C-ACC, vehicles can react almost without delay on accelerations of predecessors. This means that as soon as a predecessor, or a pre-predecessor, or a pre-pre-predecessor etc. starts accelerating out of a queue, the driver and/or vehicle can react immediately, thus improving the outflow of a traffic jam or at a traffic signal.

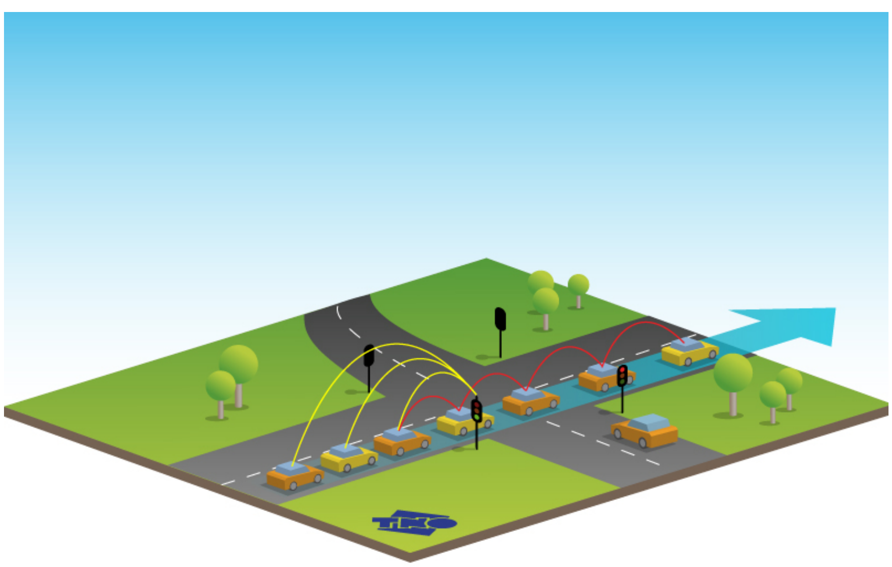

Figure 2.5: Leaving the head of a queue

The fourth and final scenario was a so-called positive cut-in scenario, as depicted in Figure 2.6. Vehicle 0 changes lane before vehicle 1 and causes a very close car-following situation and potentially an instable response of the string of vehicles. The applicable IRSA functionalities are the adaptive cruise control and cooperative cruise control. The hypothesis is that IRSA will contribute to a better stability of the string of vehicles.

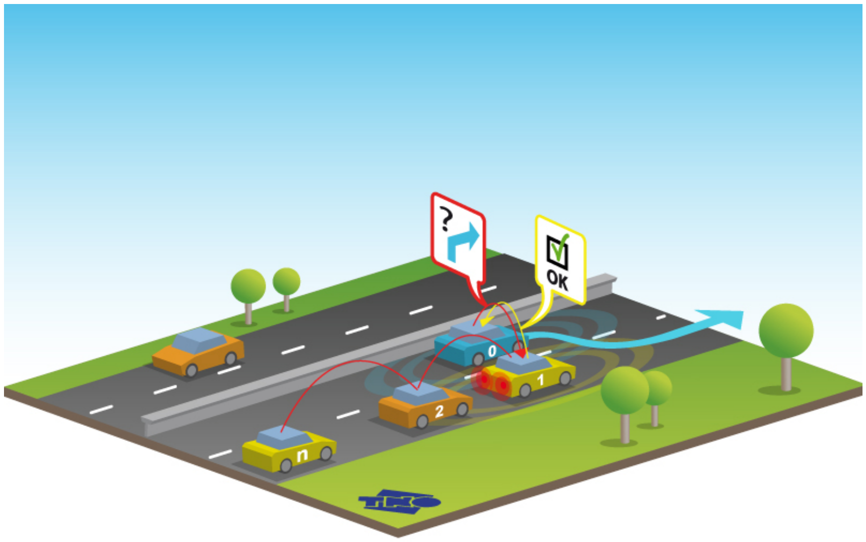

Figure 2.6: Positive cut-in situation

2.5 Experimental plan

Based on the meta-model and the different scenarios, the following experiments were conducted. Table 2.2 displays for each scenario and tool, which IRSA modes and penetration rates were studied.

Table 2.2: Experimental plan IRSA assessment

	MARS	**VeHIL**	**Driving simulator**	**Real-world Pilot**	**ITS Modeller**
Approaching a reduced speed limit zone					Advisory and controlling modes. Penetration rates: 0, 20, 50 & 100%
Approaching a traffic jam	Controlling mode. Penetration rate 100%	Advisory and controlling modes. Penetration rate 100%		Advisory and controlling modes Penetration rate 100%	Advisory and controlling modes. Penetration rates: 0, 20, 50 & 100%
Leaving the head of a queue					Controlling mode Penetration rates: 0, 20, 50 & 100%
Positive cut-in	Controlling mode Penetration rate 100%	Advisory and controlling modes. Penetration rate 100%	Advisory , intervening and controlling modes, Penetration rates 0% and 100%	Advisory and controlling modes. Penetration rate 100%	

3 System Performance

3.1 Introduction and motivation

With the increasing demand for safer passenger vehicles, the development of Advanced Driver Assistance (ADA) systems is a major research topic in the automotive industry. A widely available system since the 1990's is adaptive cruise control (ACC), which provides active support to the driver. ACC is a comfort system that maintains a set cruising velocity, unless an environmental sensor detects a slower vehicle ahead. The ACC then controls the vehicle to follow the slower vehicle at a safe distance. However, there are some drawbacks:

- ACC systems have a maximum range of about 50 to 200 m due to limitations of environmental sensors. This range is insufficient for a safe response on traffic jams or other potential danger further ahead.
- False and missed target detections can occur when driving in curves or when other vehicles or road infrastructure are blocking the line-of-sight of the sensor.
- In addition, the sensor signals can be unreliable due to multi-path reflections, weather conditions and sensor noise.

Therefore, ACC could be greatly enhanced when the field-of-view of the sensorial platform is extended to include information from other preceding vehicles. This can be achieved by implementing a Vehicle-Vehicle (V-V) communication system. Current research is focused on extending ACC systems to *Cooperative Adaptive Cruise Control* (CACC) systems, where the relative motion is accurately estimated by a combination of environmental sensors and V-V communication. However, CACC is only operational with regard to the directly preceding vehicles that are sensed by the environment sensors. This type of CACC will therefore not directly respond to other preceding vehicles further ahead.

Within the SUMMITS program, a new ADA system has been developed which overcomes the limitation of the basic CACC (Ploeg et al, 2006). The so called *Integrated full-Range Speed Assistant* (IRSA) combines the ACC functionality with a cooperative system that looks multiple vehicles ahead. The system is based on GPS navigation, environment sensing and V-V communication. Because the system also takes vehicles into account that are not directly sensed by the environment sensors, it is expected that the performance is increased significantly.

This chapter focuses on the technical performance aspects of IRSA by means of an experimental evaluation. To this end, the main research questions are summarized first. The next section shortly describes the applied research methodology, incorporating the use of a first-principles simulation model, the TNO VeHIL laboratory and the so-called Real World Pilot. Different scenarios and criteria are then formulated for objective evaluation. Finally, the results of the evaluation are discussed after which conclusions are drawn and recommendations are given.

3.2 Research questions

The overall objective of the research presented here is to design a CACC controller – which should perform adequately not only on a simulation level but also in reality – and to assess its technical performance. The criteria against which the controller performance will be judged are:

1. Safety
   A possible criterion to assess safety is the (time) headway of each vehicle.
2. String stability. String stability is the upstream evolution of headway disturbances through the platoon of vehicles. String stability is thus an essential aspect in CACC, assessing the dynamic behaviour of a platoon ('string') of vehicles equipped with CACC. Moreover, string stability also provides a measure for throughput without having to consider large amounts of vehicles.
3. Comfort
   Driver and passenger comfort is a very complex aspect. In the scope of this research, it will simply be represented by the level of deceleration. (Detailed user acceptance and comport analyses were carried out in TNO's driving simulator as reported in Chapter 5.)

Note that these aspects can be assessed with only a limited number of vehicles in the simulation and in reality. For this reason, the research focused on a platoon of four vehicles only, considered to be the minimum necessary platoon length. Obviously, practical aspects such as the effort needed to instrument a platoon of real vehicles also played a role in this choice.

3.3 Research methodology

The research started with a first-principles white box simulation model in order to determine an appropriate CACC controller structure. Based on simulations with this model, the CACC1 and CACC2 controllers (refer to section 2.3.2) have been developed. Because the focus here was on main mechanisms in (C)ACC behaviour relating to stability and comfort, practical limitations such as a limited sensor range, were ignored. In the second step, the parameters of the developed controllers have been determined and tuned based on VeHIL tests (refer to section 3.4.4), incorporating a real vehicle within a simulated traffic environment. Finally, road experiments have been carried out in order to validate the CACC behaviour under realistic circumstances.

In this methodology, each step incorporated more detailed vehicle models and CACC-controllers, taking into account more realistic effects such as vehicle limitations, sensor limitations and human comfort aspects.

3.4 Evaluation

The algorithms that were used have been described in section 2.3. The performance of the ACC, CACC1 and CACC2 control strategies has been evaluated by simulation and during a Real-world Pilot, for two scenarios against three criteria.

3.4.1 *Scenarios*

The behavior of the three controllers is determined in the following two scenarios:

- *Cut in:* starting with a string that is driving in a steady state situation, a vehicle cuts in between the first and second platoon member.
- *Traffic jam approach:* the platoon approaches a stationary object that represents a traffic jam. The stationary object is also equipped with V-V communication.

All tests started from a steady situation: the vehicles were driving 50 km/h.

3.4.2 *Criteria*

As already mentioned, the following evaluation criteria were used during the evaluation:

- *Safety*: The safety is related to the minimum distance between two successive vehicles.
- *String Stability*: This criterion is of crucial importance when more than 2 vehicles are controlled in a platoon. In case of a stable string, a disturbance in the front part of the string damps out as the disturbance propagates downstream.
- *Comfort*: The comfort of the controller is related to the longitudinal acceleration. Low acceleration levels result in a comfortable diver feeling. Comfort criterion is the maximum acceleration/deceleration value.

3.4.3 *Simulation*

Simulations of both scenarios in combination with all three controllers were performed. The simulation does not pretend to be an exact representation of the real world pilot. For simplicity, coefficients k_1, k_2 and k_3 are kept constant. In reality, they depend on different parameters. The purpose of the simulation was to find the differences in behavior between the three controller principles. In this way, a prediction of the expected real world pilot could me made. The control rules are implemented as specified in section 2.3 .A detailed discussion of the results can be found in (Stierman, 2006).

3.4.4 *VeHIL tests*

Before evaluating the systems in real world, the controllers were debugged and tuned in the TNO VeHIL facility. VeHIL stands for Vehicle Hardware-in-the-Loop. It is a unique state of the art facility that aims to make the development and testing of intelligent vehicles safer, cheaper and more manageable. It can be regarded as the missing link between simulations and road tests.

In VeHIL, a test vehicle, equipped with an object sensor based ADA system, is placed in a simulated traffic environment. To this end, the test vehicle is mounted on a roller bench, whereas other traffic participants are simulated using mobile robots, the so-called Moving Bases.

The core of VeHIL is a traffic simulation, implemented using MARS (refer to chapter 4), incorporating vehicle models that are programmed to make certain maneuvers such as baking actions, cut-ins, etc. The test vehicle is included in this simulation by feeding its measured motion (velocity, acceleration) using the roller bench, into the model. As the simulated vehicles perform their programmed maneuvers, their position, velocity and acceleration *with respect to the test vehicle* is calculated. The resulting motion data is send as command input to the Moving Bases. The resulting Moving Base motion is then detected by the environmental sensor of the test vehicle, which in turn will react according to the specific ADA application. This set-up is illustrated in figure 3.1, depicting the interaction of the various VeHIL components.

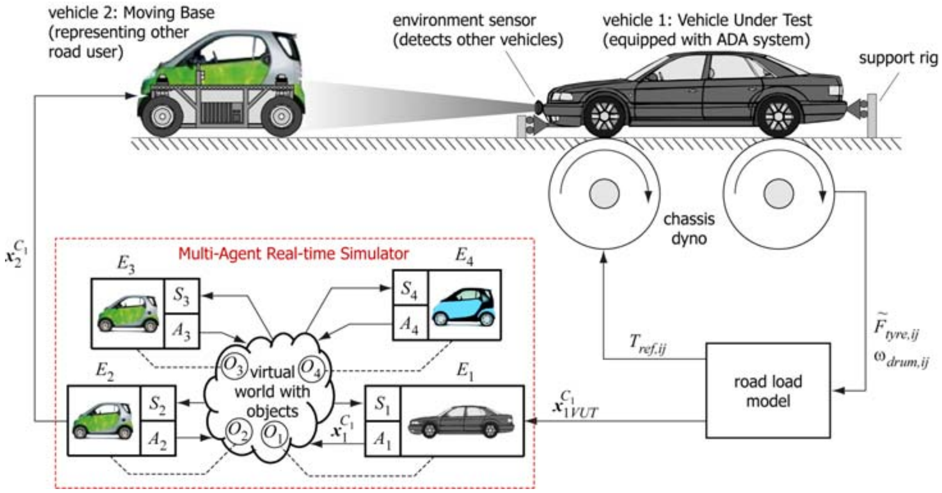

Figure 3.1 – The VeHIL set-up

VeHIL thus only considers the motion of other traffic participants with respect to the test vehicle. This is the main principle of VeHIL, having the advantage that tests are performed safely in a confined space. Moreover, experiments can be conducted with a high level of reproducibility and a high throughput. As such, it is a suitable tool for the tuning of the CACC controller in a simulated but realistic environment with a real test vehicle.

3.4.5 *Real-world Pilot*

With a string of four vehicles, the behavior of the different controller settings was tested during a so-called Real-world Pilot on a proving ground. All vehicles were equipped with V-V communication. Compared to the controller algorithms as used in the simulation, the controllers in the real world pilot are extended with some extra features so they approach the human behavior better in some specific situations. Figure 3.2 shows a photograph of the Real-world Pilot vehicles.

Note that the second vehicle has not been equipped with the CACC controller variants but instead only used the ACC controller. Because of the fact that it is the second vehicle, this has no influence on dynamic behavior. In order to enable CACC behavior of the last two vehicles, the second vehicle is still equipped with a communication system, communicating its position and velocity to the upstream vehicles.

Figure 3.2 – The Real-world Pilot

3.4.6 *Results*

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 3.3.

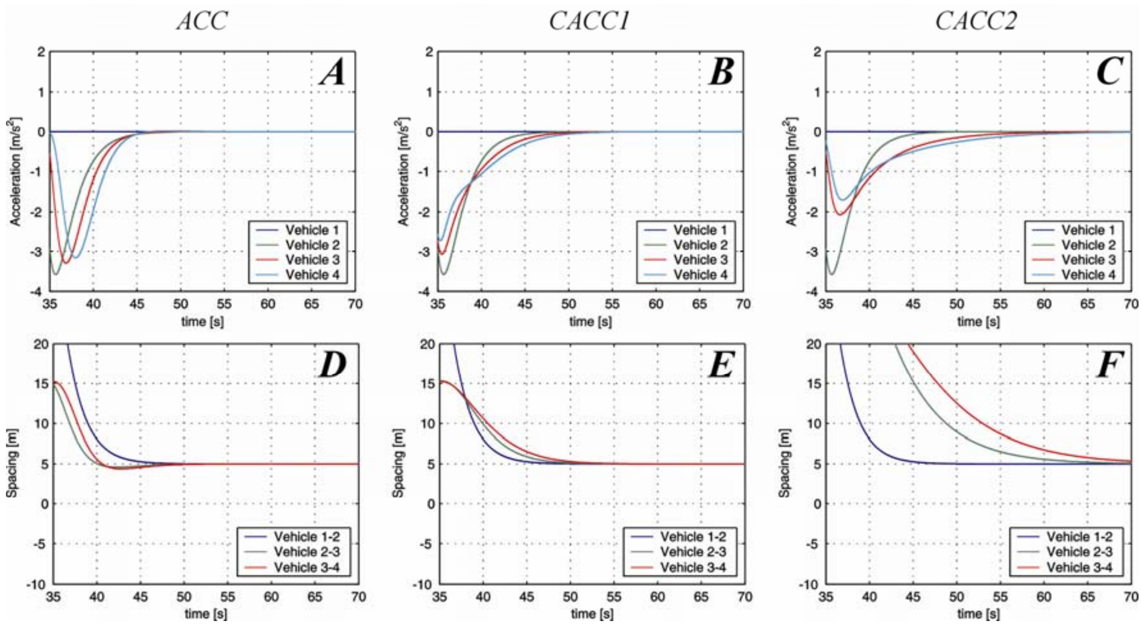

Figure 3.3 – Simulation results of a traffic jam approach

After investigating these and other similar results, the following conclusions can be 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..
- CACC1:
  - *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 (“smaller deceleration”), resulting in a moderate comfort improvement.

- CACC2:
  - *Safety*: Because the spacing is now very large, the controller can be regarded the most safe one..
  - *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.

In the simulation, the range of the V-V communication and object sensor is infinite, according to the purpose of the model, i.e. showing the very basic mechanisms in (C)ACC control behavior. As a consequence however, vehicle 3 and 4 increase the spacing in a very early stage in case of the CACC2 controller due to the approach of a standstill target.

During the real-world test, only three vehicles were used because the second vehicle has only been equipped with ACC (refer to section 3.4.5). They were equipped with Lidar sensors which have a maximum detection range of 50 m. Figure 3.4 shows the results of the real-world tests. The differences in controller behavior as found in these simulations are recognizable in the Real-world Pilot results. The difference between the ACC and both IRSA controllers is 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 are much higher than the deceleration levels of both IRSA controlled vehicles. Note that the CACC2 string was not in a steady state situation (vehicle 3 was decelerating) before reacting on the traffic jam, resulting in test data that is not fully comparable to the results of the ACC and CACC1 controller.

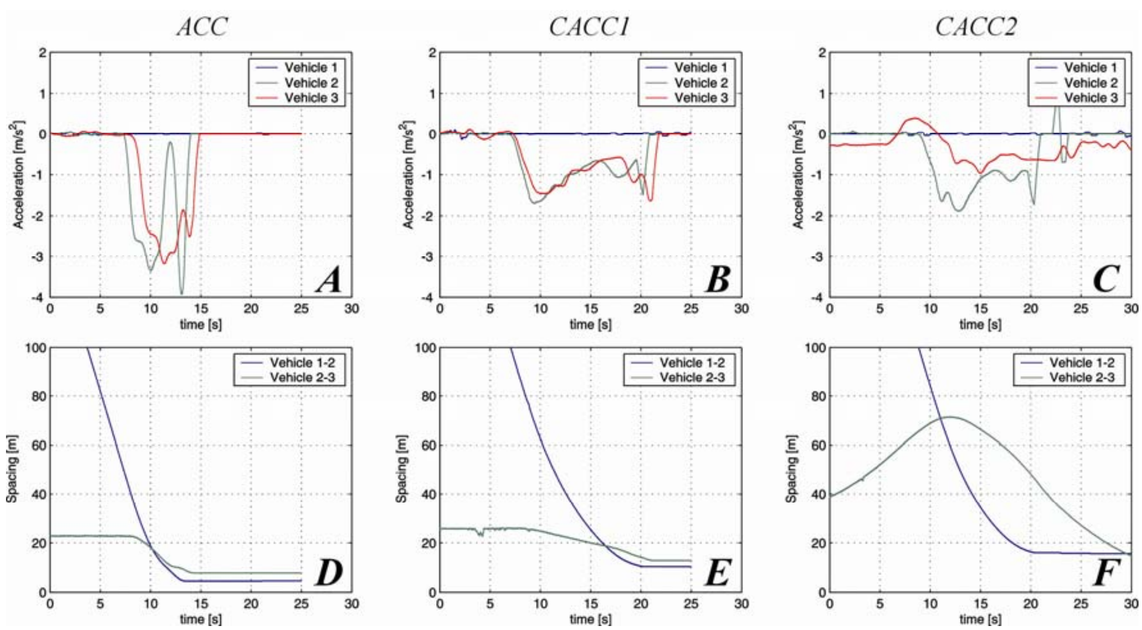

Figure 3.4 – Real-world Pilot results of a traffic jam approach

3.5 Conclusions and recommendations

Based on a realistic ACC controller, two additional CACC controllers have been developed incorporating V-V communication. To this end, both basic CACC controller structures have been designed using a first-principles simulation model. The controller parameters have been determined adequately using the VeHIL hardware-in-the-loop setup. The final validation took place using a Real-world Pilot.

If was found that V-V communication allows for significantly better performance with respect to safety, string stability and comfort due to a faster and better damped response on spacing disturbances of preceding vehicles.

The behavior of controller CACC2, i.e. common ACC with respect to the directly preceding vehicle and feedback of the average velocity of vehicles further ahead, showed the best performance with respect to safety, string stability as well as comfort. Due to its structure, this controller is also robust against non-equiped vehicles in the platoon.

The resulting CACC controller is however not yet fully developed. An important issue for further improvement is to include the actual distance into the CACC2 controller algorithm in order to prevent from a very early and unnecessary conservative reaction on standstill vehicles. Also the effects of using a weighted average of the velocities of the preceding vehicles should be investigated because it can be argued that vehicles nearby should have a bigger influence than vehicles further ahead. Finally, the current performance analysis focused on nominal behavior. It is desired to also analyze robustness, i.e. the dynamical behavior in the presence of increased levels of sensor noise and even sensor failures.

4 System robustness

4.1 Introduction

The challenge in the multi-disciplinary SUMMITS-IRSA project is to develop and assess a single system from different perspectives, using different development and simulation environments. Inevitably, different versions of models and components, such as the CACC algorithm and controller, and IRSA (sub)systems will be developed for different purposes, aspects and levels of detail. The consistency of the implementations and behaviors should be evaluated, tested and validated.

The resulting system on the top level consists of highly autonomous, nonlinear, interacting dynamical components (i.e. the instrumented cars with or without human driver involvement). Unfortunately – except for special cases – no formal methods exist for design and validation of this class of cooperative systems. Consequently sophisticated evaluation, test, and validation experiments have to be carried out in fully controlled environments in order to “close the gap” between simulation of the individual components and real-world testing of interacting systems.

The IRSA project has not defined application requirements on robustness or performance. Such requirements are obviously necessary for verification and validation. However, robustness can be evaluated quantitatively for the controlling mode[1] of operation. In order to carry out these evaluations the “pure CACC” implementations should be embedded into a vehicle control/management environment, which provides simulated, but close to real sensory inputs, implements exception handling (i.e. how to behave in “out of normal” situations) and adds new functionalities to enable the evaluation in close to real traffic situations.

This chapter – after briefly introducing the evaluation environment used and describing the extended control schemes (i.e. the embedding control/management environment) implemented – summarizes the results of CACC component evaluations at three consecutive levels of application integration and testing:

- A benchmark for evaluation of alternative implementations of the CACC.
- Robustness evaluation of the CACC component under various modes of degraded functionality.
- Robustness evaluation of the CACC component under certain not nominal platooning type circumstances (incl. lane change, take-over, cut-ins, etc.)2...

4.2 The tool used: Multi-Agent Real-time Simulator – MARS

MARS is a continuous time / discrete event simulator for highly autonomous multi-agent systems. In MARS terminology the autonomous dynamical components (e.g. intelligent vehicles, road-side controllers, etc.) of the simulation are called entities, which are generalizations of agents. MARS has a model based architecture: all experiment specific information is stored in models and MARS loads the models when

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[1] Driver intervention is not evaluated on “robustness”.

[2] To carry out these evaluations certain lateral control and cooperation scheme were implemented. This extended implementation was necessary in order to provide the high fidelity environment for evaluating the CACC solutions under realistic conditions.

the simulation is initialized. Various models are used to describe the environment the entities "live" in, the behavior (i.e. the dynamics) of entities themselves, the visualization, etc., in a self-contained form. MARS introduces a novel and powerful way of modeling agents and their interactions using abstract sensors and actuators. Real sensors and actuators can also be modeled in the framework as an extension of the abstract functionalities. MARS serves as a foundation for a new breed of tools which are capable of very accurate, real-time simulation and evaluation of cooperative vehicle systems and thus can effectively bridge the gap between "desktop" simulations and field operational tests. For details about the MARS modeling concept, the computation model and a few typical applications readers are referred to Papp (2003a, b, 2006).

4.3 A control scheme for cooperative intelligent vehicles

The increasing complexity of in-vehicle systems and the new generation of cooperating applications combined with stringent dependability requirements pose extreme design, implementation, testing and validation problems. One of the key challenges is to find a decomposition scheme, which allows for flexibility, extendibility and manageability on one hand and safe, efficient implementation on the other. System decomposition is a way to cope with complexity and a good decomposition gives a natural support for system implementation. A "classic" and popular architecture is a layered scheme: the controlled process (vehicle, in our case) is at the bottom and layers of control components are built on it. Each control component covers a well-defined control function, and this control function becomes more and more complex ("intelligent") as climbing up in the hierarchy (e.g. actuating, motion, tracking, etc). A control component has its own (sufficient) knowledge about the process and environment to generate control commands based on observations. The layered scheme has a clear signal flow (observations bottom up, commands top down) and it is relatively easy to make the implementation modular (component based). Unfortunately the classic scheme does not integrate the exception handling (i.e. deviation from nominal operation).

Figure 4.1a shows an enhanced layered scheme, which addresses these problems. In this scheme the observations (i.e. sensory readings and derived quantities/signals) are "freely" available for control components via the vehicle's internal communication bus (i.e. the observation bus). The control components are responsible also for handling exceptions (see the upcoming signal stream). Figure 5.1b details the internals of the components. Beside the control functionality (Controller Kernel) each component executes a monitor-evaluate-act (MEA) loop to track its own and related subsystems' health state. If a component receives an exception from the layer below or the exception is generated locally (by the monitor) the evaluator decides how it should be handled. If the component cannot handle the exception fully (or cannot handle at all) the exception is propagated to higher control layers.

The figure also shows a link to the safety related aspect. A control layer may use dedicated hardware components (e.g. sensors, communication links, etc.) to carry out its functionality. Should this component fail the controller should adjust its operation to this new situation or – if not capable of doing this – should emit exception(s). Safety critical dedicated components have to incorporate diagnostics (self-test) functionalities and in case of a component fault the monitoring functionality has to be informed.

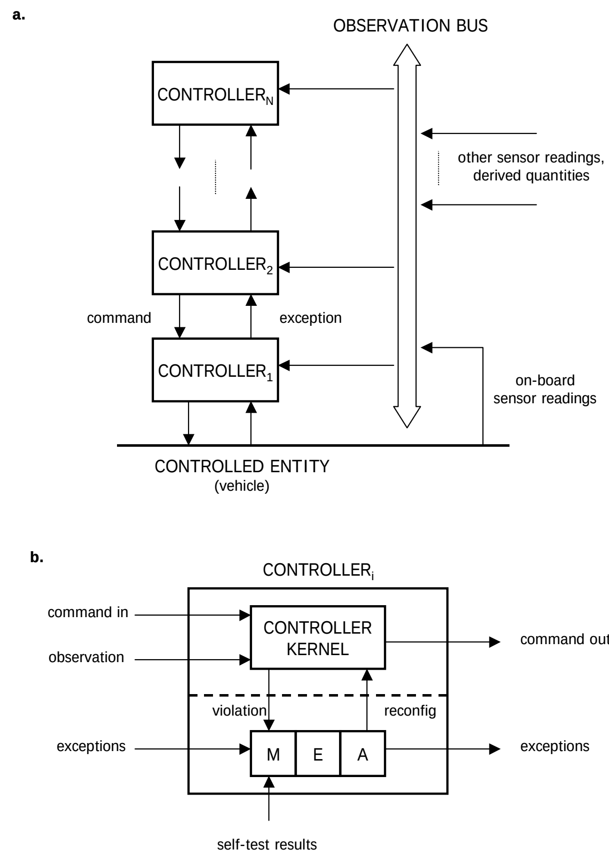


Figure 4.1: The proposed functionally layered control model with exception propagation

The architecture of the intelligent vehicles (i.e. incl. controllers) used in the experiments – and which may serve as a basis for real-life implementation – follow the conceptual scheme described above. The implementation incorporates the following components:

Detectors and devices: Each vehicle, as a controlled entity, is equipped with the following devices and detector units to provide the on-board sensor readings via the internal world model (see below) and observation bus to the controllers. These can be used with ideal (i.e. noise free), or noisy sensor models.

- Radar sensors to detect other vehicles ahead with a maximum range of 150 m. Noise models result in inaccurate detections (percentage deviation in distance and orientation) or missed detections (as small periods of fall out), and occlusion.
- GPS to obtain the vehicle's global position in the simulation world. Noise models result in inaccurate detections, and lower sampling rates.
- Radio transmitter and receiver sets. Noise models include delays in transmission (e.g. due to band-width restrictions), small periods of fall out of transmission.

Internal world model: Each vehicle has an internal world model that represents the vehicle's current "understanding" of its environment based on the available sensory and communication readings. The world model provides momentary monitoring information such as position and speed of leaders in the CACC platoon, and the traffic jam obstacles, via the observation bus to controllers.

Hierarchical control structure: Each vehicle has a hierarchical control structure as in figure 4.1.a. Each hierarchical (vertical) layer of control has a specific role and responsibility; i.e. regulation, manoeuvering and coordination (Netten, 2005). Controllers handle both longitudinal and lateral movements and obstacle avoidance. The CACC is decomposed at three levels, a cooperation controller (coordination layer), car following (manoeuvering layer) and throttle and brake regulation. .

Vehicle: It implements both the longitudinal and lateral dynamical behavior of the vehicle. Nonlinear effects (e.g. engine, brake, tire model, drive-chain characteristics, etc.) are modeled to assure close to real responses in the virtual environment.

More details on the environment, implementation, evaluations and results are presented in Netten (2006).

4.4 Benchmark of the CACC algorithms

During the development and assessment of the IRSA, the IRSA Meta-model was implemented in different tools at different levels of detail. A benchmark test was set up to evaluate the consistency of alternative implementations in terms of the degree of similarity in the internal workings and their external behavior for the IRSA traffic jam scenario (scenario 2, section 2.4).

The benchmark is set up using the MARS environment to evaluate two alternative controller implementations:

1 The CACC1 implementation used in the VEHIL and real-world pilot experiments implemented in Simulink and Stateflow.
2 The CACC1 implementation in Java used in ITS Modeller experiments.

A benchmark vehicle contains both algorithms as alternative controllers in the architecture described above. Higher-level controllers enable the switching between the algorithms, feed the same observations to both algorithms, and feed their output into the same vehicle model. The detectors are noise free.

Vehicles in lane 1 have implementation 1 enabled, and implementation 2 in the second lane. All vehicles drive the simultaneously into the same traffic jam. Any differences in the two algorithms can be observed from the visualization and the output logging of the individual vehicles and their controllers. The benchmark is run with a single vehicle (effectively in ACC mode) and with a platoon of 5 vehicles.

The similarity of behavior is evaluated from several aspects during the benchmark:

Algorithm level	controller gains controller output (accelerations, speeds, positions) most important object
Inter-vehicle behavior and safety	relative vehicle distances (headway, time headway) relative vehicle speeds and accelerations time-to-collision (TTC)

The evaluations revealed differences in the initial implementations of controller gain functions, acceleration control outputs and occasionally the selection of the most important object from the string of leading vehicles. This resulted in significant differences in behavior. For example, maximum orders of magnitude of differences were observed of 2.5 m headway, and 0.25 m/s^2 deceleration. These results were obviously fed back into the development process – the designers and implementers of the CACC algorithms have to analyze the findings and harmonize the variants of the controllers in order to assure coherent models for the various evaluation aspects and development phases.

4.5 Robustness evaluation of the CACC

"Under the hood", the technical IRSA system uses a CACC system that consists of a cruise controller, extended with radar (or lidar) sensor and detector to maintain a safe headway (ACC), and a short range radio for vehicle-vehicle (V-V) communication. This evaluation addresses the robustness of the CACC1 controller, as an IRSA system component, for disturbances in the traffic environment and in sensor input.

The CACC1 algorithm requires input information about leading vehicles, including relative or absolute distances, speeds and accelerations. The radar provides this information at high frequency sampling rates about the direct leader of a vehicle. The short range V-V communication is used to exchange information that is similar to the radar information (i.e. position, speed / acceleration) for all IRSA equipped vehicles in the leading string of "n" vehicles. Radio communication is also used at high frequency sampling rates (i.e. 25 or 50 Hz) here.

The radar and communication provide redundant information with respect to the observed information about the direct leader. In addition, communication also enables a vehicle to "monitor" leaders beyond its own radar visibility that should be used advantageously to anticipate on disturbances (perturbations) down stream. Figure 4.2 shows the contributions of the noise-free radar and communication input on CACC1 performance. The extreme (minimum) decelerations and headways observed in the traffic jam scenario are similar for communication-only or for communication and radar. When communication falls out, vehicles anticipate slightly later and stronger to the traffic jam.

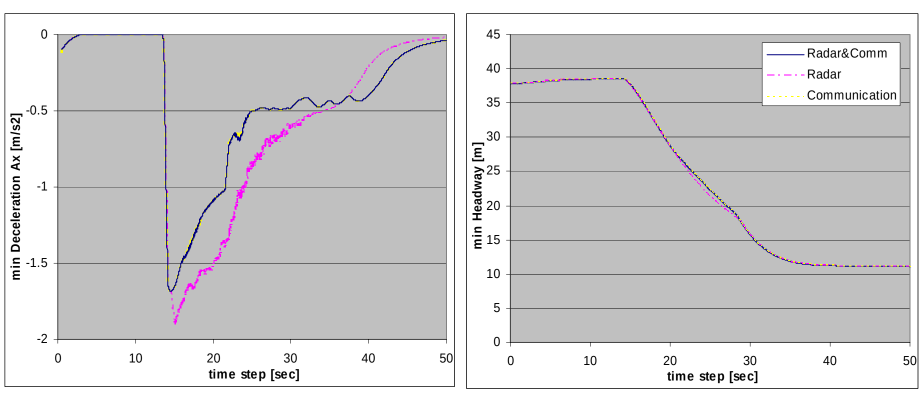


Figure 4.2 Extreme values of decelerations and headway for the traffic jam scenario with both radar and communication (solid blue), only radar (-.- pink), and only communication (.. yellow) devices enabled. (left) decelerations are smoothed with a moving average of 0.5 sec for the extreme (minimum) values in the string.

The most-important-object (MIO) in the CACC1 algorithm is the one vehicle in the leading platoon that requires the momentary absolute minimum acceleration or maximum deceleration. Usually the direct predecessor, or the tail of the traffic jam, or the cutting-in vehicle are identified as the MIO and most critical for robustness in these two scenarios. The modes for input disturbances can be simplified with respect to section 4.3 for this experiment.

- The short duration of the scenario implies that loss of radar is either modeled as a complete loss of radar, and as very short periods of loss (repeated random parts of seconds).
- Noisy GPS information has a complex effect of CACC1 performance. GPS information is fused with radar input in the internal world models of both the sending and receiving vehicles, filtering out much of the positioning errors by leading vehicles. For simplicity, only radar noise will be inserted in this experiment.
- The short duration of the scenario implies that loss of communication input is either similar to complete loss of communication, while very short periods of loss of communication are similar to the very short periods of loss of radar and not separately reported here.

Based on the system design and worst case situations, the following categories of disturbances have been identified as relevant for robustness in this stage:

- Two basic IRSA scenarios have been identified to characterize critical disturbances from the surrounding traffic (section 2.4):
  - A non-IRSA vehicle cutting in ahead of the string of five IRSA equipped vehicles driving at 50 km/h (IRSA scenario 5).
  - A string of five consecutive IRSA vehicles driving at 50 km/h into a traffic jam of stationary vehicles (IRSA scenario 2).
- Disturbances in the observation input to the CACC algorithm result from failures and processing errors in the sensors and detectors.
  - Radar disturbance from 0 – 100 %, consisting of noise (variation in range and angle accuracy) and relative periods per second for complete loss of detections.
  - Communication is switched on and off.

The simulation vehicle is equivalent to the benchmark vehicle described above. Some general robustness observations are:

- The CACC1 can handle both scenarios well in noise free conditions; i.e. vehicles anticipate on the traffic disturbance down stream and preserve stable and safe headways, damping decelerations.
- The CACC1 algorithm does not implement any filtering on input disturbances (variations or loss of input over short periods of time). Consequently, considerable fluctuations in control output decelerations are observed. In case of loss of input, the CACC switches back to CC mode and starts accelerating to the cruise speed set. This is not a fail-safe approach in either scenario. Obviously, filtering and safety measures are implemented outside the CACC algorithm in the IRSA system, but should also be formulated explicitly in the (meta-model) IRSA system specification and design eventually.

Figure 4.2 shows the effects of noisy CACC input for the cut-in scenario. The left figure shows the relative distances in the string of vehicles as an envelope of minimum, average and maximum headway values. The white noise causes the vehicles to increase headways. This effect can already be observed during the cruising situation before the cut-in (t = 18 sec). The algorithm reacts stronger to momentary perceived headway reductions by deceleration, while the reaction to a perceived headway increase does not immediately result in an equivalent acceleration. For smaller levels of noise, the effects on string stability and safety (e.g. minimum time-to-collision) are already significant. For larger levels of noise (e.g. > 30%) stability becomes an issue for the fifth vehicle.

Figure 4.3 shows the effects of noisy CACC1 input for the traffic jam scenario. The upper figure shows that 5% radar noise already causes small variations on the control output decelerations. These variations are largest for the leading vehicle. The effects for larger noise levels on safety and stability are comparable to those observed for the cut-in scenario.

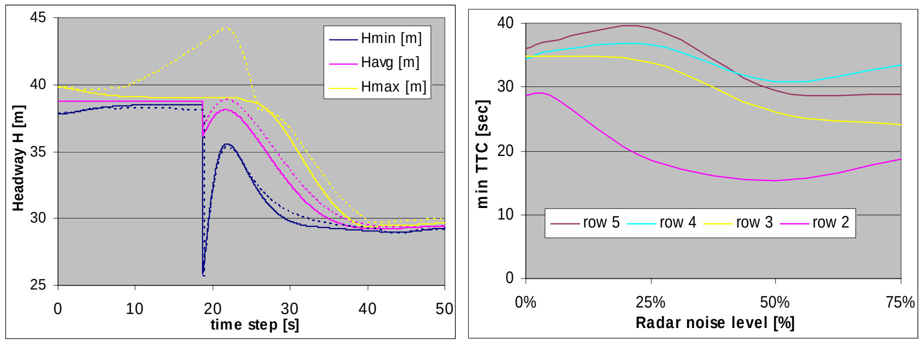


Figure 4.3: Headway and minimum time-to-collision for cut-in scenario. (left) Headway envelope for noise free (solid) and 25% noisy (dotted) radar. (right) Row number indicates the string position – row 5 is the last vehicle.

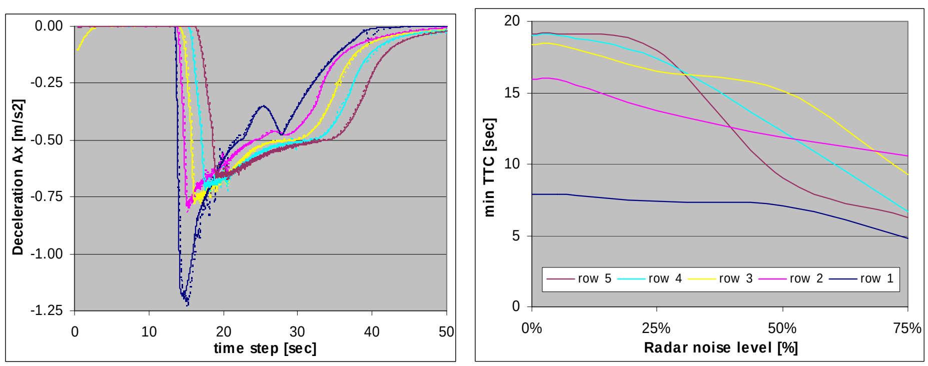


Figure 4.4: Deceleration and minimum time-to-collision for traffic jam scenario. (left) Decelerations (smoothed with a moving average of 0.5 sec) for noise free (solid) and 25% noisy (dotted) radar. (right) Row number indicates the string position – row 1 is the first vehicle.

4.6 Evaluation of CACC robustness under dynamic traffic conditions

As a next step in component evaluation and testing, the scenario is extended from isolated short term traffic situations to a dynamic and longer term traffic situations. The extended scenario includes various maneuvers resulting in lateral motions (e.g. lane change, take-over, cut-in, etc.). The extended scenarios deliver important insight into robustness of the implementations under real life traffic situations, which go beyond the "nominal platooning" use of the CACC controllers. A series of scenarios are setup in which strings of 3 or 5 CACC1 equipped vehicles drive in the middle lane with an intended cruise speed of 30 m/s and a comfortable time headway set at 2.0 sec. They are surrounded by vehicles with speeds between 20 and 40 m/s, and time headways of 0.8 sec or larger. This results in frequently changing traffic situations in which the surrounding vehicles accelerate irregularly and may frequently cut-in the string while changing lanes.

In order to be able to test the CACC algorithms under the extended scenarios the vehicle controllers have to be extended with new functionalities: the vehicles should be able to implement coordinated lateral maneuvers. The extended “onboard system” also includes a sensor and controllers for lateral obstacle avoidance, steering, and lane changing. Several approaches for changing are evaluated for the non-IRSA vehicles. In autonomous lane changing mode, a vehicle uses its own sensors to search for a gap, and accelerate to move towards and into that gap. The autonomous vehicle selects the gap based on its own time headway settings, which may conflict with other (e.g. IRSA) vehicles. In cooperative mode, vehicles can communicate according to a request-and-accept or a request-and-inform interaction protocol. In the first protocol, the requesting vehicle will change lanes only upon explicit acceptance by the accepting vehicle (e.g. IRSA vehicle). In the second protocol, the requestor will change lanes whenever it has sufficient gap space.

The evaluations indicated several robustness issues; i.e. whether the controller can adequately react to potentially unsafe traffic situations. It can be observed that the string of CACC1 vehicles experiences frequent and large fluctuations in accelerations and headway due to intersections and down stream decelerations. The CACC1 vehicles occasional have to decelerate with more than 5 m/s^2 to avoid collisions, which is much larger than the usual comfort setting of -2 m/s^2. This can also be observed for cooperative merging vehicles with smaller time headway settings. A second observation is that the (leading) CACC1 vehicles frequently exhibit maximum accelerations when a leader changes lanes. These observations indicate the necessity of additional measures to maintain system stability and safety for usage of CACC1 systems in controlling mode.

4.7 Discussion

The advance in intelligent vehicle/transportation systems puts emphasis to the local (onboard) intelligence, vehicle - vehicle and vehicle - environment interactions. Dependability of ADA systems, like the IRSA system with sensors, communication and a CACC1 controller, becomes even more important when the mode of operation and authority increases from advisory to full controlling mode. Sophisticated evaluation, test and validation environments are required to “close the gap” between simulation of the individual components and real-world testing of interacting systems. These environments should provide full control of the circumstances, reproducibility and – when approaching the final rounds of high fidelity testing – flexibility to mix real and virtual components.

The methodology for evaluating the CACC1 component of the IRSA system in full controlling mode is demonstrated in this section. Three evaluation studies were carried out on the robustness of the CACC1 algorithm for disturbances in input and traffic environment:

- A benchmark for white box evaluation of different implementations of CACC1 algorithms.
- Evaluation of the robustness of the CACC1 algorithm for noisy sensor input (radar, GPS, communication) under isolated application conditions (traffic jam, positive cut-in scenario).
- Evaluation of the robustness of the CACC1 algorithm for dynamic traffic situations, including frequent cut-ins and accelerations over longer time periods.

Some observations about robustness are fed back into the development process of the IRSA concept:

- Control algorithms will be implemented differently for different purposes. Small implementation differences do result in significant variations in controller output and ultimately in system behavior. Domain application requirements (e.g. for traffic and vehicle safety and stability) should be developed for acceptable variations in input and output. Alternative implementations should be evaluated, and ultimately tested and validated on these requirements.

- Combination of radar and communication provide some redundancy in CACC1 input that could improve system robustness for disturbances like occlusion, communication bandwidth issues, noisy detections and device failures. However, the CACC1 algorithm itself is vulnerable to variations caused by these disturbances. The CACC1 algorithm may switch back to CC-mode and start accelerating in stead of decelerating for a traffic jam. Measures are being developed in conjunction, e.g. driver intervention and filtering techniques. The IRSA concept should specify those measures for dealing with these disturbances in a consistent way.

The experiments undoubtedly show the crucial importance of high-fidelity simulation based evaluation and testing. The logical next step in the evaluation of CACC1 based cooperative systems (after completing the evaluation incorporating wider set of “sensitive” scenarios”) is to gradually bring in real hardware components (sensors, DSP boxes, vehicles, etc.) and move the experimenting into the mixed “virtual-real world”. TNO’s VeHIL facility covers exactly these needs. The fact that VeHIL relies on MARS technology makes the shift to the “mixed world” relatively easy.

5 The impacts of IRSA on driving behaviour

5.1 Introduction

This chapter addresses the behaviour of a driver with IRSA in a driving simulator environment. The scenario studied in the IRSA driving-simulator experiment was 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 (vehicle *a* in Figure 4.1). The goal of the instruction is to get a stable car-following situation with vehicle *b*. At a certain time interval a vehicle *c* cuts-in and in due time a stable car-following situation will occur again.

The time-headway (THW), which is used as input for the IRSA-system, has to be available the moment a cut-in manoeuvre starts, as indicated by Feenstra & Van der Horst (2006) and Feenstra, Brouwer & Pauwelussen (2006). This time-headway was obtained by V-V communication, i.e., *cooperative driving*. At the time instant a vehicle in the left-lane begins a cut-in manoeuvre, the THW changes to the time headway compared to the cut-in vehicle as if it was already driving in front of the subject's vehicle (Figure 4.1). This time-headway could be determined since the position of surrounding traffic was known (by V-V communication). Moreover, a message was communicated between the vehicles at the time instant a cut-in started. In reality, the time instant could possibly be detected by the steering-wheel angle or the indicator signal of a cut-in vehicle.

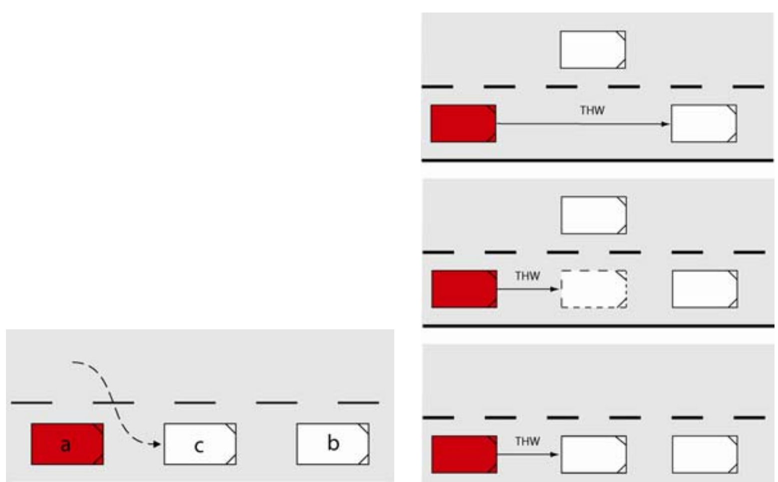


Illustration of cut-in manoeuvre by vehicle c.

The real time-headway (THW) to a possible predecessor changes to a virtual headway.

Figure 5.1: Illustration of cut-in manoeuvre

5.2 Research questions

The research questions of the driving experiment were: what are the effects of the IRSA modes on:

- the resulting time headway behaviour compared to No system?
- the acceptance (workload, usefulness, satisfaction, experienced feeling, etc.)?
- the time headway in calm and busy traffic?

5.3 Research method (driving simulator)

The experiment was conducted in the TNO moving-base driving simulator which has been described in detail by Hogema & Hoekstra (1998) and Hogema, Hoekstra & Stel (2005).

In total 32 subjects drove with three different IRSA modes and without any system ('No system').

– The first IRSA mode was an Advisory mode. It showed the time headway to the predecessor by means of icons, which were displayed just below the speedometer on the car console. Figure 5.2 shows the icons. During the transition from the amber to the red icon, a warning beep sounded. The subjects were instructed that safe driving was achieved when the red icon did not light.

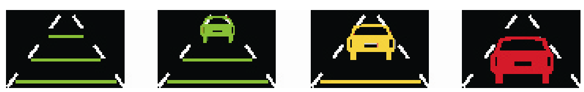


Figure 5.2: The four icons for the Advisory mode. The icons are shown in time sequential order.

– The second IRSA mode with a haptic accelerator pedal formed the so-called Intervening system. A haptic pedal generates a counterforce on the accelerator pedal, which could be compensated by the driver (Rook & Hogema (2005)). An ACC algorithm (Versteegt, 2005 & Scheepers, 2005)) controlled the counterforce, i.e. it generated a counterforce when exceeding the speed limit (100 km/h) or when the time headway dropped below a predefined value. The ACC algorithm was equipped with a filter to overcome abrupt braking when a car cuts-in.
– The third IRSA mode –the Controlling mode- used the same ACC algorithm, but this ACC system controlled the vehicle directly.

The subjects drove with the 3 IRSA modes and without system in a calm traffic environment and a busy traffic environment. For the three IRSA modes, the busy traffic route was driven twice, namely with a high and a low time headway setting (the reader is referred to Feenstra et al. (2006) for details). Each run took 9 minutes and contained maximally two cut-in manoeuvres. The sequence of the systems was balanced among the subjects.

Objective measures, including the time headway and velocities for the adjustment process, were determined quantitatively from the driving simulator data log files. The objective data were analysed by calculating the mean values and the standard deviations. These measures demonstrate the mean driver behaviour as performed in the driving simulator. Subsequently, the driver behaviour during the cut-in manoeuvre was modeled by seven parameters (Figure 5.3). Parameter THW1 indicates the time headway 5 seconds before a vehicle cuts-in. Parameter THW2 and THW3 denote the time headway just before and just after a cut-in starts, respectively. The time headway at the time instant of reaction is denoted by THW4 and the reaction time itself is denoted by ΔT. Parameter THW5 is the time headway when the car-following process is stabilized. The response time of the stabilization process is represented by τ.

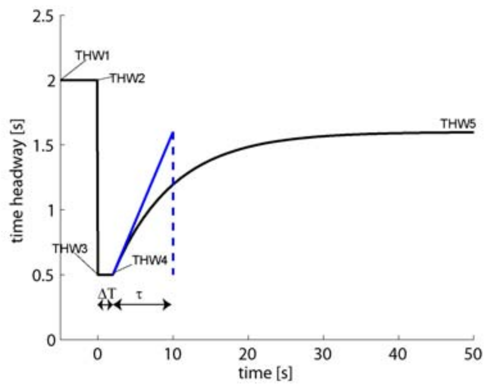


Figure 5.3: Illustration of the model parameters for a cut-in manoeuvre. A car cuts in at time instant t=0.

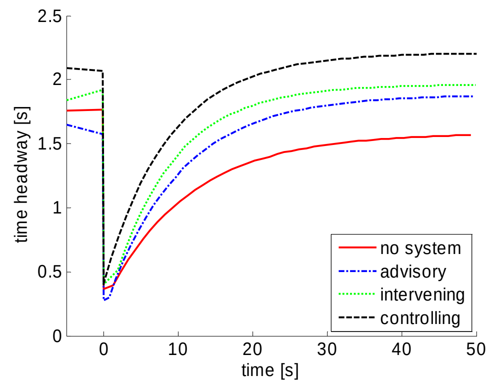
During the experiment, subjective data have been collected from the subjects as well. The subjective measures included the subjective workload and the Usefulness/Satisfying rating (Van der Laan, Heino, & De Waard, 1997). The subjective data were analysed by means of analysis of variance (ANOVA). Differences among pairs of navigation conditions were tested using Tukey's LSD post-hoc test.

5.4 Results

This section describes some results as found by the driving simulator study. For more results and detailed information, the reader is referred to Feenstra et al. (2006).

5.4.1 Model characteristics

The determined model characteristics for a cut-in manoeuvre are shown in Figures 5.4-4.6. At time $t=0$ a cut-in started. The results show that for a driver without system, the mean time headway before a cut-in was larger compared to the time headway when a stabilization process was finished. Furthermore, subjects started increasing the time headway about the same time a cut-in manoeuvre started. Van der Horst and Bakker (2006) and Hogema (1995) reported similar behaviour. For the IRSA modes in contrast, the mean THW before a cut-in was the same or even smaller compared to the time headway when a manoeuvre was stabilized (finished). Again considering the No system, the time headway for busy traffic seems smaller than for calm traffic, although no statistical evidence was found.



.Figure 5.4 Calm traffic and high THW settings

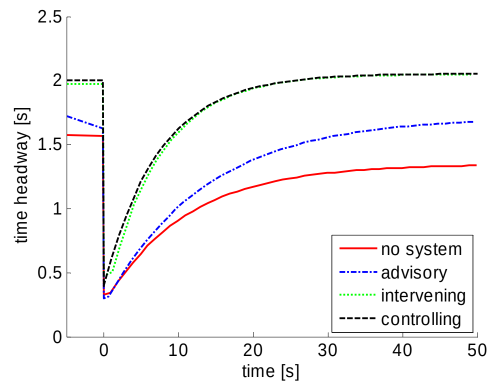


Figure 5.5: Busy traffic and high THW settings

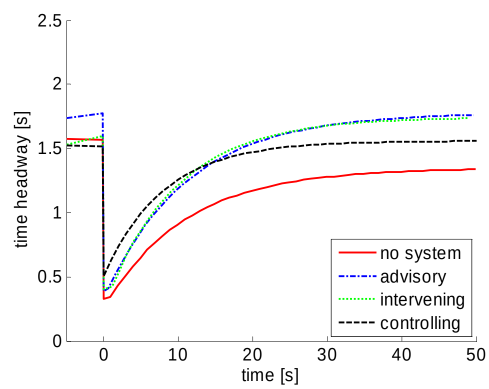


Figure 5.6: Busy traffic and low THW settings.

The figures indicate that the response time τ of the Controlling system has the smallest value for almost all traffic conditions compared to the other IRSA systems. This implies that IRSA stabilizes the fastest by using the Controlling mode. The only exception was the Intervening system for busy traffic and high THW setting, i.e. no difference was found for these conditions (again no statistical evidence was found). Finally, the end values of the stabilizing process, THW5, for the IRSA modes were compared to the THW5 value of the No-system mode. It appeared that almost all end values of the IRSA modes were significant larger than the end values for No system. The influence of an IRSA, with the applied settings, may therefore have a negative effect on the road capacity and the traffic flow but may have a positive effect on the safety (see also Chapter 6).

5.4.2 *Rating Scale Mental Effort*

After each run, the subjects indicated the experienced effort (or workload) by means of a Rating Scale Mental Effort (RSME) (Zijlstra, 1993). Figure 5.7 shows the mean values of the effort as function of the system, traffic condition, and the time headway settings. Statistical tests showed that the experienced effort for the Controlling mode was the lowest compared to the other IRSA modes and without system in this driving-simulator study (the overall values are rather low).. Note that a low workload does not necessary imply a better performance, i.e., due to a low workload the driver attention might decrease.

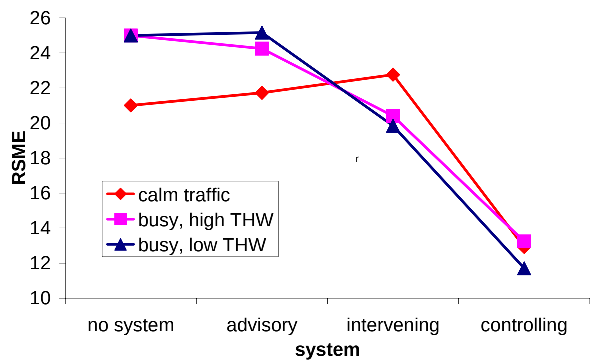


Figure 5.7: Rating scale mental effort (RMSE)

5.4.3 *Usefulness versus satisfaction*

The subjects indicated after each run their opinion about the system by a questionnaire. The questionnaire consisted of nine questions. The answers have been transformed into two variables, the usefulness and the satisfaction of the system, according to Van der Laan et al. (1997). 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 5.8. 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 where found for the other conditions, e.g., the satisfaction compared to the time headway settings and traffic conditions.

Figure 5.8: Van der Laan scale, Usefulness versus Satisfaction.

5.4.4 *Subjective driving performance*

After each run, the subjects had to rate their own driving performance by means of a number between 1-10. The mean rate scores for all conditions were statistically analyzed. The tests showed a higher mean rate in case the subjects drove in calm traffic compared to a busy traffic environment.

5.4.5 *Experienced feeling*

The subjects represented their experienced feeling by means of a questionnaire. The judgments for *Expectation* represent again the expectation of a subject before they had drove with an IRSA system, The Expectation condition was used as a baseline where the subjects considered what their feeling would be if they had driven the trajectory with a support system. The feelings were: Safety, Irritation, Stress, Feeling to be monitored, Fun in driving and Paying attention. The statistical tests showed that the irritation was increased with the Advisory mode compared to the Controlling mode. The main reason for this effect is probably the design of the Advisory mode, i.e., the algorithm of the advisory mode was not equipped with a filter for cut-in manoeuvres. As a consequence a warning was given (red icon and beep signal) the time instant a cut-in manoeuvre started. The Intervening mode was considered more irritating than the Controlling mode. The Advisory mode was considered more stressful than Intervening and Controlling mode. Probably for the same reason, viz., an improper design. Furthermore, the subjects paid most attention to the traffic when they drove the Advisory mode compared to the Controlling mode.

5.4.6 *Use of IRSA*

Finally, the subjects indicated if they would use an IRSA system in their car. The results in percentage are shown in Figure 5.9. Before the experiment, the subjects were dominantly uncertain (‘maybe’ in Figure 5.9) to use a car following system, a posteriori in contrast, the subjects where predominately positive about the Controlling mode and negative about the Advisory mode.

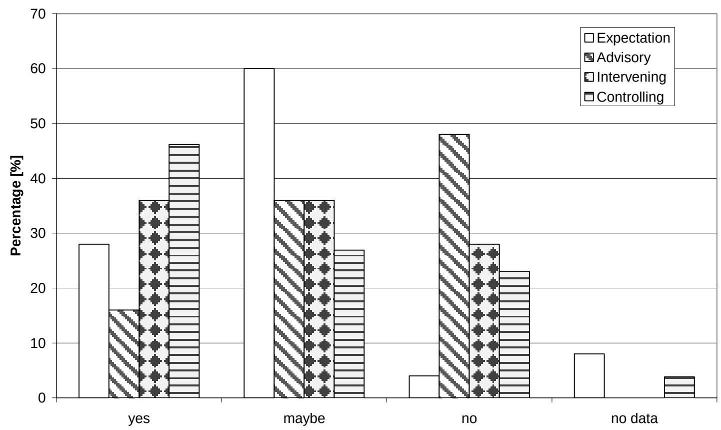


Figure 5.9: Percentage of subjects willing to use IRSA.

5.5 Conclusions

The use of IRSA in a cut-in situation was evaluated using a moving base driving simulator. An advisory, intervening and controlling variant were studied. It appears that the controlling offers the best perspective on traffic flow stabilization and was also considered to be more satisfying than the advisory variant.

6 Traffic flow impacts

6.1 Introduction

This chapter describes the experiments carried out with the ITS modeller, to establish the effects of IRSA on the traffic flow level. In other words, how does IRSA influence the interactions of large numbers of vehicles on a network? Three scenarios were modelled to assess the impact of IRSA on traffic flows:

- approaching a reduced speed limit zone;
- approaching a traffic jam;
- leaving the head of a queue (at a traffic light).

In the first two scenarios, the aim of IRSA was to help the driver to slow down in a safe and comfortable way, in the last scenario the aim was to help drivers to accelerate in an efficient way, to improve the safety and throughput at traffic lights. Different penetration rates were modelled, to reflect a gradual introduction of the system.

6.1.1 Approaching a reduced speed limit zone

Reduced speed limits can be applied for several reasons, e.g. to improve air quality or safety, or to homogenize traffic and avoid congestion. In this scenario, inspired by the implementation of a reduced speed limit on the A13 motorway in Overschie (Rotterdam) to improve air quality and reduce noise annoyance (Riemersma, 2004), there is a reduced speed limit (from 120 km/h to 80 km/h). This large difference in speed limits may cause shockwaves as drivers brake hard when they enter the section. The hypothesis is that IRSA can support the driver to slow down in a safe and comfortable way (earlier than they normally would), by giving speed or deceleration advice. In some cases, this may prevent congestion. The reduced speed limit and the location of the start of the reduced speed limit zone is communicated to the equipped vehicles by two road-side beacons: one located 1200 meters before the start of the reduced speed limit zone and one located at the start of the reduced speed limit zone. Vehicles within 300 meters of a beacon can receive the messages. The IRSA system will remember the content of the messages as long as necessary.

In the controlling mode, the vehicle will slow down automatically by the IRSA system. In the Advisory mode, the driver receives a warning to start braking for the reduced speed limit. It was assumed that in the advisory mode drivers start braking later than the controlling mode version of IRSA, but earlier than without the system. Two versions were compared: IRSA “far” (with drivers starting to brake quite early) and IRSA “close” (with drivers starting to brake quite late).

6.1.2 Approaching a traffic jam

In this scenario, the reference situation is a three-lane motorway with a lane drop halfway. The traffic is near-capacity, so congestion occurs near the lane drop. The hypothesis is that IRSA can help to improve the safety and/or reduce the congestion by warning the drivers and helping them (or the vehicles, in the controlling mode) to slow down in a safe and comfortable way, so that they drive at an appropriate speed when they arrive at the congested section.

When vehicles are driving at speeds below 70% of the speed limit, vehicles equipped with IRSA send out warning messages. IRSA vehicles within 200 meters of the sending vehicle will receive the messages. Only upstream IRSA vehicles will use the information of the messages. The system will start braking when the speed is at least 10% higher than the speed of the sending vehicle, with a constant deceleration based on the speed of and distance to the sending vehicle.

For the controlling mode, the following controllers were tested (see Section 2.3):
- *ACC*: Basic ACC controller, which aims to maintain a reference distance to the predecessor and tries to minimize the speed difference with the predecessor.
- *CACC1*: CACC controller, in which the resulting acceleration is computed by determining the individual ACC acceleration with the basic ACC controller in relation to a number of preceding vehicles (equipped with the system), and by taking the minimum of these individual ACC accelerations. The number of predecessors (equipped with the system) taken into account is 3. The distance and speed of the first predecessor vehicle (IRSA equipped or not) are measured with the vehicle's own sensors (radar). In addition to the characteristics of that vehicle, the characteristics of the first two downstream IRSA-equipped vehicles are taken into account.
- *CACC2*: adapted version of CACC1, which controls on the speed difference with the direct predecessor, added with a term based on the average speed difference with a number of slower predecessors (equipped with the system). The number of predecessors (equipped with the system) taken into account is 3. The advantage of this method compared to CACC1 is that no distance headway needs to be determined, which is hard in case the penetration rate of the system is less than 100%.
- *CACC1+*: CACC1 extended with the vehicle to vehicle communication system as described above (vehicles send messages when speed drops below 70% of the speed limit).
- *CACC2+*: CACC2 extended with the same (extra) communication system as CACC1+.

In the advisory mode, the system advises the drivers of these vehicles when to start slowing down, and how hard to brake. The system advices to start braking when the speed is at least 10% higher than the speed of the sending vehicle, equal to the controlling mode. Ideally, the deceleration is achieved by just releasing the accelerator pedal. However, we assumed that the driver will brake with the same constant deceleration as in the controlling mode (the difference is that in the advisory mode, the vehicle is not equipped with an ACC or CACC system).

6.1.3 Leaving the head of a queue at a traffic light

The Leaving the head of a queue scenario is elaborated for a traffic light. The hypothesis was that IRSA can help vehicles or their drivers accelerate in a safe and efficient way. Two different settings were tested, which were tuned to improve throughput or safety (faster acceleration may increase throughput but may decrease safety).

The first setting of IRSA is the initial CACC controller of IRSA. These settings result in a rather slow acceleration from standstill. Therefore, another version of IRSA was simulated with optimized parameter settings for accelerating from standstill, referred to as IRSA turbo. Furthermore, a simple ACC controller was implemented which was expected to perform well in this scenario. This controller tries to keep the headway to a fixed value, therefore this controller is referred to as 'fixed headway'. This was based on the assumption that keeping a minimal fixed time headway is necessary for safety reasons.

The reference scenario was calibrated such that the average acceleration from 0 to 20 km/h is 1.9 m/s2, which is reported in Bennett (1995) and Brouwer, (2003) as the average (measured) real-world value.

6.2 Research approach

The Integrated full-Range Speed Assistant influences traffic flows in several ways. Depending on the mode and the settings, following distances, accelerations and decelerations are influenced. This has effects on throughput (characterised by variables such as travel times, speeds, volumes, etc.), safety (characterised by variables such as speeds, speed distributions, headways, times-to-collision etc.) and the environment (characterised by variables such as speeds, speed and acceleration distributions, etc.).

The impacts on traffic flow were studied using the ITS Modeller. The ITS modeller is a modelling 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 modelled easily and added to the ITS modeller. The ITS modeller functions as a shell for several commercially available traffic simulation products (see Figure 6.1).

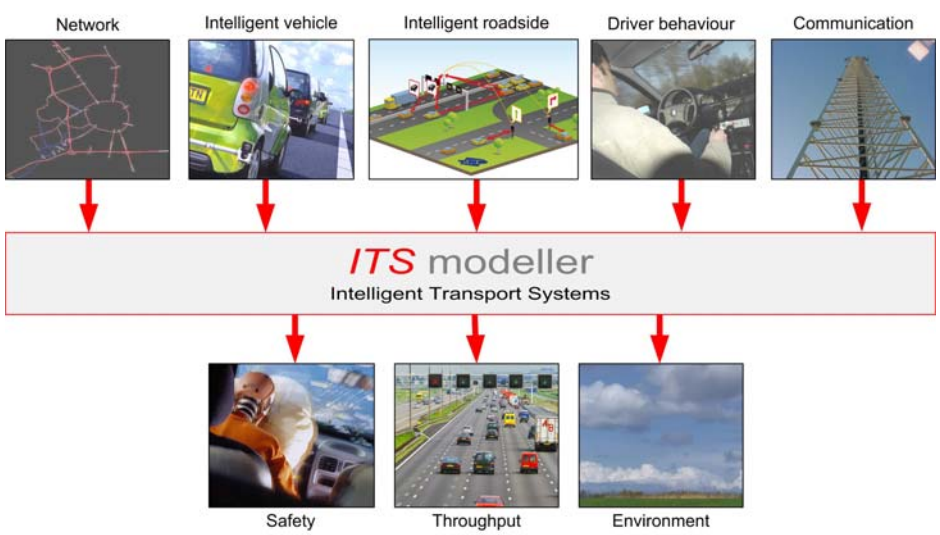


Figure 6.1: ITS modeller set-up

The effects of ITS systems can be evaluated with the evaluation modules of the ITS modeller. The traffic throughput module computes figures on route flows, route travel times, total network journey times and delays, speeds et cetera. The safety module produces statistics on the number of shock waves, times-to-collision and time headway intervals. The environment module computes the noise production levels of different types of vehicles. In addition to this, the output of the ITS modeller can be used to calculate emissions of pollutants (with TNO's detailed emission model VERSIT+).

6.3 Results

In the following three sections, the results are summarised for the three scenarios studied.

6.3.1 *Approaching a reduced speed limit zone*

The vehicles equipped with IRSA are advised to slow down earlier than drivers of non-equipped vehicles usually would. Figure 6.2 shows the speed profiles of non-equipped vehicles and vehicles equipped with the controlling mode of IRSA. It is clear that the equipped vehicles slow down much more smoothly.

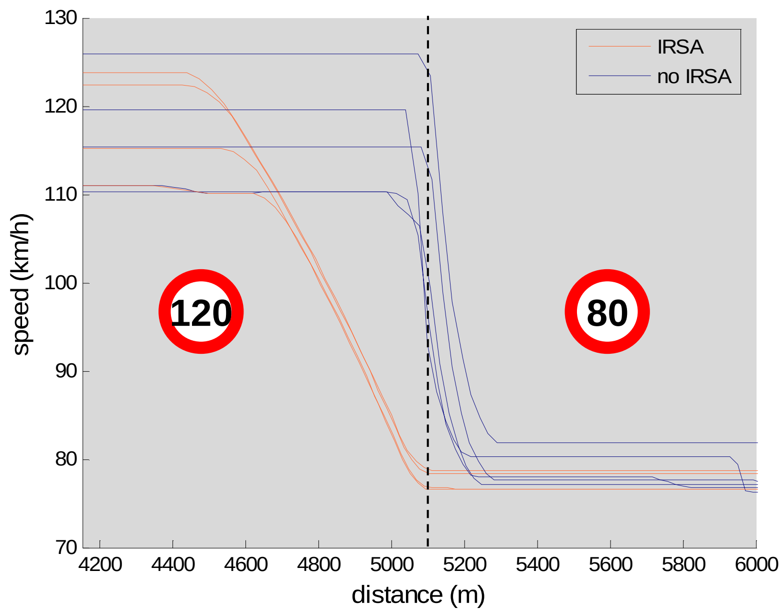


Figure 6.2: Speed profiles of equipped and non-equipped vehicles in the Reduced speed limit scenario (controlling mode, 50% penetration rate)

At the level of a cluster of vehicles, it was found that IRSA reduces the differences in speed, especially for higher penetration rates. At a 100% penetration rate, there are practically no small times-to-collision. The performance (with respect to safety indicators) improves with increasing penetration rates, and the controlling mode is, as expected, more effective than the advisory modes.

At lower penetration rates, especially for the controlling mode, the variation in speed in the area just before the reduced speed limit zone can be quite large. See for instance Figure 6.3, which shows a speed distribution with two peaks, reflecting regular and IRSA vehicles (left peak comprising IRSA-equipped and non-equipped vehicles, right peak predominantly non-equipped vehicles). This effect can only be noticed with low penetration rates or when traffic is not too dense, since in dense traffic, the IRSA vehicles will force the regular normal vehicles to slow down in the same way.

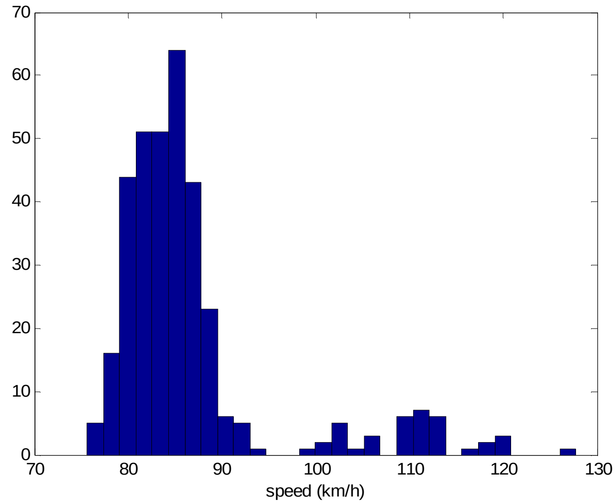


Figure 6.3 Histogram of speeds of equipped and non-equipped vehicles in the Reduced speed limit scenario (150 m before the start of the lower speed limit, 5-minute interval, controlling mode, 50% penetration rate)

Finally, no significant effects on throughput (neither positive nor negative) were found.

6.3.2 *Approaching a traffic jam*

The simulations with IRSA in a situation with congestion showed that the system has a positive impact on traffic flow. Vehicles slowed down earlier, having to brake less hard. The congestion was reduced, with safety indicators staying at the same level or improving slightly.

Figures 6.4 and 6.5 show the changes in total travel delay and standard deviation of speed, for the different variants of IRSA experimented with, as compared to a reference case with no IRSA. The penetration rates were 100%, i.e. all vehicles were equipped with some form of IRSA. Also, the results for ACC (with no form of communication) were included.

Both the travel delays and the variation in speed decrease (with the average speed increasing slightly), when the whole section is looked at. Just before the congested area, the variation in speed actually increases (as the equipped vehicles start braking at different times, depending on the difference in speed with the vehicles in the queue and how far away they are). On the whole, however, traffic appears to be more homogeneous, which is confirmed by a decrease in the variation in accelerations (by up to 40%). From this, it can be concluded that in this scenario, IRSA contributes to improved traffic safety and lower exhaust emissions. Travel times are reduced slightly, by up to 4% (in this case, on a stretch of 6200m, with a lane drop at 5100m, this translates to a travel time reduction of about 10 seconds per vehicle). Delays are reduced by more than 30% for all CACC versions and by more than 20% for advisory IRSA (see Figure 6.4).

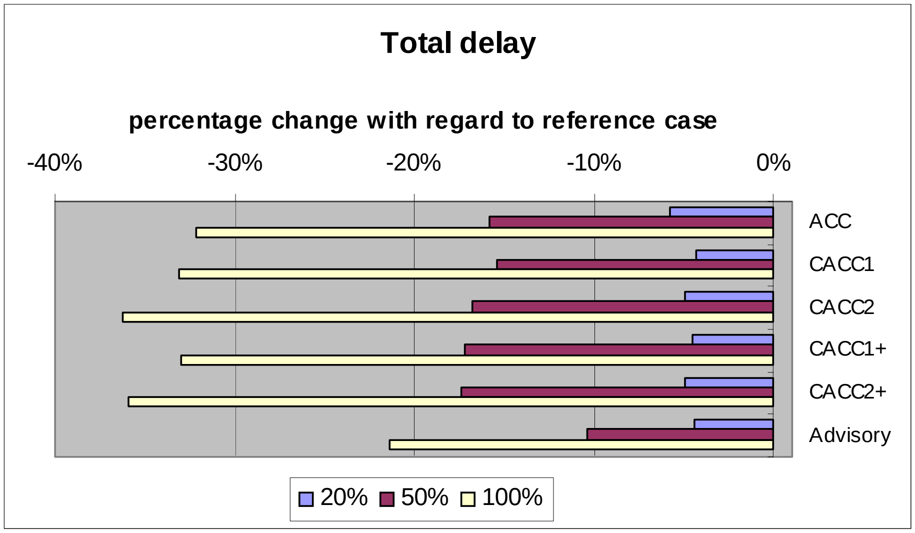


Figure 6.4: Changes in total delay, for different versions and penetration rates of IRSA in the Approaching a traffic jam scenario

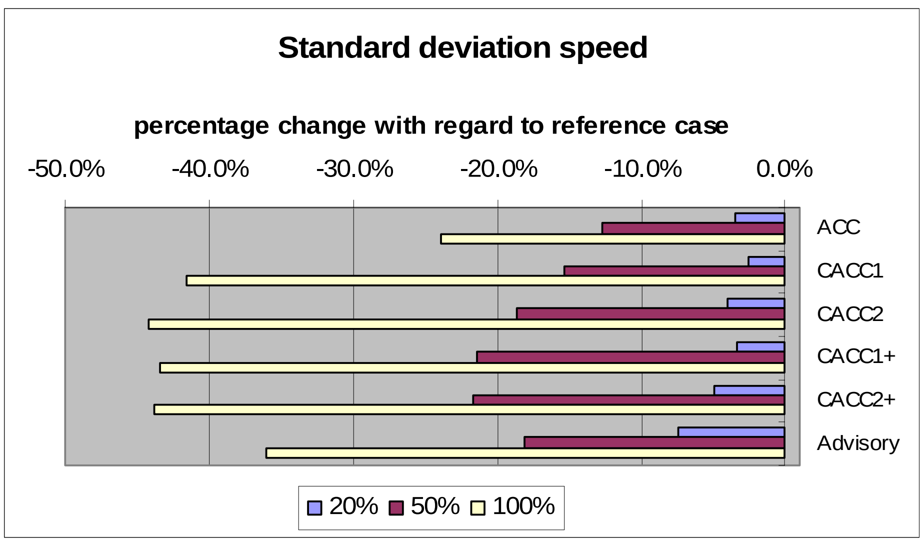


Figure 6.5 Changes in the variation in speeds, for different versions of IRSA in the Approaching a traffic jam scenario

The CACC2 version performs the best. The incorporation of information of the speeds of preceding –equipped- vehicles (at all times) and messages from vehicles driving at speeds below 70% of the speed limit help to homogenize the traffic. As can be seen in Figure 6.6, the speed distribution changes, with higher average speeds at higher penetration rates. The distance and time headways between vehicles do not change much, because the IRSA system setting for headway is quite short (1 second). However, the times-to-collision decrease (as can be seen in Figure 6.7), which means that the differences in speed between vehicles following each other are smaller than they are with no IRSA system – and traffic thus more homogeneous.

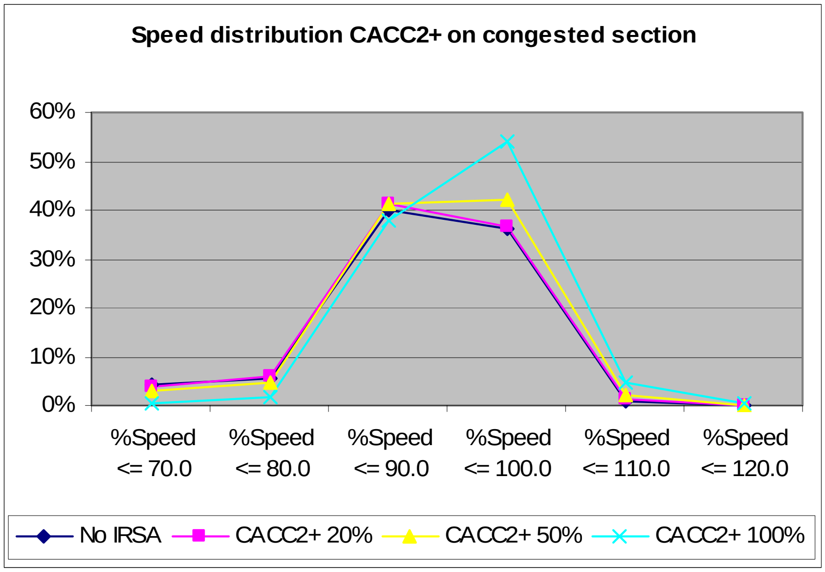


Figure 6.6: Speed distributions for different penetration rates of CACC2+ in the Approaching a traffic jam scenario

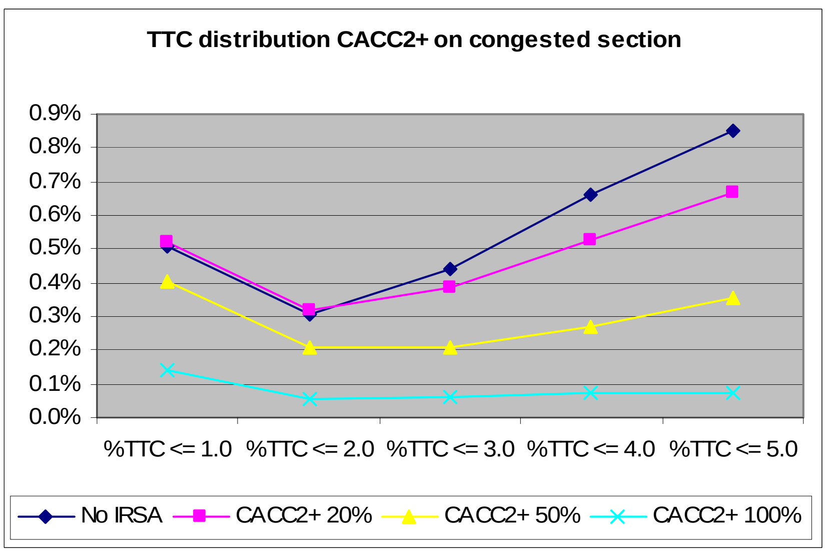


Figure 6.7: Distribution of times-to-collision (small values only) for different penetration rates of CACC2+ in the Approaching a traffic jam scenario

6.3.3 *Leaving the head of a queue at a traffic light*

The results of this scenario show very clearly how different approaches and/or settings affect throughput and safety. The initial IRSA controller (CACC1) was somewhat ‘cautious’ compared to the reference case (see Figure 6.8). This meant that the throughput (measured as the number of vehicles passing the intersection during the green time of a single cycle) was smaller than in the reference case which has been calibrated with values for accelerations found in practice. With the ‘turbo’ version of the IRSA controller the number of vehicles passing the intersection during green time was larger, which resulted in lower average travel times. The simple fixed headway controller had an improved throughput compared to the reference case, but less than IRSA turbo. This means that only keeping a fixed time headway does not optimize throughput when leaving the head of a queue. Since both controllers have the same headway setting of 1 second, it appears that a more complex, cooperative controller is needed to improve throughput. This proves the added value of the IRSA controller.

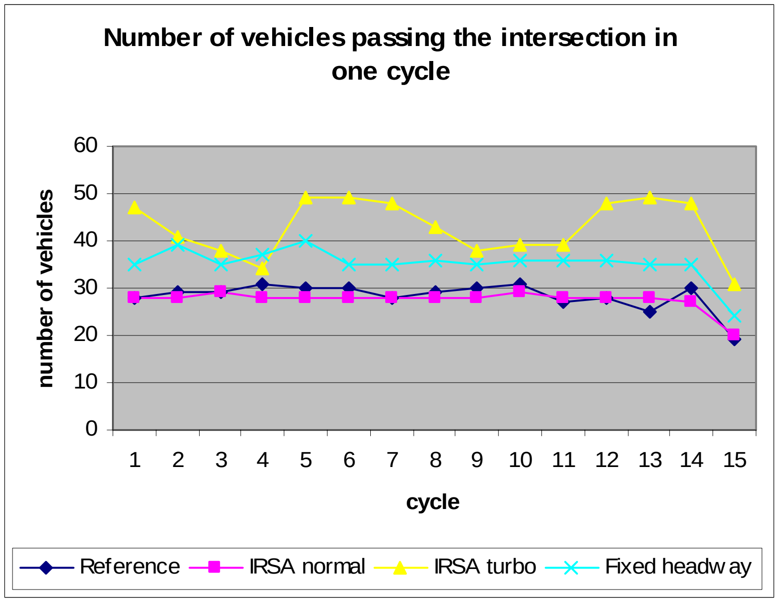


Figure 6.8: Number of vehicles passing the intersection during one cycle in the Leaving the head of a queue scenario (100% penetration rate)

6.3.4 *Conclusions*

This chapter contains just a small portion of the data collected in the simulations. More results can be found in Wilmink et al (2007). The results presented here show some essential effects of IRSA in different scenarios. These results also show that IRSA has a wide range of effects, depending on the situation and settings of the system.

The main benefit of IRSA is that the distance to the predecessors can be maintained in a better way – safer, more comfortable or with a higher throughput, depending on the settings. The added value of communication is clear when comparing the IRSA CACC versions with just ACC, especially communication with the first equipped downstream vehicles in the scenario ‘Approaching a traffic jam’.

The ITS modeller is a valuable tool in the assessment of a co-operative system like IRSA. It enables users to adapt vehicle and driver behaviour, so that different algorithms and settings can be experimented with easily. The changes in traffic patterns can be seen immediately in the traffic model’s user interface. The output of completed runs can subsequently be used to assess the effects on traffic flows. Depending on the scenario, and the hypotheses tested, different indicators are used to assess the effects: from aggregated variables such as the average journey time and mean speed to disaggregated results, such as speed profiles. All these indicators together provide the full picture needed to assess co-operative systems, especially in dense traffic with many interactions between vehicles.

7 Discussion and conclusions

In the SUMMITS-IRSA project, TNO has developed and demonstrated the SUMMITS Tool Suite, which is an integrated tool set to allow developers of ADA systems to assess issues regarding technical functioning, human factors and traffic flow in a consistent way. The Integrated Full –Range Speed Assistant (IRSA) was selected as a case to guide and test the development of the tool suite. 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 situation and leaving the head of the queue at a traffic light. Consistent results were guaranteed by the use of a common mathematical description of the IRSA system (the meta-model), traffic scenarios and selective coupling of tools. Several control models were used, varying from a common ACC algorithm, to algorithms that also use vehicle-vehicle communication with the three closest downstream IRSA equipped vehicles taking into account the time headways (CACC1) and average speed (CACC2).

Simulations, hardware-in-the-loop experiments (VeHIL)and real-world experiments revealed that the IRSA system can be implemented and performs according to expectation: V –V communication indeed enhances the control of the vehicle, resulting in better safety and comfort. Again the CACC2 controller appeared to show the best performance.

The experiments with respect to robustness were especially useful when the development approaches the implementation phase, i.e. more and more “real world” influences should be taken into account. Sensor specification, evaluation of safety related features can be carried out in well controlled virtual environment, which reduces costs and time-to-market. The MARS environment was used to check and enhance the IRSA implementation at different levels of detail thus bridging the gap between ITS Modeller and VeHIL.

The driving simulator experiments focused on the cut-in situation, with the objective to see to which level the IRSA controller can help stabilize traffic flow. The experiments focused on an advisory, intervening and controlling system. It resulted in a clear preference for a controlling system, with the best stabilization properties as well as the best acceptance amongst drivers.

The traffic flow analyses using the ITS Modeller show that in general all IRSA functions contribute to a decrease in speed variation, with an increasing effect with an increasing penetration rate. In general safety indicator levels improved at unchanged traffic efficiency. Accordingly, also the negative impacts on the environment can be expected to improve. In addition, for the scenario approaching a traffic jam, a reduction of 30% in delays was obtained. The CACC2 controller showed the best performance.

The application of the SUMMUTS Tool Suite to the IRSA system has revealed that the tool suite is very useful for the assessment of ADA systems. The effort invested in the formulation of the meta-model and common scenarios, has paid off significantly. IN particular, this was the case when iterations in the model details and parameters were required; they could be studied extremely fast. The development of the common approach has also strengthened the multidisciplinary network of researchers in TNO.

The SUMMITS Tool Suite is now available to support the development and evaluation of autonomous and cooperative ADA systems and is already being used in projects for clients of TNO. The SUMMITS Tool Suite offers flexibility to efficiently study questions related to technical performance, robustness, traffic flow impacts and human factors.

The different tools within the SUMMITS Tool Suite will be further developed, to allow more detailed communication, sensor and driver modelling. It will also be extended to provide support to field operational tests.

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9 List of products

Hardware
A haptic acceleration pedal for the Human Factors Instrumented Car had been developed and implemented. By means of a haptic accelerator pedal a more gentle interaction with the driver is obtained with respect to full control. The associated controllers are ready to be implemented.

The Instrumented Car is facilitated with air communication ability, which enables interaction with other vehicles (the Smarts of Automotive).

Software
Interfacing software has been written to enable the coupling between two TNO driving simulators (moving-base driving simulator and fixed-base driving simulator). Due to the coupling, two drivers can interactively drive in the same virtual world and are able to react on each other.

The ITS modeler, a modeling environment for Intelligent Transport Systems, including co-operative road-vehicle systems.

The MARS (Multi-Agent Real-time Simulator) technology can be characterized as a continuous time / discrete event simulator framework for highly autonomous multi-agent systems. Via libraries and modeling front-ends it can be customized to the needs of various application domains, incl. testing and evaluation of intelligent transportation systems.

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