Project n° IST-2004-028062

CYBERCARS - 2

Close Communications for Co-operation Between CyberCars

Instrument: Specific Targeted Research Project

Thematic Priority: FP6 priority 2 "Information Society Technologies" Call 4 e-Safety

CYBERCARS – 2 FINAL REPORT

Due date of deliverable: 28/02/2009
Actual submission date:
27/01/2009 – Version V.1.1
22/02/2009 – Version V.2.0

Start date of the project: January 1st, 2006 Duration: 38 months

Organisation name of lead contractor for this deliverable: INRIA

Revision: Final (V 2.0)

Project co-funded by the European Commission within the Sixth Framework Programme (2002-2006)		
Dissemination Level		
PU	Public	PU
PP	Restricted to other programme participants (including the Commission Services)	
RE	Restricted to a group specified by the consortium (including the Commission Services)	
CO	Confidential, only for members of the consortium (including the Commission Services)	

Version history

Version	Date	Main author	Summary of changes
1.0	03/01/2009	Vlacic, Ljubo	Initial document
1.1	15/01/2009	Parent, Michel	Amendments
2.0	22/02/2009	Parent, Michel and Vlacic, Ljubo	Amendments

EXECUTIVE SUMMARY

The CyberCars-2 predecessors, FP5 project CyberCars and FP5 project CyberMove, dealt with the development and evaluation of the Cybernetic Transport System (CTS)[1]. This system comprises a number of individual driverless vehicles that have the capability to travel on existing road infrastructure, without the need for dedicated guide ways. However, prototype vehicles developed in these projects were designed for low-demand road traffic environments and were not requested to communicate nor co-operate with each other. The challenge for the Cybercars-2 project was to empower these vehicles with the ability to co-operate through vehicle-to-vehicle and vehicle-to-infrastructure communication links in order for the CTS to enable higher traffic flows and improved network efficiency.

Numerous milestones have been achieved by the CyberCars-2 project. Among them are:

<u>Dual Mode Vehicles</u>

Dual-Mode vehicles are conventional vehicles that are equipped with Advanced Driver Assistance Technology and capable of "highly automated driving" (as developed also in the Have-IT Project), on request by a human driver but also of fully autonomous co-operative driving in CTS environments. It is now believed among the partners of the project that this form of vehicle will allow a widespread dissemination of the technologies for both full automation and co-operative driving.

Five prototypes of dual mode vehicles have been developed and experimented during the project, namely:

[1] A CTS can be defined as a network of driverless road vehicles, CyberCars, and a traffic management centre that controls the network flows.

EXECUTIVE SUMMARY

- IAI's Clavileno;
- TNO's Cyber Smart;
- Two Fiat's Cyber Panda and one Cyber Cinquecento.

Co-operative Communication Architecture

A specific vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication architecture was designed, developed and implemented to enable interconnectivity and interoperability between different types of CyberCars including Dual-Mode (DM) vehicles.
While CyberCars are driverless vehicles, Dual-Mode vehicles are conventional vehicles that are equipped with Advanced Driver Assistance Technology and capable of driverless driving, on request by a human driver.

The main building blocks of the CyberCars-2 communication architecture include vehicles, road infrastructure elements and the traffic management & control centre. These blocks are integrated through:

- Functional architecture; it is derived from system requirements and aimed at fulfilling user needs; it comprises functional modules, data structures and interfaces;
- Physical architecture (both the on-board units and infrastructure units); describes the way in which the required functionality and system requirements are achieved;
- Communication Architecture; it defines links between the Physical Architecture components and the communication protocols; and
- Operational Safety & Reliability Certification Procedures.

Co-operative Driving Algorithms

A fleet of Co-operative Cybernetic Transport System vehicles consists of CyberCars and Dual-Mode vehicles. They all are capable of performing driving manoeuvres in co-operation with each other including manoeuvres for:

- overtaking;
- platooning;
- docking/undocking;
- roundabout driving;
- intersection crossing;
- obstacle avoidance; and
- path generation.

The Cybercars-2 Management Centre

The CyberCars-2 Management Centre accommodates the wide deployment of a CyberCars-based co-operative transport system. Its main building blocks are:

- Supervisory Co-operative Control System (SCCS) which supervises and monitors the vehicle level operations based on decisions and commands issued by the CRTM;
- Co-operative Road Traffic Management System (CRTM), which is in charge of performing the optimization of the road traffic flows;
- CyberCars and Dual-Mode vehicles;
- Database; and
- Human operator (when required).

Performance Evaluation of Cybernetic Transport Systems

Cybernetic Transport Systems may contain a large number of individual units, creating complex interaction patterns and dependency chains among the vehicles. The highly demanded interrelations that are created with such a system are difficult to test with the limited amount of real test vehicles available. On the other hand, large scale road traffic scenarios might consist of hundreds of roads, vehicles and intersections and, as such, cannot be easily evaluated with real vehicles.

EXECUTIVE SUMMARY

Therefore, the CTS Performance Evaluation was performed through a specifically constructed simulation process which also required:

(i) the CTS tailored simulation tool; and
(ii) the evaluation methods, scenarios and road topologies

On-Road Testing of the Operational Performance of Co-operative Cybernetic Transport Systems' Vehicles
An extensive in-field (i.e. on-road) testing of operational performance of the co-operative cybernetic transport system and its vehicles was performed at:

- the IAI Test Track, Spain;
- the CRF test track in Orbassano, Italy;
- the INRIA test track in Recquencourt, France;
- the La Rochelle test track, France;
- the Oststadtring test track, Germany;
- the Karlsruhe test track, Germany; and
- the Vaihingen Campus test track Germany.

Exploitation and Dissemination of the CyberCars-2 Technologies
The exploitation and dissemination activities took many forms including:

- the presence of the project web site;
- presentation of papers at conferences and events;
- publication of leaflets, brochures and video clips;
- demonstration of the developed technology to the public and prospective end-users;
- presentation of the project outcomes through numerous media outlets; and
- collaboration with other EU urban transport projects, including CityMobil, Safespot and CVIS.

Public demonstration of the developed technology was held in:

- Las Palmas, Spain, 12/2/2007;
- Eindhoven, the Netherland, 27/03/2007;
- Brussels, Belgium, 5/05/2007;
- Versailles, France, 18/09/2007;
- Daventry, United Kingdom, 24/09-5/10/2007;
- Paris, France, 27-28/10/2007;
- Ljubljana, Slovenia, 21-23/04/2008; and
- La Rochelle, France, 18-28/09/2008

The CyberCars-2 project has therefore paved the way for Co-operative Cybernetic Transport Systems to share the future road traffic environment with all traffic participants.

APPROVAL STATUS			
	Company/Organisation	Name	Signature

Domain Leader approval	INRIA	Michel Parent	Date: <26/01/2009 > Signature: signed
Approval on behalf of the PMC	Griffith University	Ljubo Vlacic	Date: <26/01/2009> Signature: signed

CONTRIBUTING COMPANIES			
	Company/Organisation	**Name**	**Function**
Document Manager	INRIA	Michel Parent	Cybercars-2 Project Coordinator
Contributor 1	Robotiker	Lucia Isasi	WP1 Coordinator
Contributor 2	IAI	Teresa de Pedro	WP2 Coordinator
Contributor 3	TNO	Claire Minett	WP3 Coordinator
Contributor 4	INRIA	Laurent Bouari	WP4 Coordinator
Contributor 5	University of Stuttgart	Ralf Regele	WP5 Coordinator
Contributor 6	CRF	Gianfranco Burzio	WP6 Coordinator
Contributor 7	INRIA	Michel Parent	WP7 Coordinator
Contributor 8	Griffith University	Ljubo Vlacic	Project Consortium Member
Reviewer 1	INRIA	André Ducrot	Project Documentation & Web Manager
Reviewer 2			

REVISION TABLE		
Document version	**Date**	**Modified sections – Details**
V1.1	27/01/09 – 22/02/09	The Executive Summary section as well as Concluding Remarks section have been amended on request by the project reviewers

TABLE OF CONTENTS

ACRONYMS AND DEFINITIONS

ACC	Adaptive Cruise Control
ADAS	Advanced Driver Assistance Systems
ADASE	Advanced Driver Assistance Systems in Europe Project
CALM	Continuous Air Interface for Long and Medium Range
CMS	CyberCars Management Centre
CRTMS	Co-operative Road Traffic Management System
CRTM&C	Co-operative Road Traffic Management & Control
CTS	Cybernetic Transport System
CCTS	Co-operative CTS
C2C	Car-to-car
DMV	Dual-Mode Vehicle
DGPS	Differential Global Positioning System
GPS	Global Positioning System
IVSS	Intelligent Vehicle Safety System
I2I	Infrastructure-to-Infrastructure communication
I2V	Infrastructure-to-Vehicle communication
SCCS	Supervisory Co-operative Control System
TCMS	Traffic Centre and Management System
V2I	Vehicle-to-Infrastructure communication
V2V	Vehicle-to-Vehicle communication

1 INTRODUCTION

1.1 Background

The CyberCars-2 project was driven by the vision that in the near future Cybernetic Transport Systems will be seen on city roads and dedicated road infrastructures. Since Cybernetic Transport Systems are primarily based on driverless vehicles , i.e. CyberCars[2], this project was aimed at developing a set of tools and systems to enable driverless vehicles to perform the necessary driving manoeuvres in a co-operative manner i.e. in cooperation with each other and also in cooperation with vehicles driven by human beings.

Hence, the CyberCars-2 project was aimed at designing and developing a Co-operative Transport System Architecture and demonstrating that Cybercars are capable of achieving performances at least of the same order of magnitude as regular cars while offering reliable transportation, respectful of the environment.

The FP5 project's CyberCars, CyberMove and Autopia dealt with the development and evaluation of the basic building elements of the Cybernetic Transport System (CTS), i.e. CyberCars, and demonstrated the feasibility of the single driverless vehicle driving concept. Before this project was undertaken, CyberCars were able to only operate in low-demand environments with almost no mutual interactions. Due to outcomes achieved by this project, CyberCars are now capable of establishing vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication links, thus enabling the CTS to contribute to improved road safety and road traffic network efficiency. This project has therefore demonstrated that a Cybernetic Transport System is indeed capable of improving traffic efficiency and transportation reliability, and also contributing to a drastic reduction in atmospheric and noise pollutions.

1.2 Project Highlights

The Cybercars-2 project was particularly focused on the design, development, prototyping and on-road testing of:

a) a Co-operative Cybernetic Transport System (CCTS) Architecture capable of accommodating requirements for interoperable CCTS;
b) Dual-Mode vehicles[3];
c) Co-operative Driving Algorithms to enable CyberCars to perform driving manoeuvres in cooperation with each other, the road infrastructure, and dual-mode vehicles;
d) a concept of a Co-operative Road Traffic Management & Control (CRTM&C) centre capable of managing and supervising operations of Co-operative Cybernetic Transport Systems;

---

[2] Cybercars are vehicles driven by electronic & software products and systems. No assistance from a human driver is required

[3] Dual-mode vehicles are designed, developed and prototyped through an upgrade of conventional vehicles with:
a) advanced driver assistance technology, and with
b) an ability to autonomously perform various driving manoeuvres, on request by a human driver.

e) procedures for on-road testing of operational performance of Co-operative Cybernetic Transport Systems.

Further highlights of this project include an extremely successful series of on-road tests and public demonstrations of the developed co-operative CyberCars technology, and dissemination of achieved project outcomes widely across Europe and internationally.

Finally, the level of cohesion and synergy achieved from activities and work packages within this project demonstrated the high quality of the scope of this project program and its relevance to the real world. The text that follows underpins this assertion.

2 PROJECT RESULTS AND MAJOR ACHIEVEMENTS

2.1 WP1: Co-operative Cybernetic Transport System Architecture

2.1.1 Objectives

This work package was aimed at designing, developing, deploying and testing the Co-operative Cybernetic Transport System Architecture to enable

a) interconnectivity and interoperability between different types of Cybercars;
b) compatibility with ADASE[4] Architecture; and
c) increased road traffic efficiency and safety.

2.1.2 Tasks

With these objectives in mind, specific vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication requirements were defined in the context of interoperability, operational safety, reliability and compatibility with ADASE Architecture. This will assist road users to have greater leverage on this level of synergy in the next generation of Cybercars.

In particular:

a) the system architecture for each component of the CyberCars-2 fleet of vehicles (Cybercars and Dual-Mode vehicles) was analysed in depth.
b) the Cybercars-2 Architecture was defined; vehicle-to-vehicle and vehicle-to-infrastructure requirements were identified, and a proposal for communication architecture, based on protocol layers, was developed;
c) the main requirements for compatibility between Cybercars and vehicles compliant with ADASE Architecture, in terms of functionality, security and safety were identified, articulated and examined;
d) a small-scale, Cybercars-2 fleet of vehicles-based, Co-operative Cybernetic Transport System was demonstrated in La Rochelle on 8 September 2008; it comprised a fleet of CyberCars and Dual-Mode vehicles driving an 8-shape test track; and

[4] The FP 5 Project on Advanced Driver Assistance Systems in Europe

e) enhanced Safety Certification procedures, applicable to the scope of Co-operative Cybernetic Transport Systems were defined.

Since each partner of the Project Consortium brought their own driverless vehicles to the project, each with unique architecture, the WP1 effort was focused towards furthering the existing CyberCars partners' vehicle control architectures with the Co-operative Vehicles' Communication Architecture paradigm. This is essential as Co-operative Vehicles are expected to be the next big challenge in the automotive and transport industry sectors due to advancements in both users' safety and the transport systems' efficiency. They are expected to extend the functionality of the current in-vehicle and infrastructure-based systems such as Intelligent Vehicle Safety Systems (IVSS), Advanced Driver Assistance Systems (ADAS) and Traffic Control and Management Systems (TCMS).

From a safety point of view, the three basic types of co-operative applications are identified as:

- 'Co-operative Awareness Systems' which deal with information concerning dangerous road conditions, obstacles, adverse weather conditions or complex traffic road situations
- 'Co-operative Assistance Systems' which deal with traffic management scenarios for safety critical situations such as motion speed advisory, traffic re-routing, co-operative longitudinal control, co-operative intersection traversals, etc.
- 'Co-operative Driving (Manoeuvring)' applications are based on the exchange of information on mutual positions and vehicle dynamics such as lane change, overtaking, intersection crossing etc.

A wide variety of research projects addressing some of these aspects are being undertaken in Japan, USA and Europe, the latter being supported by European and national level initiatives such as eSafety, Intelligent Car of the i2010 project, Car2Car Communication, Fleetnet – Network on Wheels, Infonebbia and Invent.

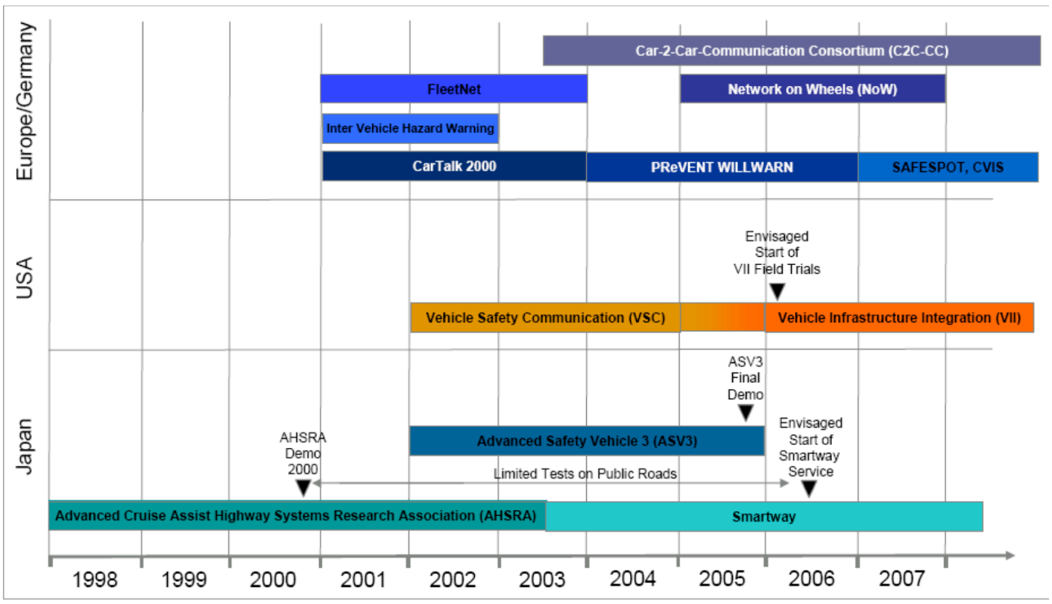


Figure 2.1-1 Vehicle Safety Communications in Europe, USA and Japan

There is a wide range of technologies suitable to fit the requirements of V2V and V2I communications. Some of them such as Cellular, Broadcasting, Satellite and Bluetooth are already mature and have become widespread while other emerging technologies such as WiMAX, ZigBee, WAVE and Ultrawideband (UWB) have promising expectations in the short-to-medium term.

While in the USA a dedicated frequency band has been made available for safety critical applications at 5.9GHz, in Europe the feasibility of different frequencies and technologies[5] is reported to be still under analysis.

If frequencies in the 5.9 GHz band are finally allocated to automotive safety critical applications in Europe then some coexistence issues will have to be resolved since this band is currently used by military radar systems and fixed satellite services, Figure 2.1-2.

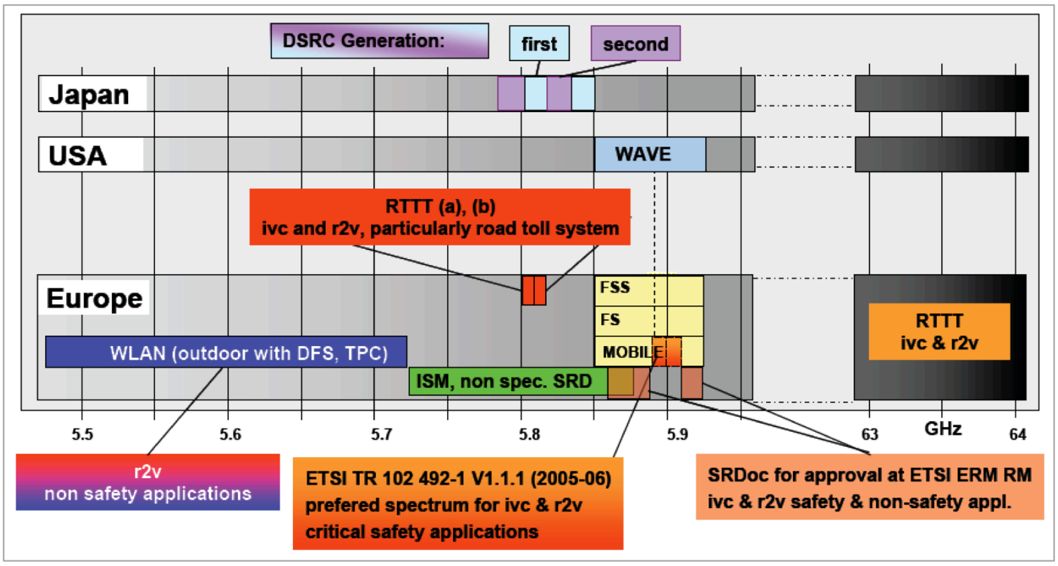


Figure 2.1-2 Global ITS Spectrum Allocation

In Europe, the ITS standardisation is coordinated by the Intelligent Transport Standard Steering Group. The most significant global effort concerning standardization procedures is ISO TC204 WG16, in charge of developing the CALM (Continuous Air Interface for Long and Medium Range) set of standards, partially released in 2006 and 2007. The scope of CALM is to provide a standardized set of air interface protocols and parameters for medium and long range, high speed ITS communications using one or more of several media, with multipoint and networking protocols within each media and upper layer protocols to enable transfers between media, V2V, V2I and I2I communication modes.

[5] There is a wide range of technologies suitable to fit the requirements of V2V and V2I communications. Some of them such as Cellular, Broadcasting, Satellite and Bluetooth are already mature and have become widespread while other emerging technologies such as WiMAX, ZigBee, WAVE and Ultrawideband (UWB) have promising expectations in the short-to-medium term.

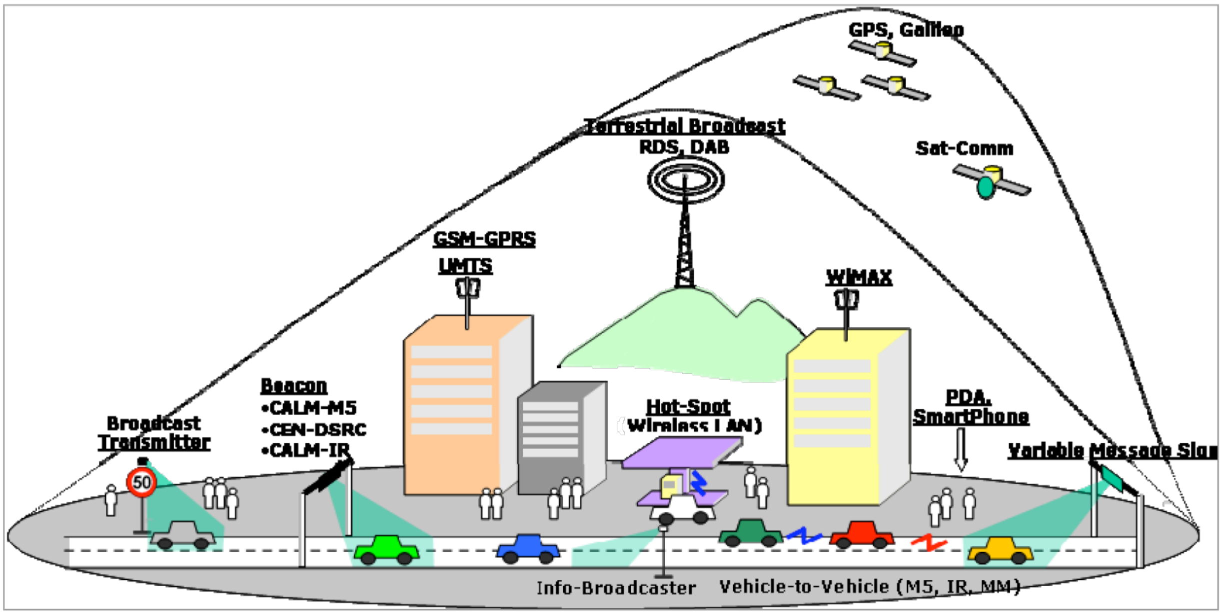


Figure 2.1-3 CALM Vision

2.1.3 Milestones and Deliverables

The CyberCars-2 Co-operative Communications Architecture is the main deliverable[6] of WP1 and is accompanied by:

a) a set of detailed field test scenarios used for on-road testing of V2V and V2I operational performances as executed by both Cybercars and ADASE vehicles in their various co-operative settings; as well as by
b) a set of operational safety and reliability certification procedures.

<u>The Cybercars-2 Co-operative Communication Architecture</u>[7]

The architecture that has been developed in this project enables communication between Cybercars of different kinds. It enables interoperability, allowing architecturally different CyberCars to perform driving manoeuvres in cooperation with each other.

Numerous ongoing R&D activities which focused on vehicular communications have now been undertaken under the umbrella of the European Commission and EU member countries. Many of them[8] explore the use of V2V/V2I communication technologies. Preliminary high-level

[6] Deliverable 1.1
[7] For details, see Deliverable D.1.1 pp.13-65
[8] CarTalk2000, COMeSafety, COM2REACT, COOPERS, CVIS, EASIS, eSafetySupport, Fleetnet-Network on Wheels, GST, INFONEBBIA, Invent, PReVENT, SAFESPOT etc.

classifications according to application fields and types of communication being dealt with is depicted in Figure 2.1-4.

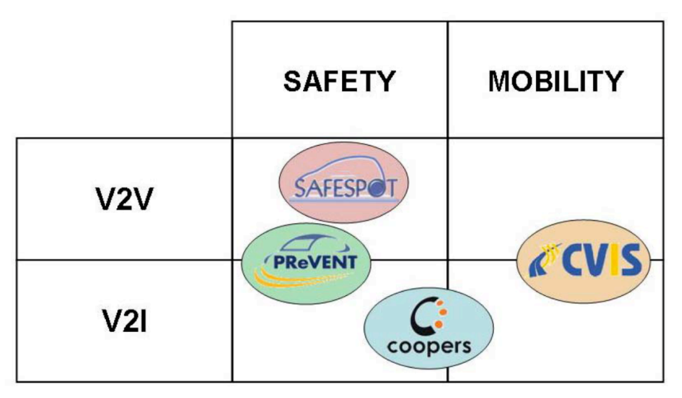


Figure 2.1-4 European Reference projects according to application field

WP-1's objective for co-operative communication architecture was to enable co-operative manoeuvres to be performed not just by different kinds of CyberCars but also to enable interoperability of Cybercars with ADASE vehicles, in real-time.

The SAFESPOT Architecture was adopted as a reference for the Cybercars-2 Architecture design due to the following facts:

- it enables advanced detection of potentially dangerous road traffic situations, and makes drivers aware of the surrounding environment;
- it is implicitly aligned to C2C-CC Reference Architecture, which is focused on the creation and establishment of an open European industry standard for Car-to-Car communication systems based on wireless LAN technologies;
- being compatible with the CALM umbrella, it offers a standardized set of air interface protocols and parameters for medium and long range, high-speed ITS communication.

The Cybercars-2 Architecture enables a set of driverless vehicles to perform co-operative manoeuvres safely in a restricted environment, i.e. in dedicated lanes by means of V2V communication and compatibility with regular vehicles. The use of V2V and, occasionally, V2I communication will improve driving safety as well as traffic efficiency in dedicated environments such as city centres, airports or theme parks.

The main building blocks involved in the CyberCars-2 Architecture are (Figure 2.1-5):

a) vehicles (both, driverless and dual-mode vehicles) which will exchange messages containing useful data to perform co-operative manoeuvres safely
b) control centres located at dedicated environments, but not necessarily close to the roads, from which traffic is controlled and the vehicle fleet efficiently monitored.
c) infrastructure elements, which can occasionally help to improve system efficiency, e.g. transmitting a DGPS correction to achieve higher accuracy, or monitoring and supervising the traffic flow from a control centre.

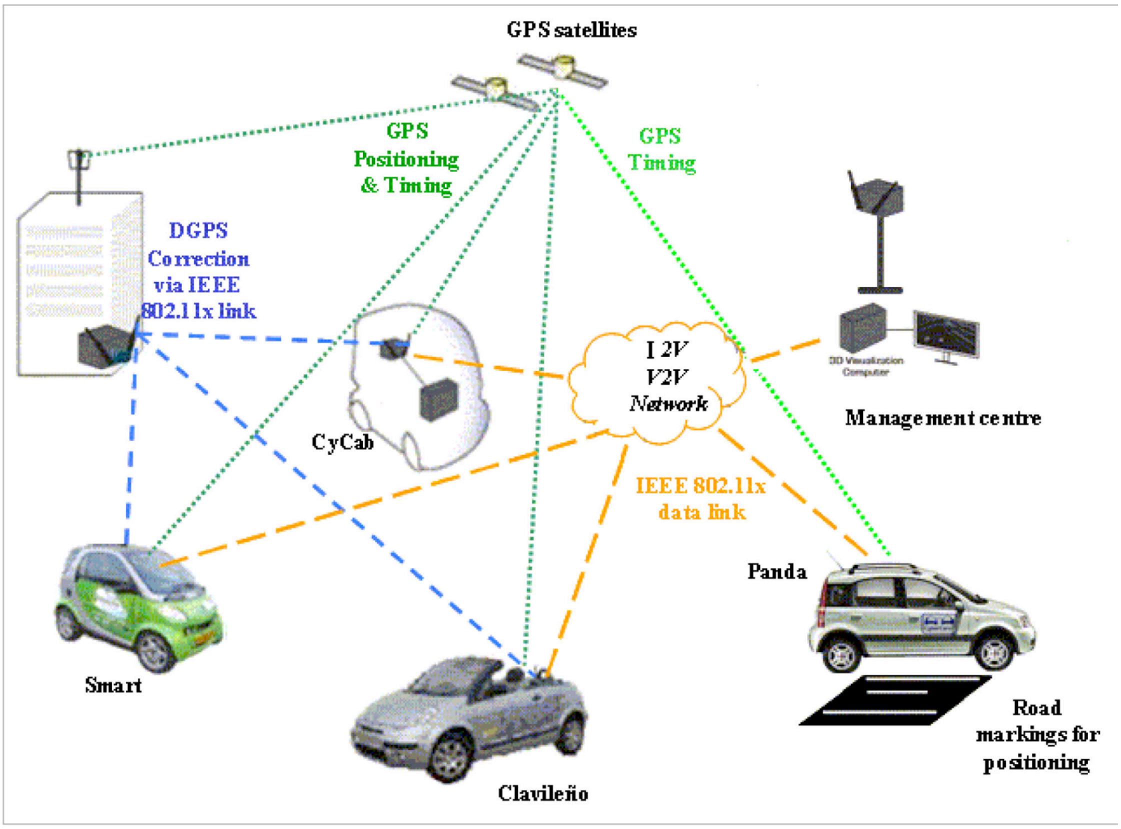


Figure 2.1-5: the Cybercars-2 Co-operative Architecture

Built in line with SAFESPOT Reference Architecture, the Cybercars-2 Architecture consists of three sub-architectures, namely:

- Functional Architecture (FA) – Figure 2.1-6: it is derived from system requirements and aimed at fulfilling user needs; it comprises functional modules, data structures and interfaces;
- Physical Architecture (PA) – Figure 2.1-7: describes the way in which the required functionality and system requirements are achieved
- Communication Architecture (CA) – Figure 2.1-8: defines links between the Physical Architecture components and the communication protocols.

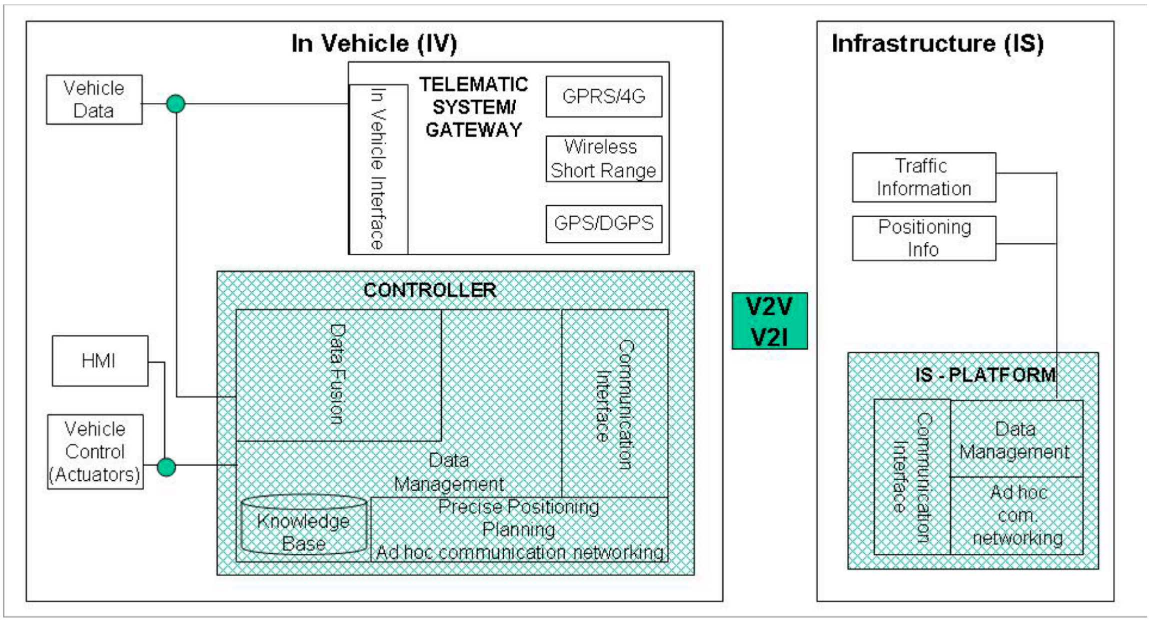


Figure 2.1-6: CyberCars-2 Functional Architecture

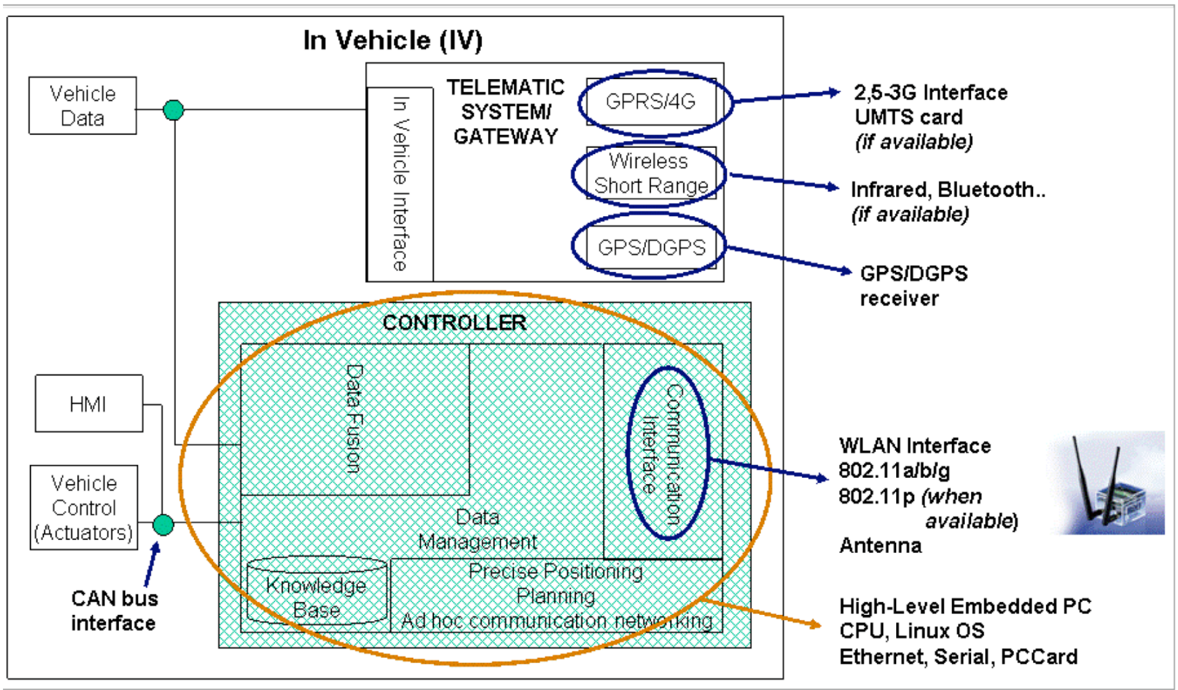


Figure 2.1-7: Cybercars-2 Physical Architecture (On-Board Units)

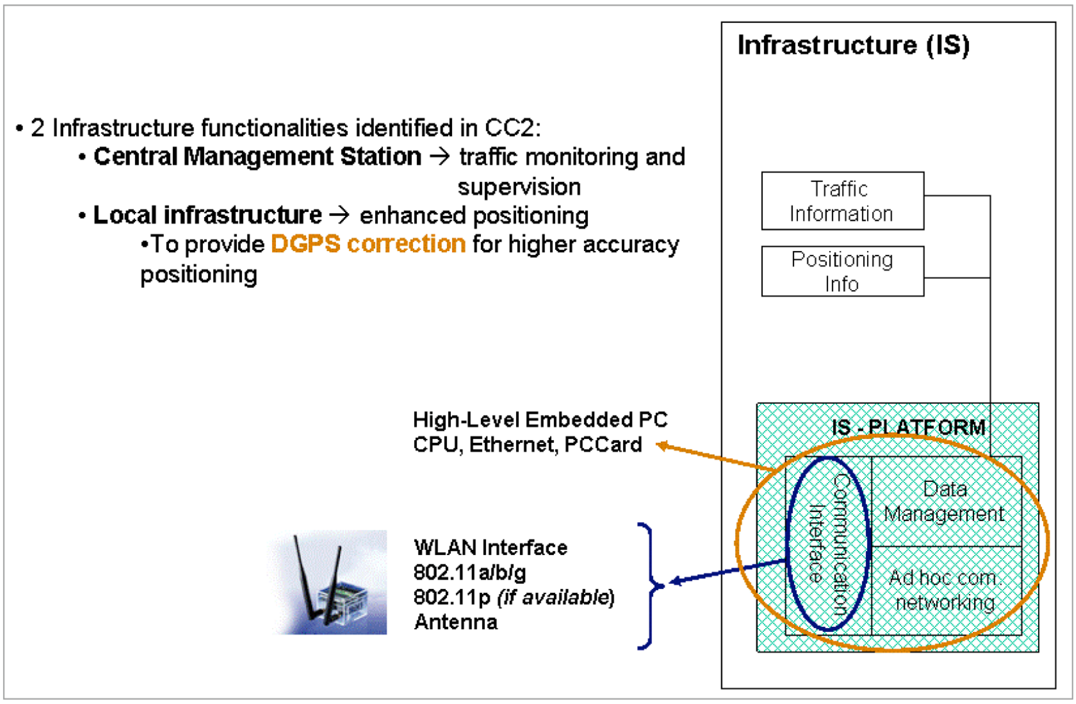


Figure 2.1-8 : Cybercars-2 Physical Architecture (Infrastructure Unit)

As one of the examples of safety critical applications, the Cybercars-2 Architecture supports ongoing efforts from European industry (C2C-CC) and standardization bodies (ETSI ERM TG37) for specifically protected frequency band allocations at 5.9 GHz range to guarantee European-wide inter-vehicle compatibility. More specifically, the Cybercars-2 Architecture seeks three main types of communication channels:

a) Short-Medium range V2V/V2I communication channels delivering the data required by the vehicles to perform co-operative manoeuvres safely;
b) Short-Medium range V2I/I2V communication channels delivering either support information to the vehicles (DGPS correction, for example) or information on the network status and traffic flow to/from an infrastructure unit nearby; and
c) Long range V2I/I2V communication channels delivering information on the network status and traffic flow to a remote infrastructure unit (V2I) and control commands back to the vehicles in order to improve traffic efficiency.

On-Road Testing Scenarios[9]

The developed set of in-field test scenarios is aimed at on-road testing of V2V, V2I and I2V operational performances as executed by both Cybercars, ADASE and Dual-Mode vehicles in their

[9] For details, see Deliverable D.1.1, pp 66-104

various co-operative settings. The following co-operative communication configurations have been specified and tested:

- Co-operative Communication between CyCab and IAI-CSIC driverless vehicles:

  The CyCab is an electric driverless vehicle developed by INRIA while the IAI-CSIC driverless vehicle is Citroen C3–based. The co-operative manoeuvres performed included Automatic Cruise Control, Intersection Traversal and Stop&Go. Figures 2.1-9 describes the field test configuration while co-operative communication requirements are described in Table 2.1-1.

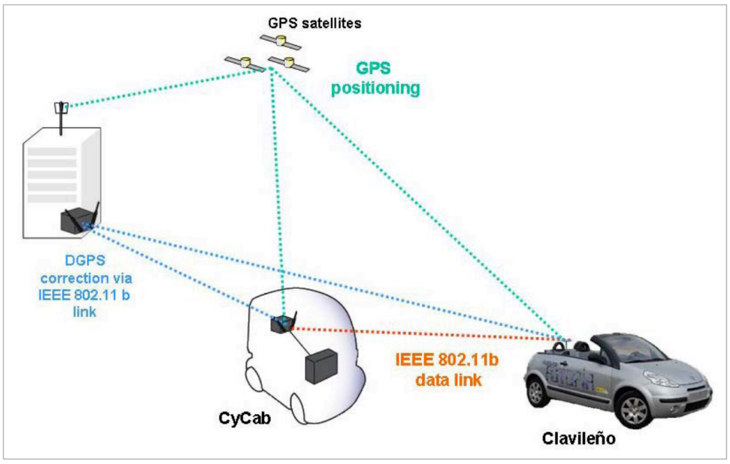


Figure 2.1-9: CyCab and Clavileno Field testing

	ACC	Intersection	Stop & Go
Type of communication	-V2V	-V2V	-V2V
Transmission mode	Periodic	Periodic	Periodic
Min. Frequency (Hz)	5Hz	5Hz	5Hz
Allowable Latency (ms)	100ms	100ms	100ms
Data to be TX/RX	Position Velocity	Position Velocity Time stamp Intention	Position Velocity
Estimated message size (bytes)	41	50	41
Max. Req. Comm. Range (m)	200	200	200

V2V communication required I2V-V2I communication required

Table 2.1-1: Communication Requirements for the CyCab-Clavileno Field Tests

The test was successfully undertaken at the IAI test track, Spain.

- Co-operative Communication between IAI-CSIC, CyCab, TNO and CRF Vehicles

  In addition to CyCab and the IAI-CSIC vehicle, this test also included operation of TNO and CRF vehicles. The TNO vehicle is a dual-mode AGS vehicle whereas the CRF vehicle is Fiat's PANDA-based dual-mode vehicle. The test configuration is depicted in Figure 2.1-10 and the co-operative communication requirements are described in Table 2.1-2.

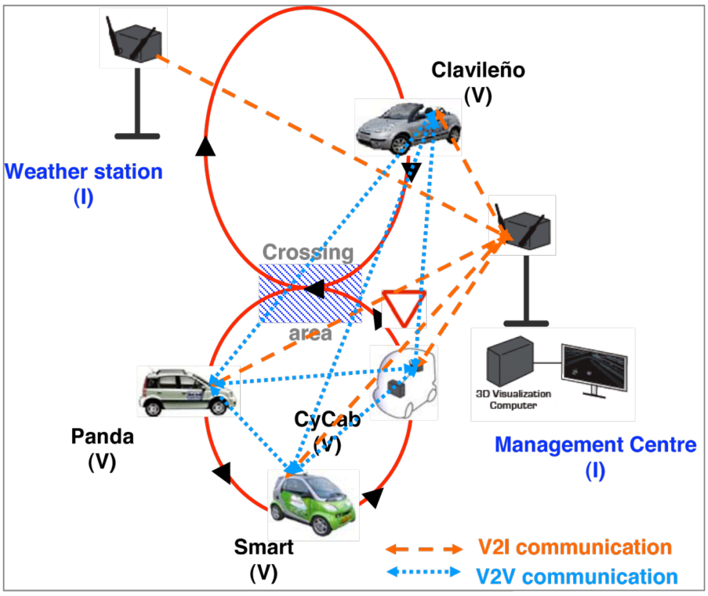


Figure 2.1-10: La Rochelle test field components

	Scen #1	Scen #2	Scen #3	Scen #4	Scen #5	Scen #6	Scen #7	Scen #8
Type of communication	V2V	V2V	I2V	V2V	V2V	V2I	I2V	I2V
Transmission mode	Periodic	Periodic	Event-driven	Periodic	Periodic	Periodic	Event-driven	Event-driven
Min. Frequency (Hz)	5Hz	5Hz	5Hz	5Hz	5Hz	5Hz	5Hz	5Hz
Allowable Latency (ms)	100ms	100ms	100ms	100ms	100ms	100ms	1000ms	100ms
Data to be TX/RX	<Name, T, N, E, S, H>		<Name, T, F>	<Name, T, N, E, S, H>		<Name, T, N, E, S, H>	<Name, T, S'>	<Name, T, F'>
Estimated message size (bytes)	~ 40	~ 40	~ 40	~ 40	~ 40	~ 40	~ 40	~ 40
Req. Comm. Range (m)	~ 150m	~ 150m	~ 200m	~ 200m	~ 200m	~ 200m	~ 200m	~ 200m

V2V communication required | I2V-V2I communication required

Table 2.1-2: The Cybercars-2 Communication Requirements Chart

The test was successfully performed at La Rochelle test site, France[10].

Operational Safety and Reliability Certification Procedures[11]

Since the Cybercars-2 Architecture makes provision for cooperation among vehicles of various types of driving automation[12], namely driverless vehicles, ADAS vehicles and dual-mode vehicles, it also addresses certification procedures. More specifically, the work in Cybercars-2 is meant to verify whether or not procedures developed by its predecessor, the Cybercars project, are suitable for assessing systems with safety critical communication equipment.

It was found that on-going work on the development of the new ISO standard, the ISO 26262, which addresses ADAS vehicles, includes methods which are mainly based on system-safety analyses and are closely related to the certification procedures developed by the predecessor project. However, the main point of difference between ADASE and Cybercars is the presence (or not) of a driver.

Thus,

a) the ISO 262:
    a. deals with ADAS vehicles
    b. focuses on incident situations
    c. perceives the driver's response to events as the main risk mitigator
b) the Certification methods for CyberCars:
    a. deals with driverless vehicles
    b. focuses on failure modes
    c. perceives the safeguards as the main risk mitigators.

The Failure Modes, Effects and Critical Analysis (FMECA) technique, being the basis of safety analysis methods, was chosen because the FMECA is extensively used by the automotive industry. According to the FMECA method, a system under consideration is to be divided into a

[10] For further details about these tests, see section 2.6.3 of this report.

[11] For details, see Deliverable D.1.1 pp.104-112

[12] ADAS vehicles are equipped with advanced electronic/software systems to assist the driver in tedious tasks (such as parking, lane-keeping and cruise control assistance etc) or in case of emergency (e.g. pre-crash sensing). In all these cases, the driver always remains in control of the vehicle. When manufacturers develop new vehicles, they must not only work within industry standards and limitations to certify their vehicles for use on public roads but also be suitable to fit into traffic regulation systems designed to encourage drivers to adhere to road traffic rules. Thus, drivers are fully responsible for behaviour of their vehicles on public roads.

DMV – dual-mode vehicles are equipped with a partial driving automation capability in which the driver is not in control of the vehicle all the time but is still fully responsible for behaviour of his/her vehicle on the road at all times.

Cybercars are vehicles driven by electronics & software products and systems. Successful operation of driverless vehicles is increasingly due to the efficient operation of these complete systems and must include safety assessment as an integral part. In the absence of human drivers, the liability shifts to the system operator or to the vehicle/product manufacturers. However, at present, there are no standards or laws that address this situation and there is great uncertainty among manufacturers and operators as to the limit of their responsibility.

number of subsystems, each being analysed separately. The functional analysis should then be applied to the whole systems' performance. These functions are the basis of FMECA, where a failure is defined as a malfunction to perform.

Thus, the main purpose of the analysis undertaken by the Cybercars-2 was not to establish whether or not the communication systems are safe but to validate the certification method. Therefore, the analyses were limited only to the communication functions. No other functions were taken into consideration. The main focus during the FMECA analysis was to observe whether communication functions or systems have properties or specifications that may influence the effectiveness of the certification method and the safety of the system.

The conclusion was that, under observation, there was no one single item or function that could not be addressed by this method.

It was further concluded that there is no reason to assume that the certification method which was initially developed for automated transport systems, cannot also be used for co-operative driverless vehicles-based transport systems.

2.2 WP2: Decision & Control Algorithms for Co-operative Driving Manoeuvres

2.2.1 Objectives

The WP2 was aimed at designing, developing, implementing and testing various algorithms for co-operative driving by both Cybercars and dual-mode vehicles on city roads.

2.2.2 Tasks

This work package dealt with the main building blocks of the co-operative communication architecture, the CyberCars and their driving manoeuvres, and was particularly focused on:

a) The design of the CyberCars' functional architecture to host and execute numerous decision & control algorithms for co-operative driving in line with the Cybercars-2 Co-operative Communication Architecture requirements;
b) the design, development, implementation and testing of a set of elementary co-operative driving manoeuvres, such as overtaking, platooning, docking/undocking, road crossing and roundabouts.

These tasks were addressed in the context of the operational safety and reliability requirements which influenced the role and the extent to which the road infrastructure may influence the performance of a particular driving manoeuvre by Cybercars.

Since contemporary CyberCars are equipped with numerous sensors, mutually interconnected through a CAN bus, the vehicles are expected to send to and receive from other vehicles and road infrastructure, information obtained from their on-board sensors which are interconnected by the CAN bus. As a result, the vehicle's database may easily become overpopulated due to these increased data flows. Thus, the WP2 had also to develop, advanced data structures & procedures for exchange of data among CyberCars in real-time because the existing data exchange techniques are not sufficient to cope with the vehicle's real-time operational requirements. The developed data-mining technique is able to facilitate real-time operations of co-operative road transport systems and their building blocks.

2.2.3 Milestones and Deliverables

The main three deliverables have been produced as follows:

a) The Cybercars' Functional Architecture (Deliverable D.2.1)
b) Vehicle's Co-operative Driving Manoeuvres (Deliverable D.2.1); and
c) Real-time Data Structures and Procedures (Deliverable D.2.2)

The Cybercars' Functional Architecture[13]

The Cybercars-2 Functional Architecture accommodates the execution of numerous decision & control algorithms for co-operative driving in line with the Cybercars-2 Co-operative Communication Architecture requirements.

The proposed vehicle architecture (Figure 2.2-1) is to operate on different kinds of CyberCars-2 fleets of vehicles, i.e. both CyCabs and Dual-Mode vehicles, to enable them to become interchangeable and interoperable in a co-operative manner. This is achieved by making low level blocks (both blue and pink, Figure 2.2-1) interchangeable from the architecture viewpoint. Since the low level modules are closely linked to the vehicle actuators, the blue modules have to be included in the architecture if the dual-mode vehicles are involved in the manoeuvre. Pink modules would be necessary if CyberCars are involved.

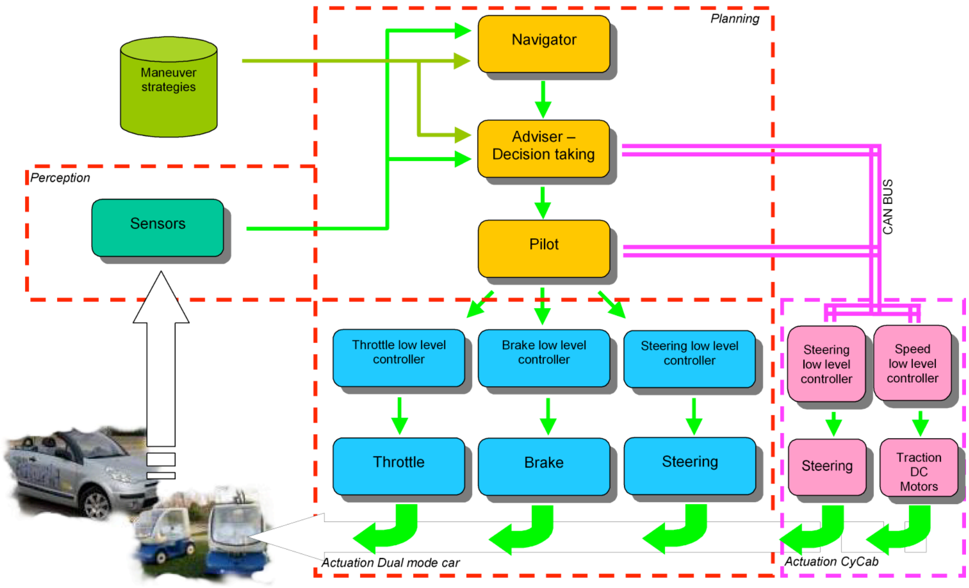


Figure 2.2-1: Mixed Vehicle Architecture for CyCab and Dual-Mode Vehicles

[13] For details, see Deliverable D.2.1, pp.10-34

The three yellow modules are always necessary and are the same for any type of vehicle. The Navigator block is responsible for finding the optimum vehicle route to target. The Adviser – Decision Making module is in charge of assigning a driving manoeuvre while the Pilot module executes the assigned manoeuvre by firing the vehicle's longitudinal and lateral controllers.

Vehicle's co-operative driving manoeuvres[14]

The following co-operative driving algorithms have been developed:

- Overtaking Manoeuvre[15]

  This manoeuvre expertly directs a vehicle to avoid a collision with obstacles while in motion. Figure 2.2-2 depicts the main functions involved in the execution of the manoeuvre.

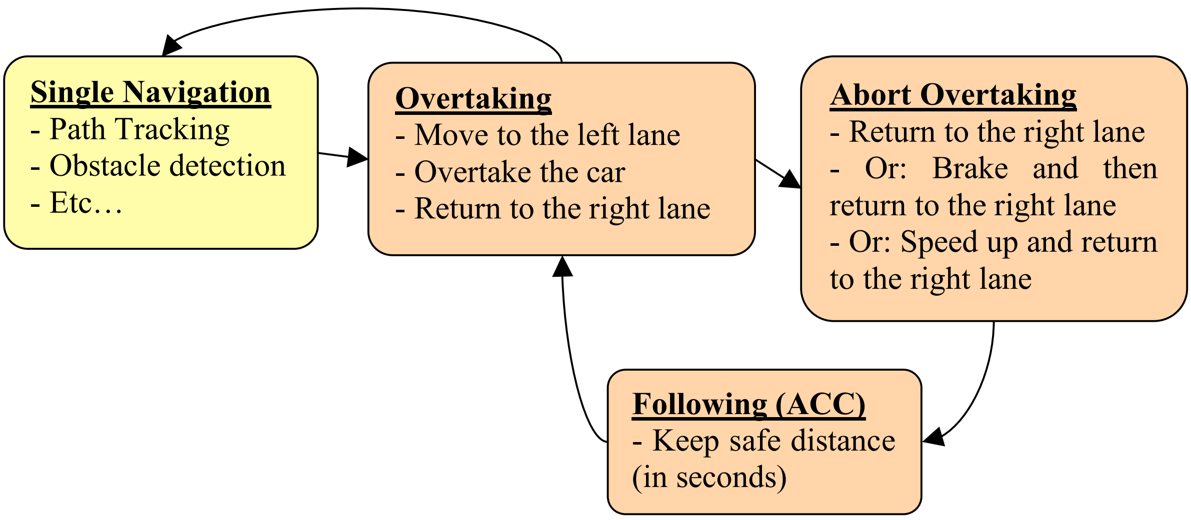


Figure 2.2-2: Overtaking Manoeuvre

- Platooning Manoeuvre[16]

  Platoons are groups of driverless vehicles in motion capable of maintaining a close and constant distance between two successive vehicles. They can contribute to greater road traffic efficiency and reduced traffic congestion. The first (leader) vehicle in the platoon decides which manoeuvre is to be performed and sends orders to all platoon vehicles to follow. (Figure 2.2-3)

[14] For details, see Deliverable D.2.1, pp. 35-77
[15] For details, see Deliverable D.2.2, pp. 12-16
[16] For details, see Deliverable D.2.2, pp. 16-31

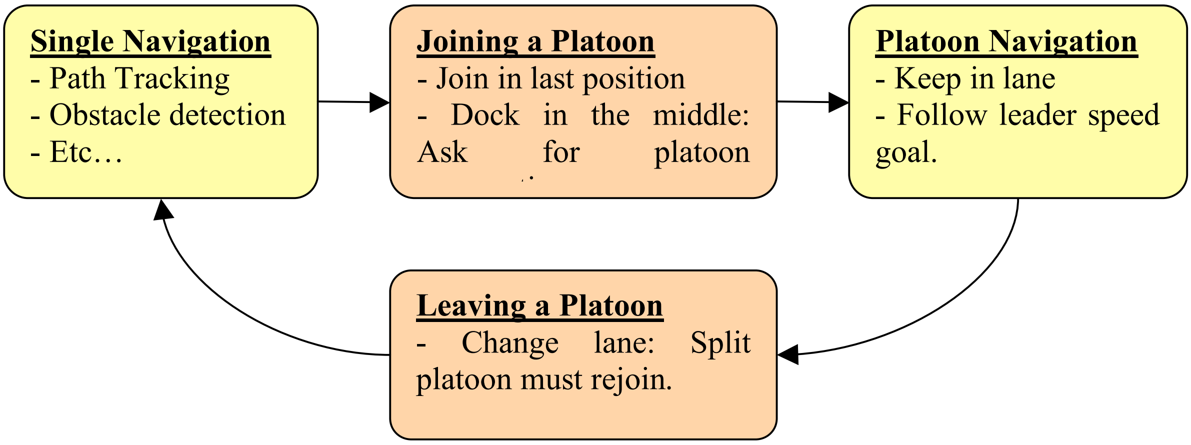


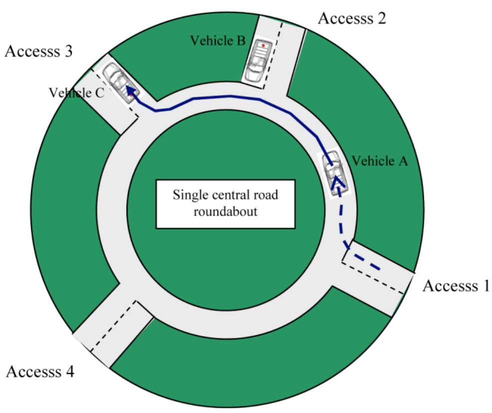
Figure 2.2-3: Platooning Manoeuvre

- Docking/Undocking Manoeuvre

  This manoeuvre enables pick-up/drop-off of passengers and parking of vehicles in a dedicated area. It is also necessary when an electric driverless vehicle is to access its docking station to re-charge its batteries. This manoeuvre critically depends on the availability and quality of V2V communication links.

- Roundabout Manoeuvre[17]

  Unlike the platooning manoeuvre which strictly depends on V2V communication links, this driving manoeuvre critically depends on V2I communication links although it still requires intensive access to V2V communication links.



[17] For details, see Deliverable D.2.2, pp.32-40

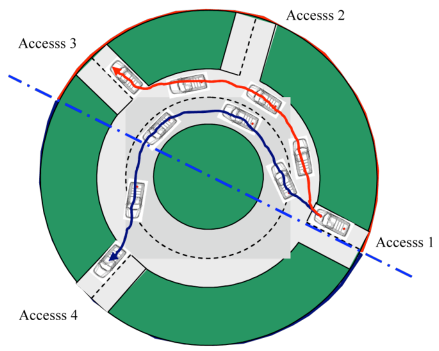


Figure 2.2-4 Single-centre and Multiple-centre roundabouts

- Intersection Crossing Manoeuvre[18]

  This manoeuvre is needed when a driverless vehicle approaches a road crossing point which is not operated by traffic lights. The main functions to be performed by a driverless vehicle are depicted in Figure 2.2-5.

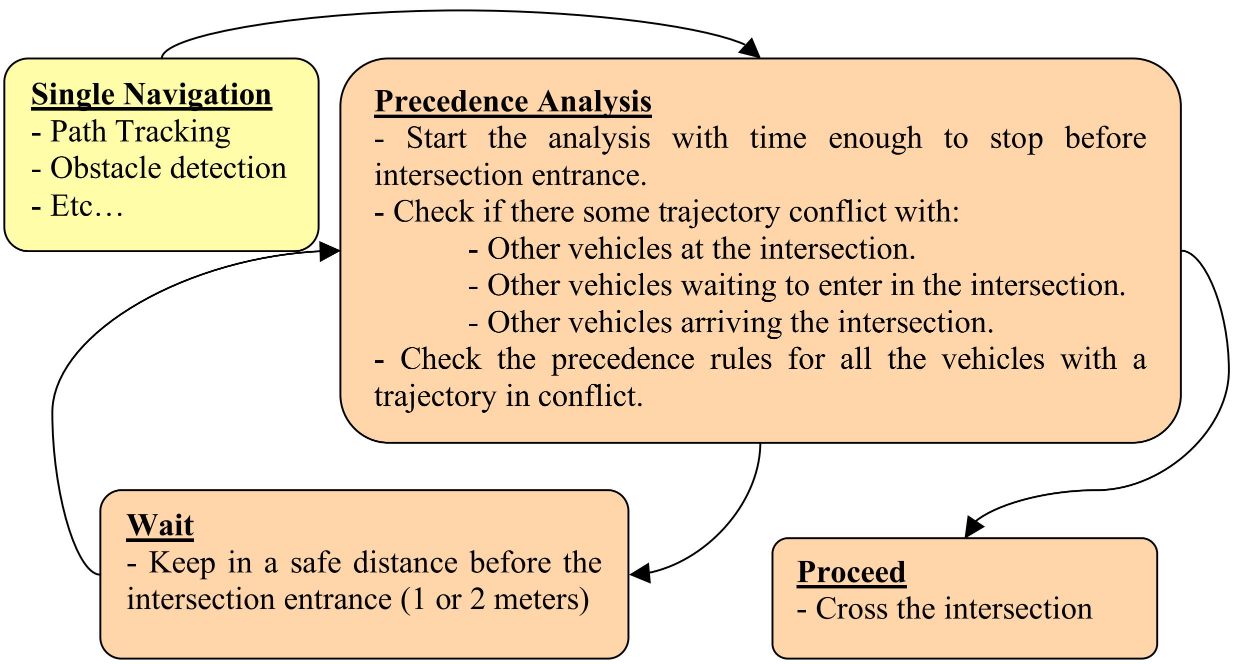


Figure 2.2-5: Intersection manœuvre diagram

Numerous road traffic situations are addressed including :

[18] For details, see Deliverable D.2.2, pp.41-48

- Intersection with priority, two vehicles, one way roads
- Intersection with priority, two vehicles, two way roads
- Intersection with priority, multiple vehicles
- etc

- Obstacle Detection and Path Generation[19]

  Cybercars are aimed at operating in an urban environment which is crowded by pedestrians, bicycles and various vehicles. These road traffic participants may suddenly and unexpectedly appear in front of CyberCars which need to be able to safely deal with these diverse road traffic situations.

  To address this issue, the Cybercars-2 project has undertaken work on the design and development of an integrated perception & planning algorithm for a fleet of driverless vehicles although research of this specific aspect of operation of driverless vehicles is not explicitly requested by the 'Description of the Project Work'. This is an on-going activity which follows the concept of a Reservation Algorithm, depicted in Figure 2.2-6.

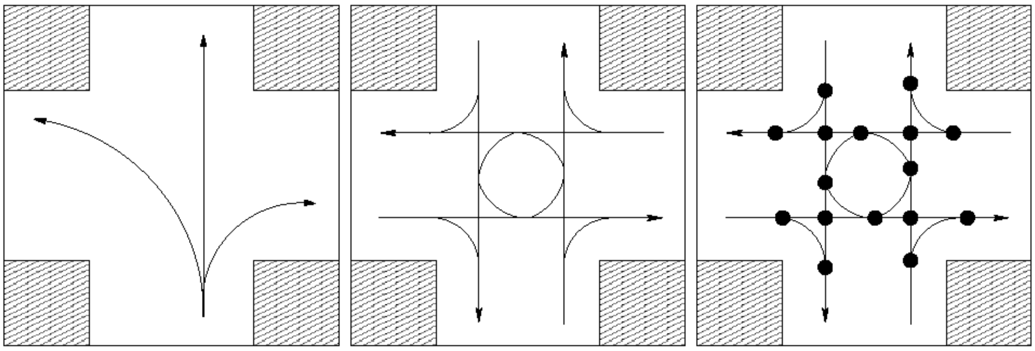


Figure 2.2-6: Regular Intersection of two roads

Figure 2.2-6 shows a case of a single vehicle having the option of choosing among three directions. The middle of Figures 2.2-6 shows trajectories that vehicles are able to follow, while the right part of Figures 2.2-6 depicts a small number of critical points on the trajectories where the risk of a collision exists. Facing the crossroad situation, a vehicle has to occupy various contiguous time-space sections of the crossroads.

Advanced data structures & procedures for exchange of data among CyberCars in a real-time[20]

In order to cooperate with each other, the road vehicles need to share information. This flow of information must be kept to a minimum to avoid a collapse of the communication channel. It is

[19] For details, see Deliverable D.2.1, pp.61-69
[20] For details, see Deliverable D.2.2 pp.5-49

envisaged that vehicles should continuously share information and act according to the information received.

Each vehicle carries its own data map and receives information produced by vehicles in the surrounding environment. Based on this, each vehicle is able to recognize a vehicle that can interfere with its own trajectory. The follow-up decision analysis determines decisions to be taken and executed by a particular vehicle.

The road infrastructure communicates with all vehicles advising them of possible events that may affect the traffic and, when necessary, sends a specific message to a particular vehicle.

To accommodate this, a two-level map structure is proposed (Figure 2.2-7).

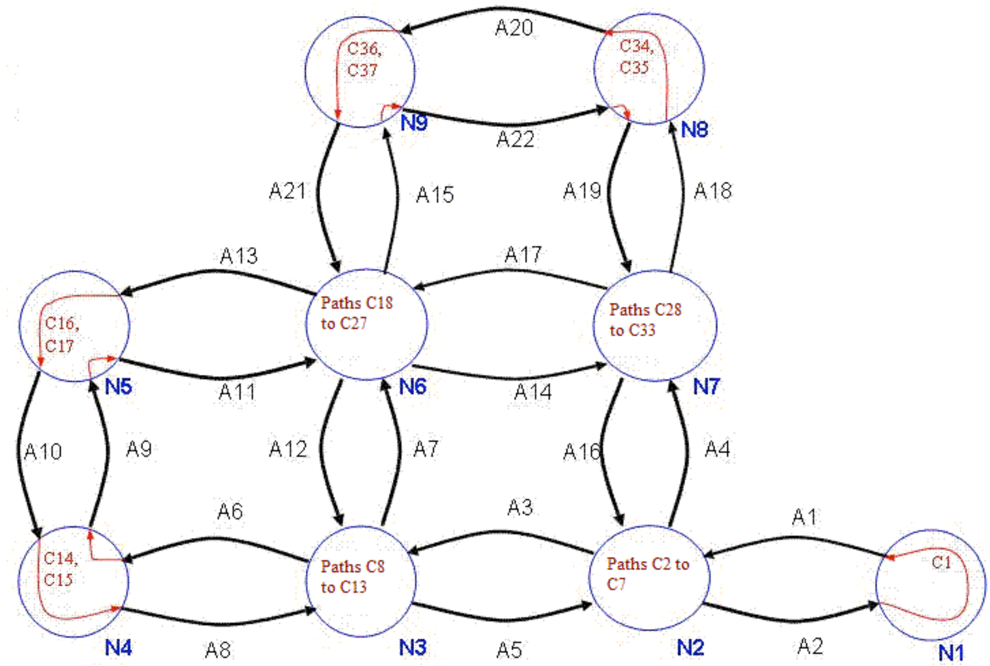


Figure 2.2-7: Graph representation

- The higher level is a graph with nodes representing crosses and edges representing paths; each edge is a directed link, a path going from the origin node to the goal node; each cross has an associated comprehensive list of all possible pathways linking all the inputs and outputs of the cross.
- The lower level is the pure cartography.

Several archives are created to contain points referenced in a database. Nodes represent crossroads and roundabouts. Edges represent the lanes of the roads, so a common street with two lanes can be represented by two edges, and each edge has an associated path. Each path may have an associated polygonal defined as a series of points. The relational data base containing the map information consists of three main tables; Nodes, Edges and Paths. Some auxiliary files, for paths and edges, contain the UTM coordinates of the corresponding routes.

A trip is defined as a sequence of nodes through which the car is to run. It finds its actual position within the initial edge and goes towards the final node. When the car is near this node, it adds the cross data (the exit edge and the time) in the data package to be broadcasted. Thereafter, it accesses the coordinate file of the path within the node, and finally chains to the exit edge.

2.3 WP3: Supervisory Co-operative Control, and Co-operative Road Traffic Management

2.3.1 Objectives

Work Package 3 (WP3) deals with the development of co-operative concepts for traffic management systems to help facilitate the wide deployment of CyberCars-based co-operative transport systems.

2.3.2 Tasks

It is envisaged that the Co-operative Road Traffic Management (CRTM) Centre is in charge of performing the optimisation of the road traffic conditions on a global scale while the Supervisory Co-operative Control System (SCCS) is in charge of collecting, processing and generating appropriate information for a vehicle to enable it to fulfill the optimisation requirements. Basically, SCCS supervises and monitors the vehicle level operations based on decisions and commands issued by the CRTM. It also handles certain exceptional situations such as accident detection, alarm handling and flagging the need for Cybercars maintenance. Thus, CRTM and SCCS, together with a human operator (when required) and a database, form the CyberCars Management Centre (CMS) – Figure 2.3-1.

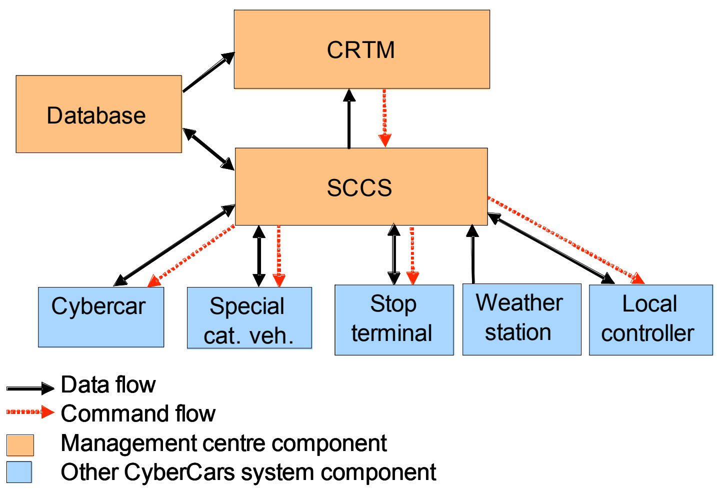


Figure 2.3-1: CyberCars-2 Management Centre

The focal point of this work package was focused on the design and development of the SCCS system. Due to the uncertainty of what form future transportation systems may take, the applied system design methodology made provision for the integration of varying design concerns. In time, they may evolve and offer high level flexibility which will allow the re-modularisation of previous design solutions without incurring invasive modifications and re-architecturing (e.g. easy integration of stakeholders' needs if needed).

2.3.3 Milestones and Deliverables

The Supervisory Co-operative Control System and the Co-operative Road Traffic Management System present the two main deliverables of this work package.

Supervisory Co-operative Control System – SCCS[21]

The SCCS has no equivalent in a conventional urban roads traffic system which is built on human driven vehicles. It is in charge of gathering useful information from the vehicles and the intelligent road infrastructure. This data is acquired through the SCCS wireless communication network and is brought to the SCCS processing unit which aggregates and forwards it to the CRTM. As a result, several management commands are issued by the CRTM and, through the SCCS communication network, delivered to CyberCars and intelligent road infrastructure. In addition, the SCCS is capable of handling specific network incidents that are not expected to be processed by CyberCars such as accident detection, identification and flagging of the need for special category vehicles etc.

A SCCS inherits some general requirements typical of urban transport systems. These general requirements are intended to overcome open issues or barriers that normally appear in conjunction with an implementation of large scale systems. In addition, a set of specific requirements has been identified according to capabilities expected from the system and tasks assigned to it.

General requirements

- Technological requirements
  - On-board and off-board equipment must operate satisfactorily
  - Suitable safety equipment must be provided where required
  - Actions (manoeuvres by the vehicles and control by the Management Centre) must be performed in such a way that safety is never compromised
  - Communication between parties involved must be secure, efficient and robust
  - The system and its components must meet standards and regulations under which they are expected to operate such as good/bad weather conditions, different user categories etc.
- Economic and societal requirements
  - Coexistence with mixed traffic
  - To solve intentional problems (traffic jam avoidance, pollution decrease, traffic efficiency improvement, etc)
  - Reduced likelihood of technical failures
  - Impact on the economy of the country and existing workforce
- Organisational and deployment requirements

[21] For details, see Deliverable D.3.1, page 16-61

- Potential conflict of interest between different stakeholders
- Aesthetic impact on the environment
- Project management for deployment
- Financial risks

- Regulation and lawmaking requirements
  - Liability
  - Harmonization with pre-existing legislation

Specific requirements

- Communication network that connects the CRTM with vehicles and infrastructure
- Specified common data exchange protocol
- Data processing for the purpose of:
  - providing accurate real-time traffic status information
  - delivering the commands generated by the CRTM back to the vehicles and the intelligent infrastructure
  - storing and updating traffic data records

An operation of a small-scale prototype of the SCCS, consisting of CyberCars and Dual-Mode vehicles, was demonstrated at La Rochelle test track in September 2008. The obtained results are presented in D.3.2 and D.4.2 in full detail.

Co-operative Road Traffic Management System - CRTMS

The Cybercars Co-operative Road Traffic Management System (CRTMS) and Supervisory Co-operative Control System (SCCS), together with a human operator and database, form the Cybercars Management Centre (CMC). Thus, the CRTMS is the Cybercars equivalent of a conventional traffic management system, extended to include non-conventional tasks related specifically to traffic management for Cybercars. It manages traffic using protocols such as re-routing and dynamic speed limits. The CRTMS is also responsible for the management of incidents and organizing the execution of vehicle and infrastructure maintenance. To this end, the CRTM outperforms a conventional traffic management system by its ability to control its vehicles and command their operations in real-time.

The CRTMS consists of a three-level system structure (stakeholder needs, use cases and management protocols) to ascertain optimal performance of the Cybercars network. The main identified management protocols are: Routing, Conflict Prioritization, Speed Management and Lane Organization.

Requirements for each of these protocols are outlined in the deliverable D.3.2 including implementation strategies. A case study example was used to show how these strategies were evaluated. The simulator developed by WP5 was used for the evaluation of selected strategies and testing under various traffic conditions. It was found that the developed CRTMS protocols may contribute to increased network performance. It was also found that the specific characteristics of a scenario under observation, can be influenced by way of varying network topology, traffic volume and driving behaviour. To this end, the three distinct decision making levels have been drawn, as depicted on Figure 2.3-2 assuming that each of these can restrict or overrule the level(s) beneath it.

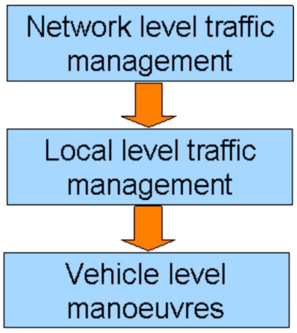


Figure 2.3-2. The three distinct decision making levels

The lowest level of this hierarchy deals with both the stand-alone and co-operative vehicle manoeuvres. These actions can be negotiated amongst Cybercars through V2V communication.

The middle decision-making level controls specific segments of road infrastructure such as a specific intersection, car parks and/or a specific bridge/rail crossing. The interaction between CyberCars and local control infrastructure is based on V2I communication.

The highest decision-making level deals with network management tasks such as traffic flow for a string of intersections in order to achieve low travel time, high safety, low pollution or a combination of these.

In summary, the SCCS and CRTM (Figure 2.3-1) work together to perform network level traffic management. The CRTM makes decisions and issues commands which are then passed on to the appropriate participants (such as CyberCars or local controllers) by the SCCS.

This classification also outlines links to other work packages. Thus, WP1 provides information on the possibilities and limitations of V2I communication, as an input to WP3 which sets the network operational parameters based on which vehicle manoeuvres are to be selected, enabled and performed (through the development within WP2 and WP6). WP4 sets the scene to test operational performance of both CyberCars and Dual-Mode vehicles and the entire traffic system under protocols developed by WP3 which are also used by WP5 for traffic simulation purposes.

The protocols developed for the Cybercars Co-operative Road Traffic Management system potentially offer a substantial increase in terms of network performance. The selected management protocols were extensively evaluated using a set of defined traffic scenarios. It was found that, in general, the use of management protocols could significantly improve traffic flow, leading to better traffic distribution. As a result, there were fewer incidences of congestion and the travel time was also shortened.

It became apparent that a choice of the most appropriate management protocol is strongly related to the specific characteristics of the observed scenario, such as network topology, traffic volume and driving behaviour.

It was found the best improvements to overall traffic efficiency can be achieved by favourable implementation of the routing protocols, while the conflict prioritization protocols are slightly less important. The speeding protocols will have a minor impact and the lane organization protocols are only useful under special circumstances, although their impact can be substantial if cleverly applied.

Furthermore, the management protocols developed for the CRTMS are based on the precondition that CyberCars can cooperate and communicate with each other and with road infrastructure. Therefore, the benefits in terms of network performance can be attributed to the co-operative aspect of the Cybercar system.

Because of the non-uniform performance of management protocols under different circumstances, the choice of strategies and protocol types for a given traffic system is very important. For example, when applying simple, broad protocols, the performance increase will not be particularly high but the system will remain stable and predictable. On the other hand, when very sophisticated and complex protocols are used, the potential for an increase in performance will be considerably higher, but the reactions of the system are likely to become less predictable. In the end, a careful step-by-step approach to the application of specific protocols, combined with continuous evaluation of the achieved performance will give the best results.

2.4 WP4: On-road Operational Performance testing of Co-operative CTS Vehicles – Proof of Concept

2.4.1 Objectives

To undertake on-road testing of a Co-operative Cybernetic Transport System Architecture including testing its ability to fulfill the interconnectivity and interoperability communication requirements imposed upon all system components.

2.4.2 Tasks

A small-scale Co-operative Cybernetic Transport System was constructed and prototyped based on a fleet of Cybercars and Dual-Mode vehicles (five in total). Extensive on-road testing was undertaken in La Rochelle, France, on an 8-shape test track during September 2008.

The ACC, Stop & Go and Co-operatives Road Crossing driving manoeuvres were performed based on the extensive use of the V2I and I2V communication links. The applied on-road test procedures also included testing of interconnectivity and interoperability between the transport system and an infrastructure control centre that was built in the vicinity of the test track. The latter test cases were primarily focused on traffic monitoring and supervision to enable remote control and positioning of driverless vehicles, remotely from the road traffic management centre.

2.4.3 Milestones and Deliverables

While:

a) the Co-operative Cybernetic Transport System Architecture was developed by WP1;
b) algorithms for co-operative driving manoeuvres, co-operative control and road traffic management were developed by WP2 and WP3 respectively; and
c) Dual-Mode vehicles were developed by WP6,

the main milestones of this work package were delivered from the activities focused on:

d) integration of all system components in the context of interconnectivity and interoperability among driverless vehicles and;
e) extensive on-road testing of the driving performance of a small-scale Co-operative Cybernetic Transport System and its ability to efficiently cooperate with a road traffic management centre.

An additional salient point of this work package is CyberView - a 3D software tool that was developed to: (i) retrieve data exchanged between the vehicles, and (ii) display the vehicle network data (Figure 2.4-1). To this end, Google Earth was also used as it enabled the display of every vehicle found nearby, in real-time (Figure 2.4-2).

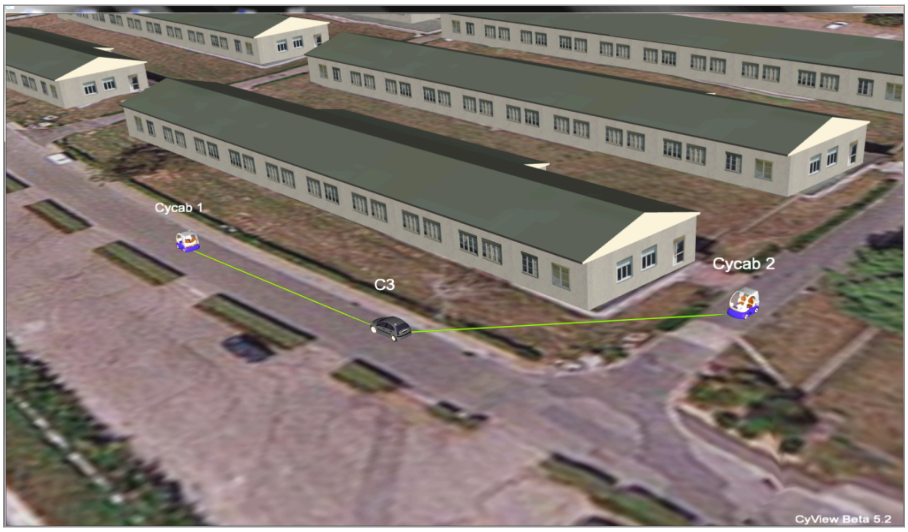


Figure 2.4-1. A Screen Shot Produced by the CyberView 3D showing one of the test track at INRIA's Rocquencourt Campus

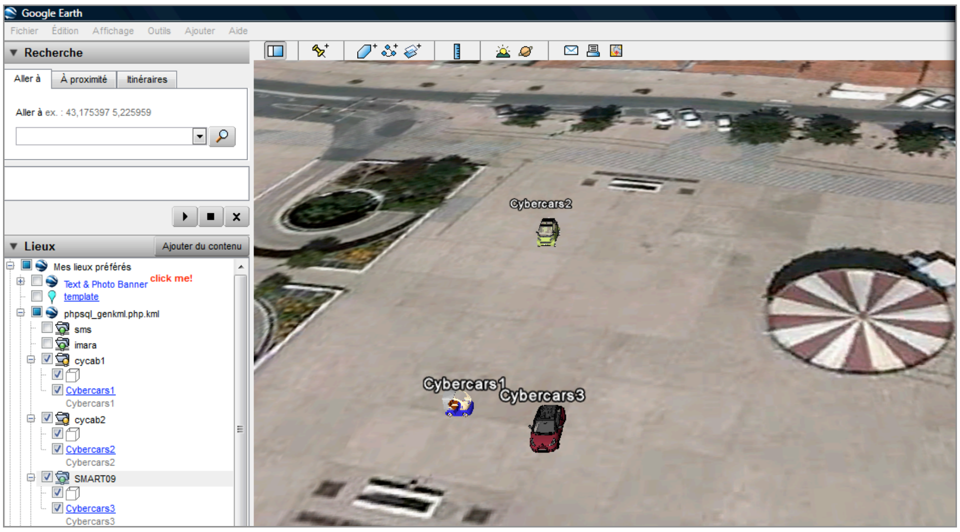


Figure 2.4-2. Position of nearby vehicles (those that are not necessarily part of the CCTS)

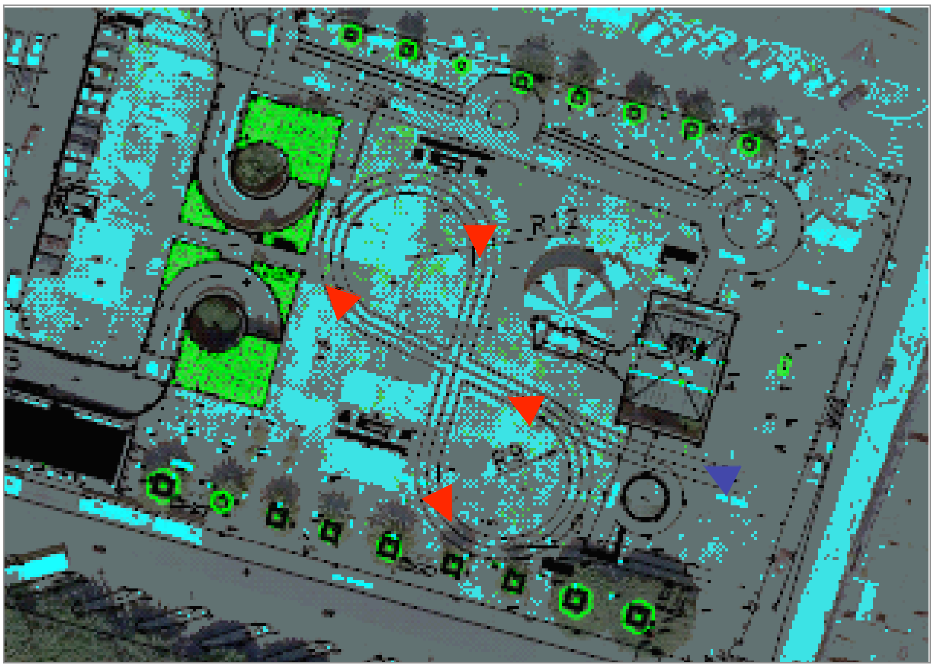


Figure 2.4-3. La Rochelle Test Track

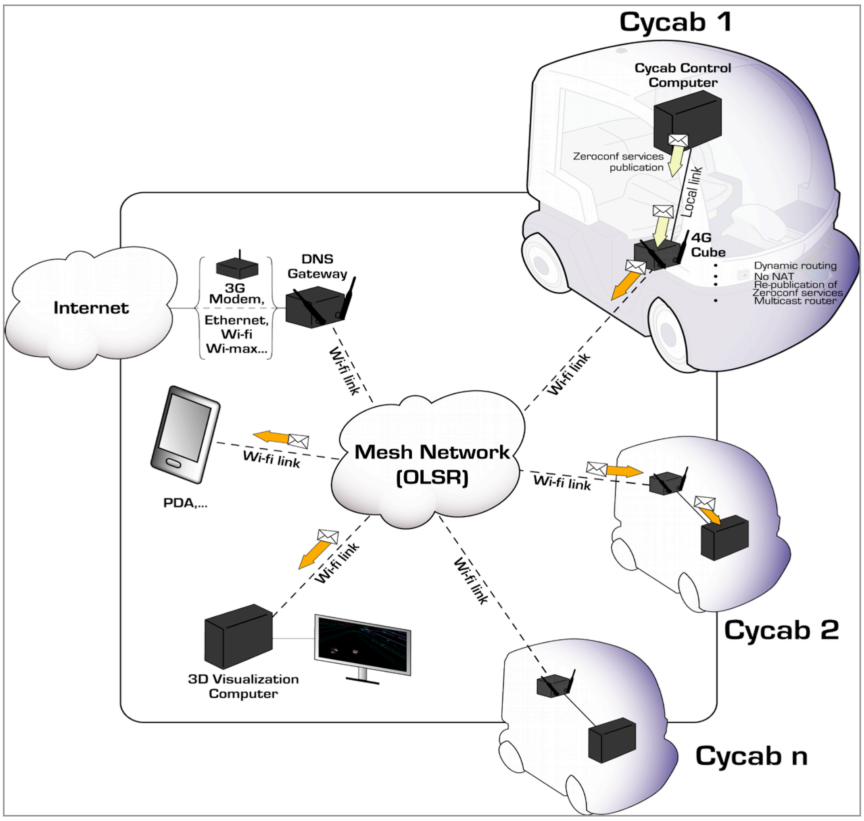


Figure 2.4-4. CyCab Mesh Network with OLSR

The La Rochelle test track is shown on Figure 2.4-3. A fleet of five co-operative driverless vehicles prototyped by INRIA/Robosoft (2x), TNO, Fiat and IAI formed CCTS through OLSR mesh network (Figure 2.4-4) and performed required driving manoeuvres.

The communication system architecture, implemented in the communication box 4G cubes, is shown on Figure 2.4-5.

A specific operating system was used for the 4G cube: OpenWRT, a reference in the embedded router OS world which uses a 2.6 Linux kernel IPV6 and 802.11p.

The implemented solution consists of three main parts:

- The hardware architecture consisting of a 4G cube and a Linux OpenWRT operating system.
- The HTTP server, developed in Python using twisted web2 and embedded in the 4G cubes, provides the web services and automatic service discovery.

- The HTTP client: simple C++ code or RTMaps components (for the specific needs of the IMARA laboratory) and for general use, the specification of the HTTP 1.1 protocol for Discovering is provided;

  The communication system is built around web services which assemble the Rest API. Being modular in design, new services can easily be developed and quickly deployed. In the current version, there are three web services: Discover, Expose and Fetch for exchanging all kinds of data (structures, images, lidar scan, etc).

  The HTTP protocol is used for communication between servers and to manage inputs and outputs on the system application.

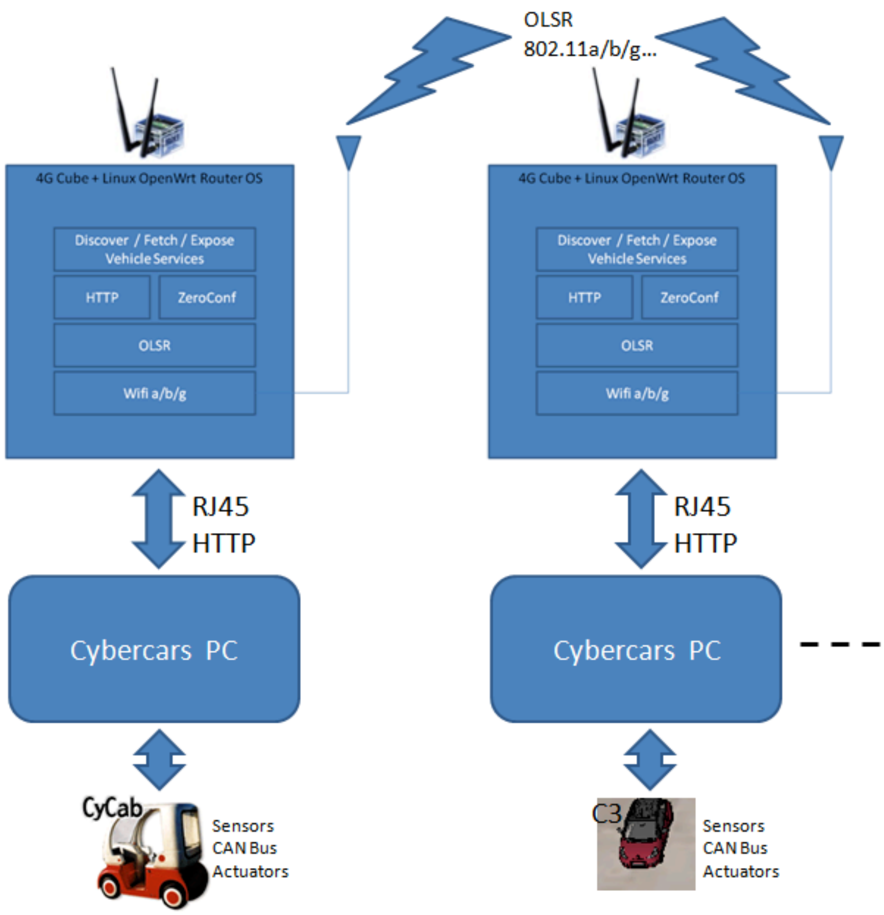


Figure 2.4-5. Communication System Architecture

The obtained test results are summarised in the following table.

Scenario	Detailed description	Data structure transmitted and received	Successful/ Unsuccessful (performance)	Problem detected	Results
V2V Adaptive Cruise Control	A vehicle must maintain its distance from the vehicle ahead.	CC2 structure	Successful	Unreliable GPS signal	D4
V2V Intersection Management	En route to an intersection, vehicles are expected to reduce their speed to avoid a collision.	CC2 structure	Successful		D4
V2V Stop&Go	A vehicle must maintain its distance from the vehicle ahead in traffic jam situations	CC2 structure	Successful		D4
V2I Emergency Braking	The control center to send an emergency stop signal to all vehicles in the loop.	CC2 structure	Successful		D4
V2I Communication Failure	If the 4G cube is switched off, all the vehicles should stop.	CC2 structure	Successful	Cybercars did not restart although the cube was re-plugged	D4
V2I Intersection Management	The speed of the vehicle is controlled by the Traffic Management Centre	CC2 structure	Successful		D4

The obtained results demonstrated:

a) the ability of the Co-operative Cybernetic Transport System to perform its operations based on V2V and V2I communication links;

b) that the 4G cube communication box, in handling all dynamic discovery/management requirements, simplified the efficient deployment and operation of co-operative communication links and underpinning protocols and;

c) that the applied HTTP 1.1 interface is operable under any type of architecture and in almost any high and low risk application scenarios.

2.5 WP5: Performance Evaluation in Large Scale Systems

2.5.1 Objectives

The main objective of this work package was to develop a simulation tool to enable: (i) evaluation of different driving concepts for CTS vehicles towards optimizing the CTS system performance; and (ii) identification of possible hazards and/or limitations of the use of CyberCars technology in real world applications.

2.5.2 Tasks

To meet the given objective, a simulator would need to support a wide variety of different road traffic scenarios, road topologies and vehicle behaviours. Emphasis should not be on the precise recreation of the geometric movements of a single vehicle but rather on the correct representation of interactions between vehicles and their co-operative behaviours.

With these requirements, it was clear that any existing simulation tool would require additional heavy adjustments and work efforts. Together with high licensing costs, it was concluded that design and development of a brand new CTS centric simulation tool was necessary.

2.5.3 Milestones and Deliverables

Cybernetic Transport Systems may contain a large number of individual units, creating complex interaction patterns and dependency chains among the vehicles. The highly demanded interrelations that are created with such a system are difficult to test with the limited amount of real test vehicles available. Also, large scale road traffic scenarios might consist of hundreds of roads, vehicles and intersections, and as such cannot be easily evaluated with real vehicles. It was therefore decided that the evaluation of the system performance should be done through a simulation exercise. Consequently, the design and development of: (i) the CTS tailored simulation tool and (ii) the design and development of the evaluation methods, scenarios and road topologies are the main milestones produced through realization of this work package.

CTS Simulation Tool[22]

The explicit goal imposed upon the CTS simulation tool was to simulate all kinds of traffic situations from highly restricted rail-based systems, to complex inner city road networks with versatile traffic rules and access to possibly large numbers of high-speed freeway networks.

The developed simulator is written in Delphi and runs under Windows. Due to the complexity of the driving behaviour models, any adjustment of the existing behaviours or addition of new behaviours and/or sensors including communication elements, would require recompilation of the overall program.

[22] For details, see Deliverable D.5.1, pp 5 - 31

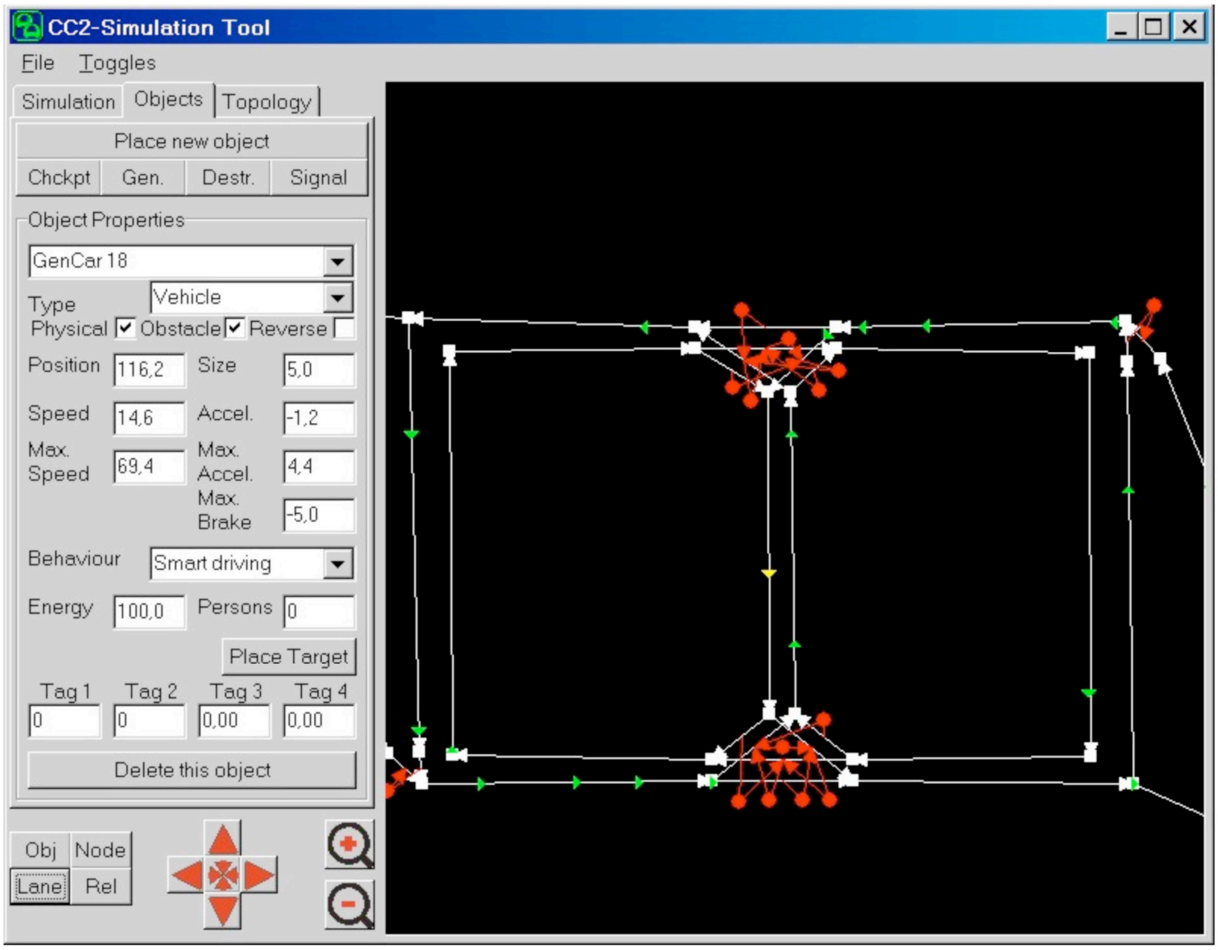


Figure 2.5-1: CTS Simulator Screenshot

The capability, operational attributes and main elements of the developed CTS simulation tool are as follows:

- The world model simulation that consists of: (i) lanes, (ii) lane relations and (iii) lane objects
- Representation of the basic road topology that enables definitions of: (i) lane type, (ii) the length of the lane, (iii) speed limit, (iv) definition of lane successors, (v) definition of lane predecessors, and (vi) drive priority lanes
- Representation of the lane relations including: (i) signalled and non-signalled lanes, (ii) neighbouring lanes and (iii) opposing lanes
- Representation of road objects, obstacles and vehicles, including their motion speed and motion direction to the point of defining acceleration and braking force values, and also on-going and target positions
- Representation of typical traffic situations including traffic participants and road traffic signs and signals

- Creation of numerous vehicle behaviors and co-operative manoeuvres, and, ultimately,
- Creation of versatile traffic scenarios

These features allow for fast and easy simulation of different behaviour models, road topologies and traffic scenarios.

CTS Performance Analysis[23]

While the simulation package milestone deals with the tool to enable simulation of operations of the Cybernetic Transport System, this deliverable describes the obtained evaluation results, including the implemented evaluation method, traffic scenarios, road topologies, vehicle types and their driving behaviours.

The traffic model developed for the simulator allowed for the representation of all road connections, conflicts and relations although it is silent with respect to specific geometric parameters such as lane width, road curvatures and road slopes. Several test tracks used by the Cybercars 2 project for various demonstrations of on-road performance of its vehicles were accepted as good representatives of the real-world traffic systems and thus, were modeled and evaluated. That decision enabled a direct comparison of the simulation results and those obtained from testing of on-road performance of the real driverless vehicles. Therefore, all test tracks were modeled by using the precise topological structures, lane lengths and conflict points from the real world equivalents. The resulting models are shown on several figures that follow from Figure 2.5-2 to Figure 2.5-9.

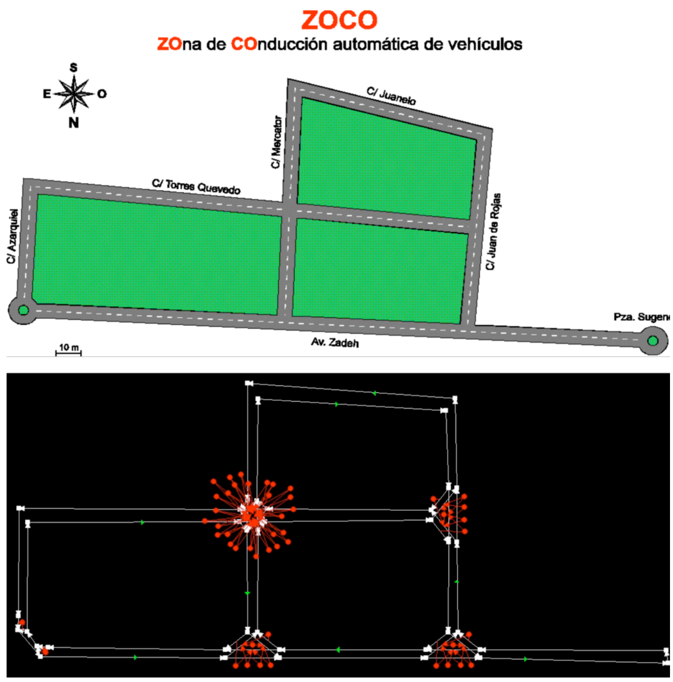


Figure 2.5-2 Layout and Simulation Model for the IAI Test Track, Spain

[23] For details, see Deliverable D.5.2, pages 9-61

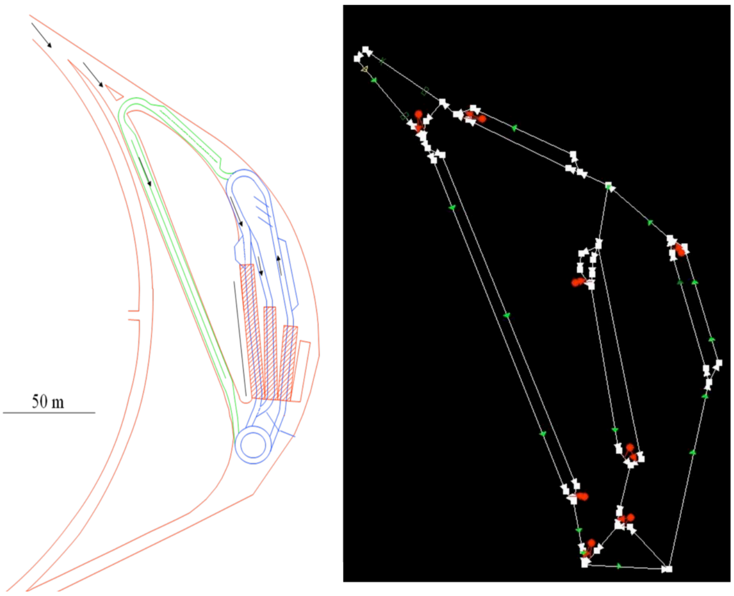


Figure 2.5-3 Layout and Simulation Model for the CRF Test Track, Italy

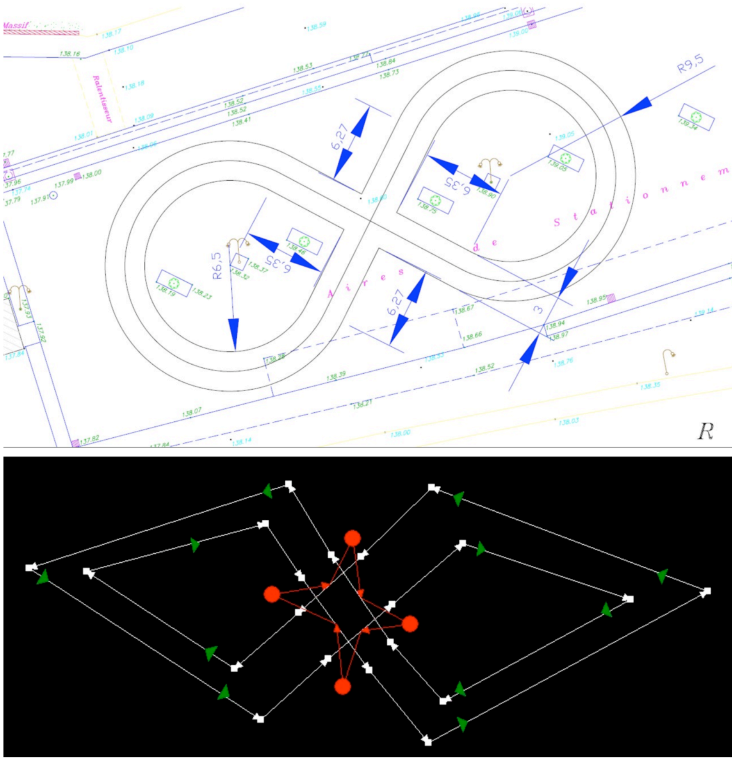


Figure 2.5-4 Layout and Simulation Model for the INRIA-Rocquencourt Test Track, France

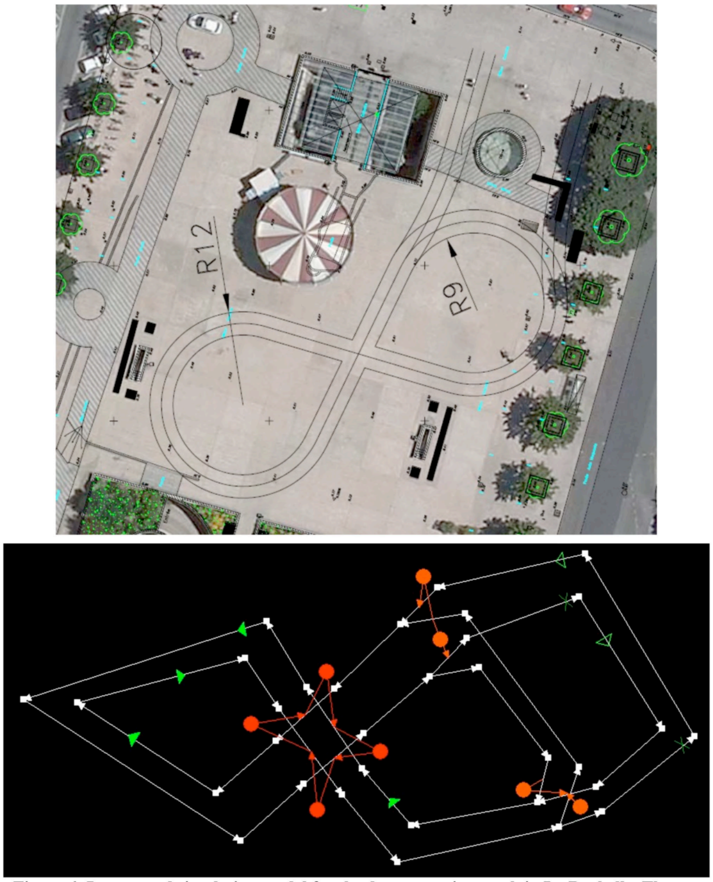


Figure 2.5-5 Layout and Simulation Model for the La Rochelle Test Track, France

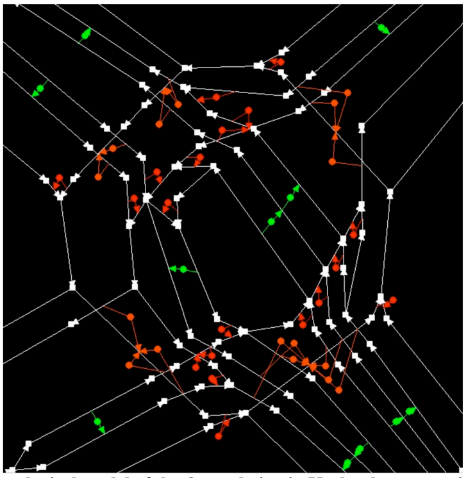


Figure 2.5-6 Layout and Simulation Model for the Oststadtring Test Track, Germany

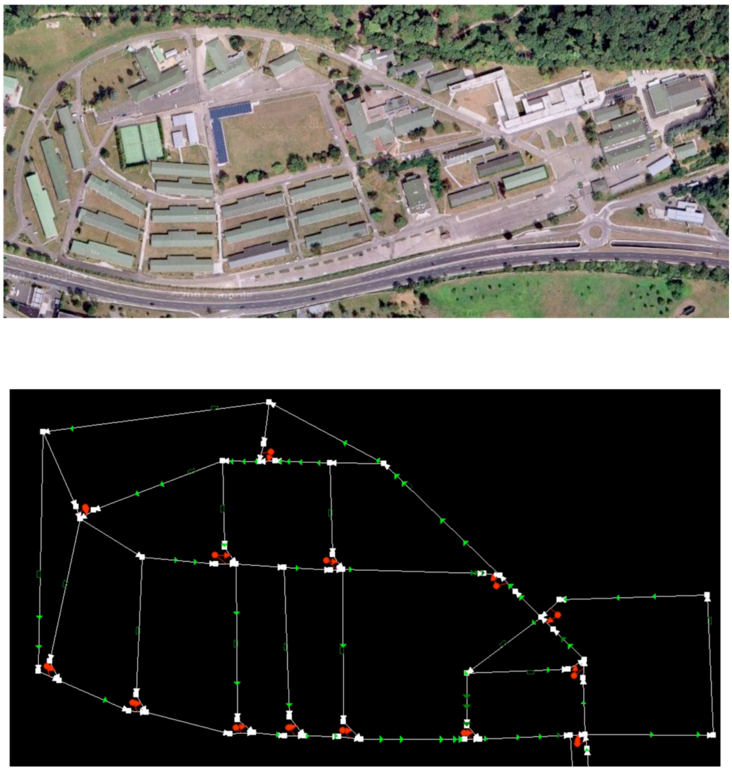


Figure 2.5-7 Layout and Simulation Model for the INRIA Rocquencourt Campus Test Track, France

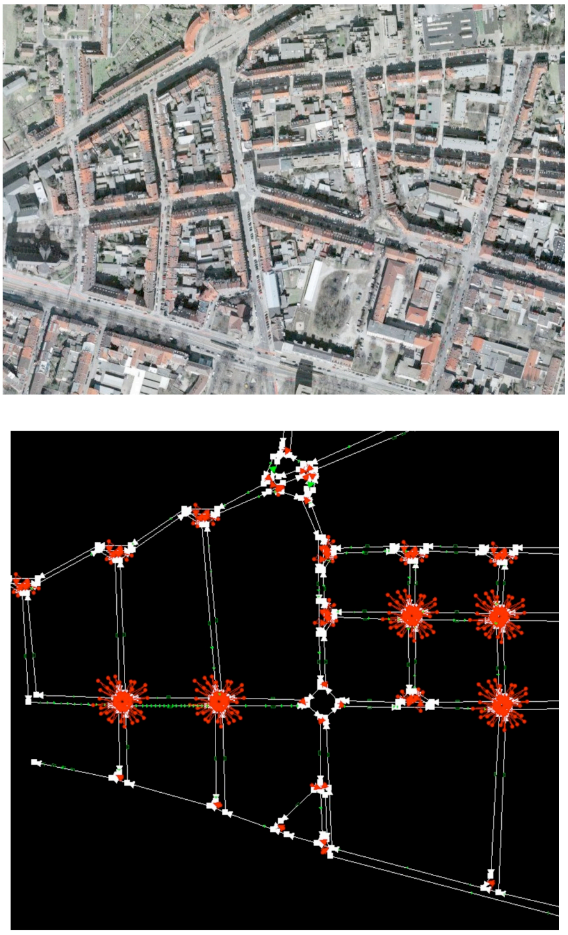


Figure 2.5-8 Layout and Simulation Model for the Karlsruhe Test Track

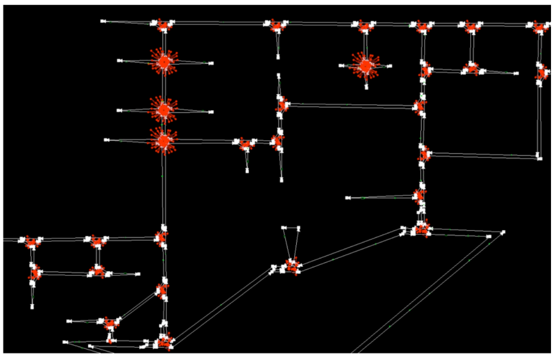


Figure 2.5-9 Layout and Simulation Model for the University of Stutgart, Vaihingen Campus Test Track, Germany

Since the driverless vehicles that were prototyped by the project consortium partners (namely, INRIA CyCab, TNO Smart09, IAI-CSIC Clavileno, CRF CyberPanda and SJTU CyberCar) differ from each other, different vehicle models had to be used for the purpose of simulating operational performance of each of these vehicles. In addition, a generic vehicle model was developed and included in the simulation to represent conventional road vehicles such as passenger vehicles, vans, buses and/or trucks. These conventional vehicles were assigned a set driving behaviour. Most geometric information, like width and height of the vehicle, was not used because of the abstraction level of the simulation. However, the vehicle's dynamic attributes such as speed limits, acceleration and braking values were included in the simulation models.

With respect to a co-operative behaviour of the Cybernetic Transport System, the following problem areas were identified as most important, and consequently modeled and evaluated:

a) Distance keeping; the distance keeping systems[24] are considered to be critical for the vehicle's safety. Here, the distance keeping task also included modeling of the vehicle's ability to execute an emergency stop manoeuvre and also the vehicle's ability to maintain its distance not just from the vehicle ahead but also with respect to other road obstacles.
b) Intersection crossing; since there are many different types of intersections, such as road crossings, lane merging, roundabouts, multilane intersections etc, it would be almost impossible to create a model that equally describes any type of intersection. The undertaken simulation postulated that a road topology will be regarded as a simple intersection if at least two lanes are merged or are crossing each other. This means that an x-crossing was regarded as a set of simple intersections.
c) Overtaking and lane changing; this is a complex driving manoeuvre that requires a multitude of different driving actions over an extended time period. Similar to conventional vehicles driven by human beings, driverless vehicles can also perform overtaking manoeuvres with different strategies. The developed simulation and evaluation programs have made provision for implementation of these different strategies.

[24] Adaptive Cruise Control (ACC) systems are control systems that control a safe distance from the head vehicle.

This simulation did not evaluate:

d) routing and path finding manoeuvres, as these operations are considered part of the road traffic management strategy and, as such, were evaluated by the work package WP 3.2
e) platooning, as this manoeuvre is regarded as one of the possible solutions to the road traffic congestion problem.

For the driverless vehicles that are prototyped, tested and used by this project, it can be concluded that safe operation of the Cybernetic Transport System can be guaranteed by co-operative driving algorithms. With the driving speed of 10 km/hour, the ability of driverless vehicles to maintain a safe distance and perform an emergency stopping is unquestionable. This conclusion also relates to their ability to safely perform overtaking manoeuvres, as well as an intersection crossing. Right-of-way negotiations and deadlock prevention may only be of higher complexity.

Conversely, the project did not test the operational performance of the Cybernetic Transport System for faster driving speeds; e.g. those greater than 10 km/hour. Such tests may reveal the need for a complex safety control system to enable failure-free operations of the entire CTS and its components in the context of road safety requirements and the zero-road-accident strategy.

2.6 WP6: Development of Dual-Mode Vehicles

2.6.1 Objectives

The objective of WP6 was the development of Dual-Mode Vehicles by way of equipping conventional vehicles with ADAS systems, and capable of operating in automatic mode in specific road situations and traffic scenarios, on request by human drivers.

2.6.2 Tasks

Dual-Mode Vehicles are designed by combining the versatility and the comfort of conventional ADAS vehicles with the efficiency and the safety of driverless vehicles.

The main four operational modes foreseen are:

a) manual driving mode where a vehicle is driven by a human driver;
b) an assisted mode during which a human driver may seek assistance from ADAS systems to operate specific manoeuvres such as the lane-keeping driving manoeuvre;
c) automatic mode during which the vehicle is able to perform all driving manoeuvres without assistance from human drivers, and
d) remote control mode which enables remote control and management of vehicle motions with no assistance from human drivers.

2.6.3 Milestones and Deliverables

Dual-Mode Vehicles[25]

A Dual-Mode Vehicle was developed and prototyped by way of upgrading a conventional vehicle with ADAS functions, and then further upgrading it with the ability to safely operate CTS-like road traffic scenarios with no assistance from human drivers.

Figure 2.6-1 depicts the Dual-Mode Vehicle's main modes of operation while Figure 2.6-2 shows specific details about manoeuvres in each mode. Figure 2.6-3 points to specific sensors and devices which were required in order for the Dual-Mode Vehicle to perform the required functions and driving manoeuvres.

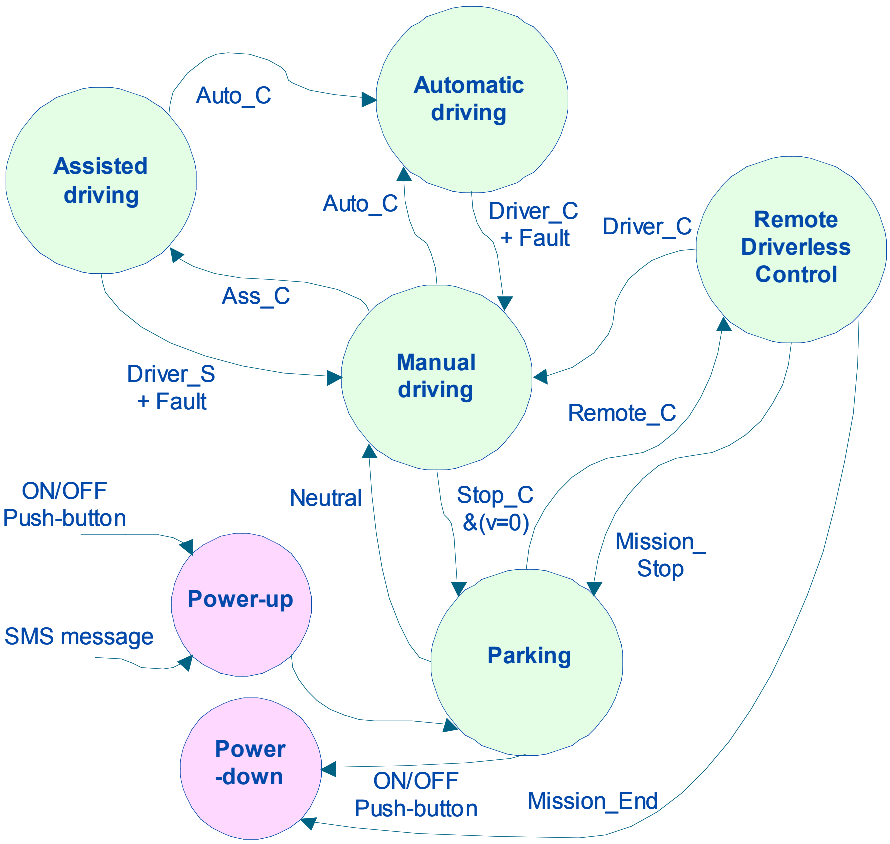


Figure 2.6-1: Modes of operations

[25] For details, see Deliverable D.6.1, pp.7-44; and also Deliverable D.6.2., pp.1-15

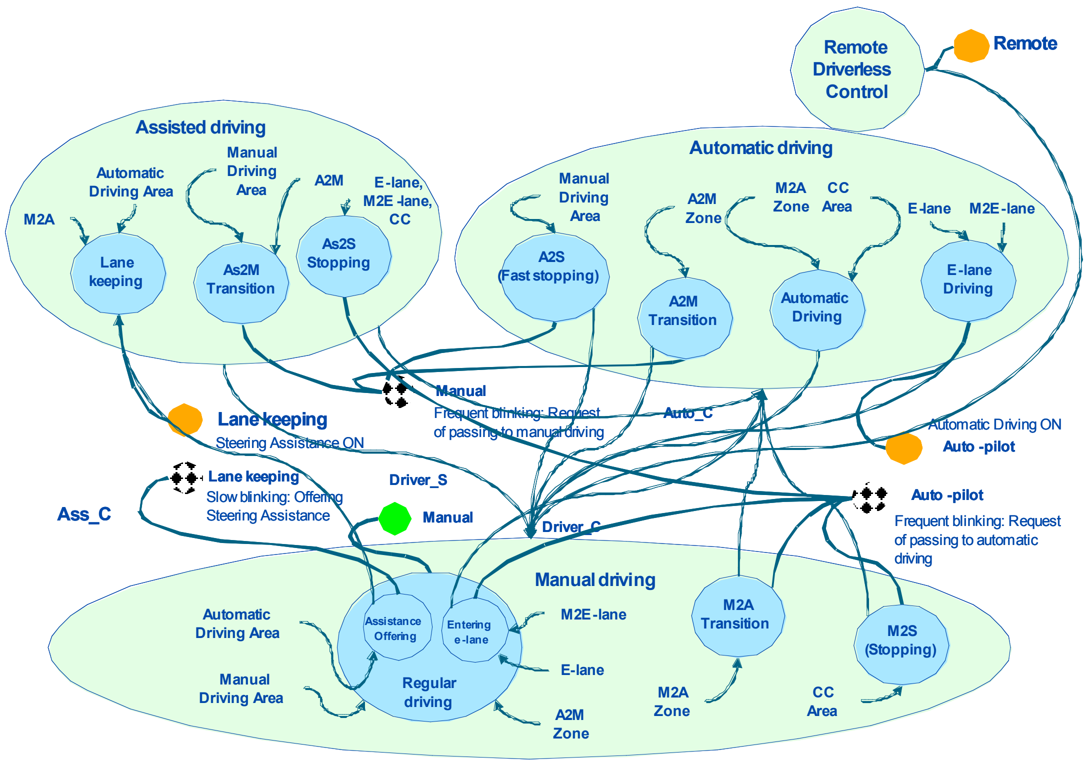


Figure 2.6-2: Modes of operations and corresponding driver's actions

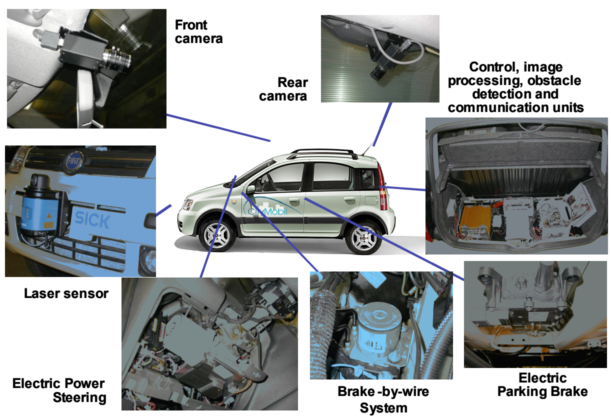


Figure 2.6-3: Additional Equipment required for the purpose of upgrading and enabling an ADAS vehicle to operate as a CyberCars vehicle

The basic ADAS functions have been initially developed under the umbrella of the EU ADASE Project, and further developments are still in progress by various research groups world-wide. Functions such as assisted-reverse parallel parking, lane-keeping, and stop-and-go automatic driving in congested road traffic situations have been developed to improve driving safety, comfort and increase driving pleasure.

Although CTS and ADAS Architectures are based on similar elements, they are not necessarily fully compatible in terms of interconnectivity and interoperability. That and other issues such as human perception, human-machine interface and the vehicle's cognitive ability remain to be addressed.

The three Dual-Mode Vehicles are prototyped for the purpose of achieving the Cybercars-2's research plans and performing a series of robust and exhaustive testing of co-operative driving. Figures 2.6-4 shows car models selected for prototyping dual-mode vehicles, namely the two FIAT Panda vehicles and one FIAT 500 model.

Extensive on-road testing of the prototyped Dual-Mode vehicles was undertaken for the purpose of:

a) evaluating performance of the prototyped vehicles, in particular those linked to co-operative driving requirements; and
b) testing compatibility between Dual-Mode and Cybercars vehicle concepts.

Numerous test scenarios were performed at the CRF Test Track in Orbassano (Italy) and Place de Verdun in La Rochelle (France). The former is a restricted area where the vehicles run on safety circuits without pedestrians and unknown moving vehicles present, while the latter is a public place in the town.

Figure 2.6-4: Car models selected for prototyping Dual-Mode Vehicles
(Figure 2, page 9, D.6.1)

The CRF track–based tests included testing of the vehicles' general functionalities while La Rochelle–based tests were specifically focused on V2V and V2I communication links, related co-operative driving manoeuvres, as well as testing of compatibility of Dual-Mode vehicles with CyberCars.

Performances of the controls during automatic guidance	
Lateral error in steady state running in straight line	± 0,10 m
Maximum lateral error in curved line	± 0,15 m
Accuracy of speed control in steady state conditions	± 0,5 km/h max
Accuracy of speed control in presence of noise on the signals	± 1,5 km/h max
Accuracy of distance control during an emergency braking	± 0,5 m max
Accuracy of distance control for steady state platooning	± 0,2 m
Accuracy of distance control for platooning while braking the vehicles	± 0,35 m

Figure 2.6-5: Dual-Mode vehicles' Automatic Mode Driving Performance

Figure 2.6-6 : Dual-Mode vehicles performing a platooning manœuvre at the CRF-Orbassano Test Track, Italy

Figure 2.6-7: Dual-Mode vehicles performing a platooning manoeuvre at La Rochelle technology demonstration site (Place de Verdum), France

In Automatic Mode of operation, the Dual-Mode vehicles were able to perform the same functionalities as Cybercars. Moreover, they were able to perform selected driving manoeuvres in cooperation with Cybercars. All these features were tested and demonstrated on specifically designed test tracks, depicted in Figure 2.6-6 and Figure 2.6-7.

2.7 WP7: Exploitation and Dissemination of the Cybercars-2 Technology across Europe and Internationally

2.7.1 Objectives

Communicate and disseminate the developed CTS technology across European countries and internationally. Analyse potential urban sites, show the interest towards Cooperative CTS and collaborate with complementary European projects on urban transport. Prepare the exploitation of the project results.

2.7.2 Milestones and Deliverables

The project has been extremely successful in disseminating Cybercars-2 knowledge and outcomes across Europe and internationally. The exploitation and dissemination activities took many forms including:
(i) the presence of the project web site,
(ii) presentation of papers at conferences and events,
(iii) publication of leaflets, brochures and video clips,
(iv) demonstration of the developed technology to the public and prospective end users,
(v) presentation of the project outcomes through numerous media outlets, and
(vi) collaboration with other EU urban transport projects.

A productive and efficient project management team contributed to this success through high level integration and cohesion of all work packages and their activities, whilst keeping the number of project meetings to a minimum. The project's inaugural meeting was held in Paris on the 2nd October 2006, followed by meetings in: Rouen 26-27/06/2006; Las Palmas 2/12/2007; Versailles 17/09/2007; Orbassano 21/01/2008; Madrid 18-19/02/2008; Brussels 4/03/2008; Rocquencourt 28-29/05/2008 and La Rochelle 19/09/2008.

(i) The project web site - http://www-c.inria.fr/cybercars2/

The project web site was designed as part of the cybecars.org web site to highlight a link of the Cybercars-2 project with its predecessor projects CyberCars, CyberMove, Netmobil as well as its sister project CityMobil and child project CyberCars3.

The CyberCars-2 web site (http://www-c.inria.fr/cybercars2/) provides comprehensive information about the project, its program scope, work packages, publications & videos and project milestones and outcomes. It lists the project consortium members and provides relevant contact details.

(ii) Publication of brochures, posters and video clips

Work is underway on the design and production of the CyberCars-2 Project Achievements booklet which profiles the project objectives, its program scope, milestones and outcomes.

Several posters addressing various aspects of the realization of the project's specific topics are published in conjunction with events attended/organised by the project consortium members.

Selected video clips demonstrating the essential performance that have so far been achieved by the CyberCars-2 fleet of vehicles are presented on the project web site. Among them are video clips from: (a) Las Palmas Eurocast demonstration; (b) Brussels Euro Open Day demonstration; (c) Rocquencourt CyberCars Cooperation demonstration; and (d) La Rochelle Cooperative Cybernetic Transport System demonstration.

(iii) Demonstration of the developed technology to the public and prospective end users

- 28 March 2007: In conjunction with the Symposium on Cooperative Vehicle-Infrastructure Systems (organized by TNO) in Eindhoven; one cybercar performing automated driving was displayed and a stand with posters was presented (in partnership with CityMobil).

- 5 May 2007: In conjunction with the European Open Day: Building of the European Commission in Brussels; two cybercars with manual driving (for safety reasons due to the high pedestrian density) were displayed along with several posters displayed on the fence of the EC building (in partnership with CityMobil).

- 18 September 2007: In conjunction with the i2010 Intelligent Car Event 2007 and opening of the IP PReVENT Exhibition in Versailles; a CyberCar from IAI performed a demonstration of an automated vehicle at this event.

- 24 September – 5 October 2007. Daventry Showcase: Four cybercars (1 static), demonstrating both vehicle-to-vehicle technology and a platooning driving manoeuvre were presented to the public. This event was mainly organized by the CityMobil project.

- 27-28 October 2007: In conjunction with the Transportation Festival 2007 in Paris; a cybercar was presented in a live demonstration, whilst two more were presented at the static exhibition.

- 21-23 April 2008, Ljubljana: In conjunction with the Transport Research Arena; one cybercar was exposed at the exhibition during this conference (in partnership with CityMobil).

- 29 August 2008, Shenyang, China: The V2V communication concept, based on four CyberCars, was demonstrated in conjunction with the Chinese National Contents on Smart Cars initiative.

- 18-28 September 2008, La Rochelle: Operations of a small-scale prototype of a Supervisory Cooperative Control System and full-scale prototypes of CyberCars and Dual-Mode vehicles were demonstrated. These demonstrations included their ability to perform vehicle-to-vehicle and vehicle-to-infrastructure communications.

(iv) Presentation of the project outcomes through numerous media outlets

- Several[26] international broadcasts featured the Cybercars-2 project including BBC World, Euronews and Discovery.
- A 50 minute educational film, designed specifically for world television audiences and financed by the European Union Project VIA, will feature the cybercars, including CyberCars-2.
- Each public demonstration of the Cybercars-2 fleet of vehicles attracted numerous press articles and local TV broadcasts.

(v) Presentation of papers at conferences and events

Workshop organised jointly by CyberCars-2 and City Mobil Projects

The Workshop on *Automatisation pour les Transports Urbains* was held on 19 September 2008 in La Rochelle under the auspices of the EU FP6 CyberCars-2 and City Mobil projects. The following papers were presented:

Challenges and Main Drivers for Urban Mobility: From Policy to Innovation; by Patrick Mercier
CityMobil Advanced Transport for the Urban Environment; by Ahmed Benmimoun
Advanced City Cars; by Gianfranco Burzio
Advanced Bus Rapid Transit; by Jean-Laurent Franchineau
Cybernetic Transport Systems; by Vincent Dupourque
Applications of PRT; by Martin Lowson
Automation for Urban Transport; by Andre Vits
Cybercars: Origins, Past Projects, Future Work; by Michel Parent
Benefits of Advanced Transport Systems; by Adriano Alessandrini
Urban Integration; by Thierry Chanard
Cybercars in China; by Ming Yang

[26] Euronews' broadcast about La Rochelle demonstration can be seen at the following site: http://www.euronews.net/en/article/03/12/2008/the-hands-free-future-for-transport

The La Rochelle demonstration was also profiled by TF1: http://www.ushuaia.com/ushuaia-terre/videos-photos/videos/transport/0,,4095967,00-la-voiture-verte-sans-chauffeur-a-la-rochelle-.html

Experiences in La Rochelle; by Jacques Mollard

Keynote conferences and invited presentations

The CyberCars-2 Project Coordinator, Dr Michel Parent was a keynote speaker at several international conferences and symposia presenting the results of the CyberCars-2 project. Among these events are: SI International (http://www.rm.is.tohoku.ac.jp/SIInt08/) in Nagoya in 2008, ICARCV (http://www.icarcv.org/2008/) in 2008 in Hanoi, Mobilis 2007 (http://www.mobilisconference.com/fr/index.html) in Mulhouse, and LT'2007 (http://ort.ec-lille.fr/lt2007/index.html) in Tunisia.

Dr Michel Parent also presented the CyberCars-2 Project at various committee meetings of the Transportation Research Board in Washington in 2007, 2008 and 2009.

Special Issue on Cybernetic Transport Systems of the Journal of Robotics and Mechatronics

Prof Vlacic and Dr Parent will edit a *Special Issue on Cybernetic Transport Systems* that will be published as Vol.22 No.6 of the Journal of Robotics and Mechatronics, the Fuji Technology Press, Japan, in December 2010.

Conference Papers

1. J E. Naranjo and Ricardo García. *Proyecto Cybercars2: Close Communications for Cooperation Between Cybercars*. In Proceedings of the 2º Simposio de Control Inteligente Huelva, May 2006. CD ISBN 84-689-8640-2
2. T. de Pedro, R. García, C. González JE. Naranjo y J. Alonso: *Toma de decisiones para Cooperación de Vehículos Autónomos en Maniobras Críticas*. In Proceedings of the 2º Workshop de Robots de Exteriores. Avila, España, julio 2007. ISBN978-84-611-8055-4
3. J. Cannou, D. Salé, M.Traonmillin, Y. Dupourqué: *The Anglet Experiment: A Cybercar on the Beach.* In Proceedings of the Eurocast 2007 Las Palmas February 12-15
4. J. Naranjo, R. Garcia-Rosa, C. Gonzalez, T. de Pedro, J. Alonso-Ruiz, J.Vinuesa: *Automatic Co-operative Driving for Road Intersections based on GPS and Wireless Communications.* In Proceedings of the Eurocast 2007 Las Palmas February 12-15
5. L. Oliveira, G. Monteiro, P. Peixoto, U. Nunes: *Toward a Robust Vision-based Obstacle Perception with Classifier Fusion in Cybercars*. In Proceedings of the Eurocast 2007 Las Palmas February 12-15
6. J. Alonso-Ruiz, J. Suarez, J. Jimenez-Gil, T. de Pedro: *Cooperation between Autonomous Cars : Overtaking Maneuver*. In Proceedings of the Eurocast 2007 Las Palmas February 12-15
7. Olivier Mehani and Arnaud de La Fortelle: *Trajectory Planning in a Crossroads for a Fleet of Driverless Vehicles*. In Proceedings of the Eurocast 2007 Las Palmas February 12-15
8. Nicolas Simond, Michel Parent: *Free space in front of an Autonomous Guided Vehicle in Inner-City Conditions*. In Proceedings of the Eurocast 2007 Las Palmas February 12-15
9. Wided Miled, Jean Christophe Pesquet and Michel Parent: *Robust Obstacle Detection based on Dense Disparity Maps*. In Proceedings of the Eurocast 2007 Las Palmas February 12-15

10. Yann Dumortier, Rodrigo Benenson, Mikael Kais: *Real-time Vehicle Motion Estimation Using Texture Learning and Monocular Vision*. In Proceedings of the International Conference on Computer Vision and Graphics Varsaw (Poland) september 25-27 2006
11. Thierry Ernst, Arnaud De La Fortelle: *CAR-TO-CAR AND CAR-TO-INFRASTRUCTURE COMMUNICATION SYSTEM BASED ON NEMO AND MANET* In Proceedings of the Intelligent Transportation Systems World Congress 2006, London, UK
12. Wided Miled, Jean Christophe Pesquet, Michel Parent: *Dense Disparity Estimation From Stereo Images*. In Proceedings of the 3rd International Symposium on Image/Video Communications, Hammamet, Tunisia, may 2006
13. Plamen Petrov, Michel Parent: *Adaptive Control for Reversing a Two-Vehicle Platoon.* In Proceedings of the Symposium on Control in Transportation, Delft, Netherlands 29/08/2006
14. J. E. Naranjo, C. González, Ricardo García, Teresa de Pedro, Javier Alonso, M.A. Sotelo, D. Fernández: *AUTOPIA Architecture for Automatic Driving and Maneuvering.* In Proceedings of the IEEE Intelligent Transportation Systems Conference September 2006.
15. Wided Miled, Jean Chistophe Pesquet, Michel Parent: *Wavelet Constrained Regularization For Disparity Map Estimation*. In Proceedings of the European Signal Processing Conference 2006 Florence -Italy
16. Mehani O., Benenson R., Lemaignan S., Ernst T.: *Networking Needs and Solutions for Road Vehicles at IMARA*. IN Proceedings of the ITST 2007, 7th International Conference on Intelligent Transport Systems Telecommunications Sophia Antipolis/France 06/08/2007
17. Nicolas Simond: *Obstacle Detection from IPM and Super-Homography* In Proceedings of the IEEE IROS 2007 / International Conference on Intelligent Robots and Systems San Diego, California / USA
18. Bouraoui L., Petti S., Laouiti A., Fraichard T., Parent M.: *Cybercar cooperation for safe intersections*. In Proceedings of the 9th International IEEE Conference on Intelligent Transportation Systems - IEEE ITSC 2006 Toronto, Canada 09/17/2006
19. Benenson R., Petti S., Parent M., Fraichard T.: *Integrating Perception and Planning for Autonomous Navigation of Urban Vehicle*. In Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS) Beijing, Chine 10/09/2006
20. Sébastien Boissé, Rodrigo Benenson, Laurent Bouraoui, Michel Parent, Ljubo Vlacic: *Cybernetic Transportation Systems Design and Development: Simulation Software CyberCar*s. In Proceedings of the 2007 IEEE International Conference on Robotics and Automation - ICRA'2007 Roma, Italy 10/04/2007
21. R. Regele: *Using Ontology-based Traffic Models for more efficient Decision Making of Autonomous Vehicles,* In Proceedings of the 4th International Conference on Autonomic and Autonomous Systems, pp. 94-99, March 2008, Gosier, Guadeloupe
22. E. Onieva, V. Milanés, J Alonso, Josh. Pérez, T. de Pedro: Ajuste Genético de Controladores Difusos para Conducción Autónoma. In Proceedings of the ESTYLF-EUSFLAT 2008, Langreo, Asturias, España, Septiembre 2008
23. Benenson, R.; Fraichard, T. & Parent, M. *Achievable safety of driverless ground vehicles* In proceedings of the 10th IEEE International Conference on Control, Automation, Robotics and Vision, 2008
24. J. Alonso, E. Onieva,R. García, T. de Pedro: *An experiment to improve the safety and the flow traffic in a cross-roads by V2V Communications* To appear in Proceedings of EUROCAST 2009
25. J.Pérez [(1)], C. González, V. Milanes, E. Onieva, J.e Godoy, T. de Pedro: *Modularity, adaptability and evolution in the AUTOPIA architecture for control of autonomous vehicles.* To appear in Proceedings of the IEEE International Conference on Mechatronics, 2009
26. Dumortier, Y.; Herlin, I. & Ducrot, A. *4-D Tensor Voting Motion Segmentation for Obstacle Detection in Autonomous Guided Vehicle* In Proceedings of the 2008 Intelligent Vehicles Symposium , 2008, 379-384

27. Marzat, J.; Dumortier, Y. & Ducrot, *A.Real-time Dense and Accurate Parallel Optical Flow using CUDA* In Proceedings of the International Workshop on Computer Vision and Its Application to Image Media Processing , Tokyo January 2009

Journal Papers

28. J. E. Naranjo, C. González -IEEE member-, Ricardo García, Teresa de Pedro "Co-operative Throttle and Brake Fuzzy Control for ACC + Stop & Go Manoeuvres"
IEEE Transactions on Vehicular Technology, vol 56, n. 4, pp 1623-1630 ISSN 0018-9545. July 2007
29. M.A. Sotelo , José E. Naranjo, Ricardo García, Teresa de Pedro, Carlos González "Using Fuzzy Logic in Automated Vehicle Control"
IEEE Intelligent Systems. vol. 22, n. 1, pp 36-45. January/February, 2007
30. J. E. Naranjo, C. González, Ricardo García, Teresa de Pedro, ACC+STOP & GO MANEUVERS WITH THROTTLE AND BRAKE FUZZY CONTROL, IEEE Transactions on Intelligent Transportation Systems , Volume 7, Number 2, pp. 213-225,June 2006. SCI.
31. Benenson R., Petti S., Fraichard T., Parent M. Toward urban driverless vehicles International Journal of Vehicle Autonomous Systems vol 6 issue 1-2; Publisher Inderscience Enterprises Ltd. ISSN 1471-0226 (eISSN : 1741-5306)
32. R. García-García, M.A. Sotelo, I. Parra, *JE. Naranjo* y M. Gavilán: *3D Visual Odometry for Road Vehicles.* To appear in Journal of Intelligent Robotic Systems
33. JE. Naranjo, C. González, R. García, T. de Pedro; *Lane-Change Fuzzy Control in Autonomous Vehicles for Overtaking Manoeuvre* In IEEE ITS, vol 9, n. 3, September 2008, ISSN 1524-9050
34. V. Milanés, JE. Naranjo, C. González,. Alonsa, R. García T. de Pedro: *Sistema de Posicionamiento para Vehículos Autónomos.* In Revista Iberoamericana de Automática e Informática Industrial, vol 5, n. 4. ISSN1697-7912, octubre 2008 pp 36-41
35. V. Milanés, JE. Naranjo c. González j. Alonso, T. de Pedro: *Autonomous Vehicle based in cooperative GPS and inertial systems.* In ROBÓTICA, vol 26 pp 627-663. 2008. Cambrige University Press, doi: 1.01017/S0263574708004232
36. Pauplin, O. & de La Fortelle, A. *Application of Artificial Evolution to Obstacle Detection and Mobile Robot* Control Frontiers in Evolutionary Robotics, I-Tech Education and Publishing, Vienna, Austria, 2008, 379-392
37. Benenson, R.; Petti, S.; Fraichard, T. & Parent, M. *Towards urban driverless vehicles* International Journal on Vehicle Autonomous Systems, Interscience, 2008, 6, 4-23
38. Feng-hui Wang, Ming Yang and Ruqing Yang. *Simulation of Multi-Agent Based Cybernetic Transportation System,* In Simulation Modeling Practice and Theory, 2008, Vol.16, No.10, pp.1606-1614
39. Haigui Xu, Chunxiang Wang, Ming Yang. *Position Estimation for Intelligent vehicles Using an Unscented Kalman Filter.* In International Journal of Vehicle Autonomous Systems, 2008, Vol. 6, No. ½, pp.186-194
40. Xing Fang, Ming Yang, Xinrong Peng. *Design and Implementation of Hardware-in-the-loop Simulation System for Intelligent Vehicles*. In Journal of Huazhong University of Science and Technology (Nature Science), 2008, S1:258-261 (in Chinese)
41. Jianping Xie, Ming Yang, Hui Fang. *Laser Radar Based DynamicPerformance Evaluation of RTK-GPS*. In Journal of Huazhong University of Science and Technology (Nature Science) 2008, S1:119-121 (in Chinese)
42. Shunxi Wu, Ming Yang. *Natural Pole-Map Based Localization for Intelligent Vehicles*. In Journal of Shanghai Jiao Tong University, 2008, Vol. 42(10), pp.1745-1748 (in Chinese)

43. Hao Li, Ming Yang. *A Non-linear Inverse Perspective Transform Based Method for Camera Distortion Calibration.* In Journal of Shanghai Jiao Tong University 2008, Vol. 42(10) pp.1736-1739 (in Chinese)
44. Wenbing Xu, Yongfeng Xia, Chunxiang Wang. *Anti-interference Design for Power Management System of Driverless Electric Vehicle*. In Electrical Measurement & Instrumentation, March 2008, Vol. 45, No. 3 (in Chinese)
45. Zilong Liu, Ruqing, Ming Yang, Chunxiang Wang, Xinhua Weng, Qi Liu. *Lateral Position Tracking Optimal Control of Unmanned Vehicle*. In Journal of Shanghai Jiao Tong University, 2008, Vol. 42, No. 2, pp.257-261 (in Chinese)
46. E. Onieva V. Milanés, J. Pérez, T. de Pedro: *Unmanned Car Lateral Fuzzy Control by Genetic Algorithms.* To appear in Mathware and Soft Computing

(vi) Collaboration with other EU urban transport projects

- A close collaboration has been developed with the EU FP6 CityMobil project which resulted in a number of joint activities including theorganization of demonstrations and a showcase of CTS technology in: Eindhoven (28 March 2007); Brussels (5 May 2007); Daventry (05 October 2007); and Ljubljana (21-23 April 2008).

- The two projects jointly organised the Workshop on *Automatisation pour les Transports Urbains* was held on 19 September 2008 in La Rochelle.

- Also, through professional channels established by its Consortium members, the CyberCars-2 project established close links with several EU projects that deal with vehicle-to-vehicle communication technologies . Among them are[27] CVIS, EASIS, Intersafe-2, SAFESPOT, COMeSafety, Have-IT and GeoNet.

(vii) Exploitation of the CTS technology

- Through the sister projects CityMobil and CityNetMobil, more than 20 cities in Europe have expressed their interest in implementing CTS. In particular, following demonstrations of the cybercars in Daventry and La Rochelle, both these cities are now studying the implementation of cybercars in great detail.

- One of the Project Consortium members, Griffith University's Intelligent Control Systems Laboratory (ICSL) submitted the Business Case for "A CTS Development and Demonstration Project" to Brisbane City Council, Australia, in March 2007. The main objective of this business case was to highlight the opportunity which currently exists to implement an operational cybernetic transport system to solve one of the existing transport tasks in Brisbane. Proposed collaborative arrangements for the project were suggested. The follow-up activity produced the strategy report "Bridging the CTS Gap – from Concept to Reality" which was submitted to Brisbane City Council in March 2008, prior to Council proceeding into the "Industry

[27] Further details can be found in Deliverable D.1.1

Engagement" stage of the CTS initiative, as an update on the status of the CTS project and to outline the tasks recommended to progress the project from concept to implementation. Thereafter, the Council commissioned a production of "The Site Identification Transport Planning Report" with a goal of identifying candidate sites for the implementation of CTS. That report is being submitted to the Council. Further update on this initiative can be obtained by contacting Professor Ljubo Vlacic via email l.vlacic@griffith.edu.au or by phoning +61 7 3735 5024.

- Based on the results achieved by the CyberCars-2 project, the Spanish Government has decided to fund the following two initiatives:

  - *TRANSITO: Coordinación Local entre Vehículos e Infraestructuras,* from 2009 to 2011; Project Leader:Teresa de Pedro Lucio; Project Identifier: TRA 2008-06602-c03-01

  - *GUIADE: Guiado Automático de Vehículos de Transporte Público mediante Percepción Multimodal para Mejorar la Eficiencia*, from 2008 to 2011; Project Leader: Teresa de Pedro Lucio; Project Identifier: Mª de FOMENTO

  Details on these projects can be obtained by contacting Dr Teresa de Pedro Lucio via email tere@iai.csic.es

- The CTS technologies, developed over the course of this project, will play an important role in the EU FP7's most recent project CATS, in particular, in the design and implementation of the platooning techniques for a new vehicle concept named 'Cristal'.

- Over the course of the CyberCars-2 project, Veolia Transport, France, has studied the concept of deploying the V2V cooperation technology into fleets of their Bus Rapid Transit (BRT) vehicles, currently operational in the city of Rouen. These buses, if equipped with longitudinal control, could contribute to the improved road safety and comfort, shortened time schedules and increased fuel efficiency. The V2V communication concept, as designed and developed by this project, could play a key role in achieving that goal, providing that public transport vehicles with close distances in between are allowed on the dedicated lanes. A project proposal, based on this concept, is now being prepared.

3 CONCLUDING REMARKS

The CyberCars-2 predecessors, FP5 project CyberCars and FP5 project CyberMove, dealt with the development and evaluation of the Cybernetic Transport System (CTS). This system comprises a number of individual driverless vehicles that have the capability to travel on existing road infrastructure, without the need for dedicated guide ways. However, prototype vehicles developed in these projects were designed for low-demand road traffic environments and were not requested to communicate nor co-operate with each other. The challenge for the Cybercars-2 project was to empower these vehicles with the ability to co-operate through vehicle-to-vehicle and vehicle-to-infrastructure communication links in order for the CTS to enable higher traffic flows and improved network efficiency. Another challenge of the project was to evaluate how traditional vehicles, that are normally equipped with co-operative advanced driver aids' systems, could share the same infrastructure with cybercars and subsequently open the way to the large scale introduction of fully autonomous driving in various environments.

Numerous salient points have been achieved by the CyberCars-2 project including:

- the design, development, prototyping and on-road testing of the Co-operative Cybernetic Transport System Communication Architecture;
- the design, development, prototyping and on-road testing of the Co-operative CyberCars'driving algorithms;
- the design, development, prototyping and on-road testing of Dual-Mode vehicles;
- the design, development, prototyping and on-road testing of solutions for the Co-operative Road Traffic Management and Control Centre (including communication technologies);
- recommendation of procedures for on-road testing of the operational performance of Co-operative Cybernetic Transport Systems; and
- wide dissemination of the developed technology across Europe and internationally.

This project has paved the way for Co-operative Cybernetic Transport Systems to share the future road traffic environment with all traffic participants in order to improve road safety, comfort and driving pleasure, traffic efficiency and fuel economy.

Where to from now?

So far, under the auspices of FP5 and FP6 funding umbrellas, numerous initiatives[28] were funded and supported with the following goals:

- making our roads and transport systems safer, more efficient and environmentally friendly;
- increasing people's mobility
- achieving equality in accessing the transport needs.

The majority of these initiatives dealt with conventional vehicles (those under control of human drivers). By way of advancing information, communication, sensor, electronic and other vehicle technologies, these initiatives brought solutions toward improved road safety[29] and increased driving comfort and pleasure[30]. Their vision is that a further increase of mobility and controllability can be achieved through a driverless vehicle concept and co-operative driving in particular. The 2005 ADASE Road Map envisaged that 2012 will herald the first on-road application of driverless vehicles.

---

[28] Among them are: ADASE I & II, Carsense, Chauffeur, Utopia, In-Response, Direct, CyberCars, CyberMove, CarTalk 2000, NetMobil, CyberCars-2, PReVENT, GST, COM2REACT, CyberCars3, eSafetySupport, COMeSafety, SAFESPOT, COOPERS, CVIS, the i2010 Initiative and their flagship projects, the eSafety Forum Communications Working Group, the Car2Car Communication Consortium (C2C-CC) and other national initiatives in EU member countries, Japan and USA.

[29] Such as: collision avoidance, lane departure warning, pedestrian detection, road sign recognition, rear-end collision avoidance, pre-crash sensing, etc

[30] Such as: advanced cruise control, stop & go, adaptive cruise control, reverse parallel parking, driver information system, etc

The other, much smaller group of FP5 & FP6 funded projects, led by the predecessor CyberCars project, conducted their research towards the same direction, whilst exploring driverless vehicle concepts from inception. They coined the concept of a so-called "Cybernetic Transport System" (CTS) which is based on driverless road vehicles (cybercars). The CTS concept has already received recognition worldwide. In their report on "Mobility in 2030" published in 2004, the World Business Council for Sustainable Mobility attributed CTS-like road transport systems with the great potential towards meeting sustainable mobility; and envisaged that 2030 will witness the manufacturing stage of driverless vehicles.

Indeed, the CyberCars-2 project, being carried as an extension of its predecessor has, through numerous on-road testing and public demonstrations of the developed co-operative technologies, offered proof that a *Co-operative* Cybernetic Transport System concept is a viable way forward in meeting sustainable mobility.

What can be seen at this stage is not just a great synergy between the co-operative driverless vehicle concept and an advanced driver assistance concept, but also a significant merger.

We therefore propose to the European Commission to call for new research project submissions to enable that merger to happen, to its full scope and with its full intensity.

This may/will lead to deployment of a *new concept of urban mobility, enabling driverless and ADAS-equipped-conventional vehicles to co-operate with each other and thus, share road traffic environments.*

It is going to be yet another big challenge to the society-at-large, as it is to deal not only with further technology enhancement, but also with a change of our driving habits and culture.

The submissions should be aimed at:

- enhancing *reliability* and *robustness* of the currently developed enabling technologies for both conventional and driverless vehicles;
- enhancing *reliability* and *robustness* of the currently developed road infrastructure technologies;
- developing solutions to enable efficient and reliable *integration* of the existing technologies at a single vehicle level, road infrastructure level and the transport system at large;
- developing new technologies towards *optimizing* vehicle performance (both driverless vehicles and ADAS-equipped conventional vehicles) and also operational performance of the entire transport system; and
- preparing the society-at-large to accept and accommodate deployment of a *new concept of urban mobility* including deployment of the *new technology certification procedures* as well as a *change in the current human mobility behaviour and driving culture.*