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Model Based Systems in Automotive Domains: Applications and Trends

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1. Introduction

1.1. Abstract

This report is the first deliverable produced by the Monet Automotive task group and is made up of two parts:

- A brief introduction to Model Based Systems (and specifically model-based diagnosis) in the automotive domain, with a short compendium of applications developed in the last few years. The compendium will be extended during the lifetime of the task group, with the aim of including the most important systems developed in the area. The current version includes some of the systems which are well documented in the literature.
- A first attempt to single out directions for future research and development in the field. This has been compiled with the help of expert representatives from many companies. The task group circulated a questionnaire listing some directions for the future (singled out at the task group kick-off meeting) but leaving experts the possibility of indicating other issues they considered important. The results of this process have been analyzed by the task group members, producing a second questionnaire which listed the eight issues that the experts proposed as the most relevant ones. The second questionnaire asked for a ranking of the issues. Finally, the task group produced this first attempt to indicate future directions for research and applications, taking into account the results from the questionnaires. Some of the questionnaires (those of the experts who agreed to disclose their answers) are added as an appendix to this document. Others have been used internally during the task group discussion that produced this document but cannot be distributed.

1.2. Purpose of this Document

Model-based Diagnosis (MBD in the following) is an approach to diagnosis that was proposed in the early 80's to overcome limitations of the traditional expert systems approach, see [Hamscher 92] for a collection of papers and [Davis 88] for an introduction.

The philosophy of the model-based approach can be sketched as follows. Diagnosis should be based on an objective model of the device (system) to be diagnosed. More specifically, different types of models can be considered: structural (concerning the physical or logical structure of a device), functional (describing the functions of a device), behavioural (describing how a device works, i.e., how its functions are achieved), teleological (describing the purposes of the use of a device), or a combination of these factors.

Models should be reusable, in two ways. On the one hand, the same model of a device should be used for different problem solving tasks (such as diagnosis, simulation, reconfiguration, etc.). On the other hand, models should be compositional: the model of a device should be usable in all the cases where the device is used as a component of a larger system.

Since the 80's a lot of work has been carried out and

- several approaches to modelling have been proposed and investigated;
- definitions of diagnosis and formal accounts of the task have been presented;
- algorithms for solving the problem and overcoming its complexity have been designed;
- applications have been developed.

MBD attracted researchers from many different fields of Artificial Intelligence (AI) (and engineering) and played both the role of test bed for several approaches to Knowledge Reasoning (KR) and reasoning and the role of generator of new problems and approaches.

From an industrial point of view, diagnosis (or, more generally, guaranteeing the availability of systems) is a primary need. Indeed, several diagnostic systems have been implemented since the mid 70's and some of them were success stories for AI. More recently, however, some links became stronger and this led, at least in some areas, to important projects and applications.

In this task group we focus on the automotive domain which is currently one of the most interesting areas of application for these technologies. There are several reasons why diagnosis (and MBD in particular) have become more and more important in this field.

First of all, the increasing complexity of the cars (especially from the electronic point of view) called for more sophisticated diagnostic techniques (both on-board the car and in the workshop).

Second, legislation required the presence of diagnostic systems in the Electronic Control Unit (ECU) of the car. Third, competition between manufactures led them to investigate new features for attracting customers and for augmenting their satisfaction. Thus, the interest of car manufacturers is growing and they are looking at model-based reasoning as one way of managing the increasing complexity of cars and the high maintenance costs and unnecessary downtime deriving from such a complexity.

The application to the automotive field is very promising from a commercial point of view, but also challenging from the technical point of view, for several reasons.

First of all, the systems to be diagnosed are complex, but many of them can be managed with state-of-the-art technologies. Second, different physical domains are involved, ranging from mechanical, to hydraulic, electric and electronic systems. Thus the field is an ideal one for applying and experimenting modelling and diagnostic techniques. Third, most of the critical devices to be diagnosed (especially on-board) are dynamic feedback system with an active control (performed in most of the cases by the software running on the ECU's); diagnosing these system is a very challenging problem and stimulated a lot of work from the research perspective. The application on-board the car imposed several new problems and constraints, mainly due to the resources that are available on-board and to the real-time constraints.

In this report we briefly discuss some of the application systems which have recently been developed and which demonstrate the very promising contribution that MBS can provide in the automotive domain. We then provide a first view of the next steps that are needed in the field. This second part has been compiled by distributing a questionnaire to experts in companies of the automotive sector and then compiling an analysis of the answers.

The work is the result of a discussion involving expert representative from several automotive manufactures and suppliers (e.g.: Actia, Audi, BMW, Centro Ricerche Fiat, Daimler Chrysler, Siemens, Magneti Marelli, Bosch) as well as small companies (such as Adersa, FirstEarth, Occ’m and Rose) and research institutions and Universities active in the field.

2. The Situation: Some Examples of Applications and Projects

2.1. IDEA (Integrated Diagnostic Expert and Assistance)

IDEA is a diagnostic system developed by Centro Ricerche Fiat and currently installed in some 1600 Fiat and Alfa Romeo workshops. It can diagnose some 70 different types of electronic systems and a team of engineers at Fiat develop models for new maintenance of the knowledge bases following the evolutions of the systems.

IDEA can be connected to the testers in the workshop and guides the technicians in the activity of performing diagnosis. This task is accomplished by interpreting the signals using models, tracing back the signals to the failures that might have generated them.

The library of models includes most of the electronic controlled systems used in current cars, such as the ABS, traction control, suspensions control, engine control.

2.2. VMBD

The VMBD (Vehicle Model Based Diagnosis) project (funded by the European Union) involved a number of partners including car manufactures (Daimler-Benz, Fiat, Volvo), suppliers (Bosch, Dassault Electronique, GenRad, Magneti Marelli and Occ'm) and Universities (Aberystwyth, Paris XIII and Turin).The goal of the project was to make a step forward in the use of model-based diagnosis both on-board the car and in the workshop.

The project was successful from several points of view. As an immediate effect, it led to the development of three prototype applications, based on state of the art techniques, and demonstrated on real cars: the Common Rail fuel delivery system (on a Lancia car), the DTI fuel delivery system and the automatic transmission (on a Volvo car). The models adopted are mostly qualitative ones (some simple quantitative models had to be used for measurement interpretation and for fault detection).

For the two fuel delivery systems we adopted models based on qualitative deviations. The components are modeled in terms of qualitative differential equations that include appropriate parameters whose values allow for the representation of fault modes of the components. The equations for deviations (in which the variables represent deviations of quantities from expected values) are obtained via algebraic transformations. This form of modeling proved to be very useful since in most cases it is relevant to reason in terms of variables deviating from their expected values, rather than in term of absolute values.

The off-board system adopted standard MBD; the on-board one experimented with the direct use of MBD (for the DTI using Raz'r) and a precompilation approach: in the Common Rail, diagnostic trees are synthesized starting from the solutions to a set of simulated cases computed using the model-based approach. This allowed the project to produce diagnostic systems that can be easily implemented on current ECU's.

The applications developed for the Volvo car (using MDS and the simulation tool ASIM, both developed by DaimlerChrysler research) demonstrated the applicability of MBD for the troubleshooting of automatic transmissions. The applications covered typical customer complaints, ranging from 'soft' problems with shift-quality to diagnosis based on failure code events, caused for example by component faults in the hydraulic (such as valve stuck close) or mechanical (such as slipping clutch) subsystem.

Probably the most important (if not immediate) effect of the project is that it contributed to publicising MBD; manufactures and suppliers had the opportunity of having a close look at the technology, using it on their systems and viewing the advantages (and problems) that it can lead to; as a result, some of them decided to invest in MBD.

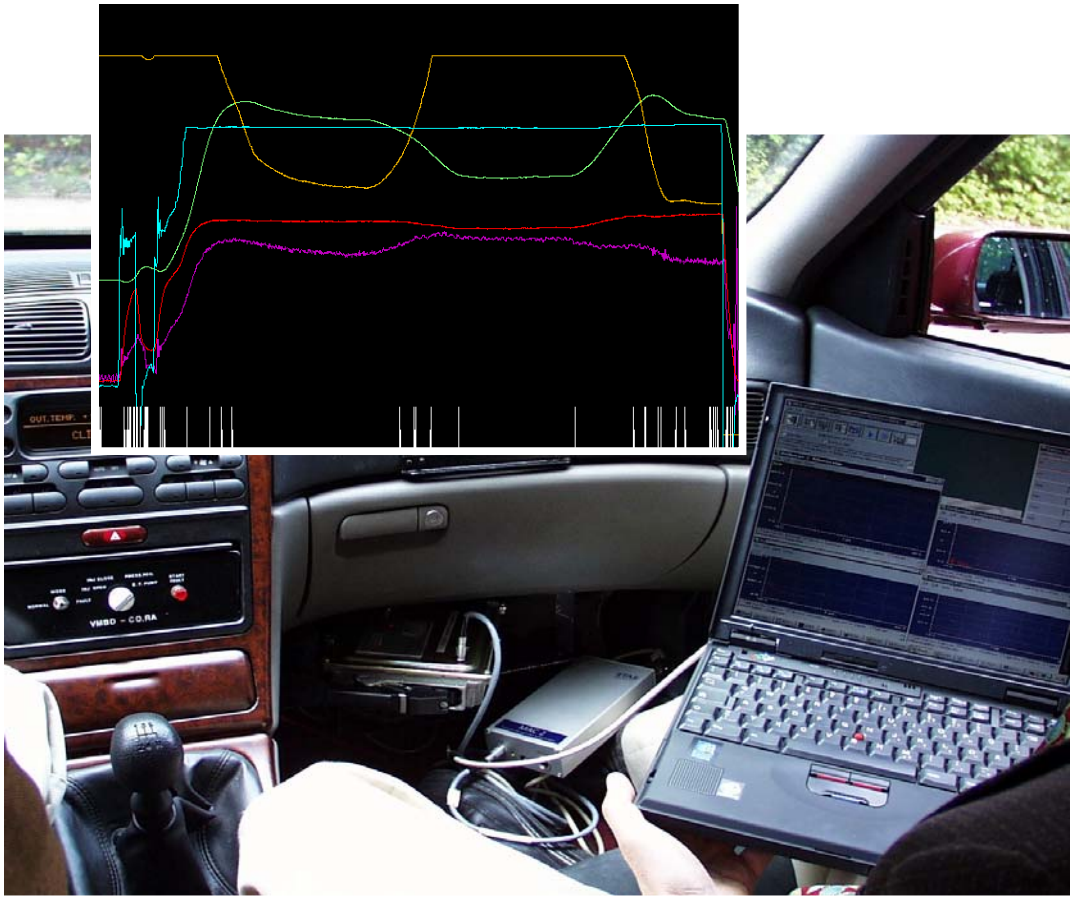

Figure 1 – The Lancia car with on-board diagnostic system

Figure 2 – The Volvo car equipped with the diagnostic engine

2.3. FMEA Generation: AUTOSTEVE

The AutoSteve tool provides automated support to engineers that develop electrical systems. It has grown out of long-term research into the use of Model Based Reasoning (MBR) to address the needs of Safety and Reliability analysis in the Automotive industry. It is now finding further application within the Aerospace and Defence industries.

AutoSteve simulates the activity of a circuit and produces a textual Failure Mode and Effects Analysis (FMEA) report similar to that produced by an engineer. Traditional approaches to simulation have required detailed numerical models. The innovation in AutoSteve is to make use of qualitative models of components; these are both easier to build and can be simulated much earlier in the design lifecycle. A key benefit of this approach is that FMEA reports can be produced earlier than traditional approaches, providing time to act on the findings and substantial cost savings.

A component model is required for each class of component in the system. The model describes the structure and behaviour of a component under both normal operation and failure modes.

The structure is defined as a network of resistive nodes, where each node can take one value of Zero, Load or Infinite. These values are used during simulation to determine if current can flow through various sections in the component.

The behaviour describes how the resistance values change as a result of the changing inputs to the component. There are two ways to provide the description:

- Expressions – a set of if-then-else style expressions that describe the state the resistances under certain conditions.
- State Charts – more complex behaviours ca be modelled as state charts, which provide a powerful graphical modelling language to represent behaviour.

In addition to describing the normal operation of the component, it is also necessary to define the different component failure modes to be explored in the FMEA. For each failure mode, the user describes the way in which the failure affects the component. This may be a structural change, a behavioural change or a combination of the two.

The University of Wales, Aberystwyth, in collaboration with the Ford Motor Company and Jaguar Cars, researched techniques to automate the analysis of electrical designs. The original tool, FLAME, established the approach of using MBR techniques to automate key stages of FMEA for electrical systems. FLAME has now been redeveloped into the commercial AutoSteve tool which is in use at European and US OEMs and Tier-1 suppliers within the automotive industry.

Based on the FMEA and simulation work, the AutoSteve tool also performs Sneak Circuit Analysis (SCA). This is an important technique that considers the situations where an unexpected combination of inputs to a system can cause a function to occur unexpectedly. The analysis uses the same underlying models that are required for FMEA. The SCA functionality is available within AutoSteve and as a separate tool called SneakExplorer.

The modelling technologies and approach to performing design analysis are producing important savings for commercial companies. In 2001, the Ford Motor Company formally recognized the benefits of this approach. Ford made a European Technical Achievement Award in recognition of the savings in development time and costs generated from introducing automated FMEA and Sneak Circuit Analysis to the company.

2.4. RAZ’R

Raz’r, by OCC’m Gmbh (www.occm.de) is a set of software components for building model-based diagnostic systems. It includes modules for model creation and maintenance, prediction (simulation), truth maintenance, diagnosis and generation of tests (probes).

It has been used for building some application in the automotive sector, starting from the VMBD project (where it has been used in the development of the application for the Volvo car), to the IDD project (where some Raz’r components are being connected to design tools such as Matlab/Simulink). Moreover, it has been used in other applications built by Occ’m for companies in the Automotive Sector.

2.5. MDS

MDS is a system for building model-based applications, continuously developed since 1994 by DaimlerChrysler research in Berlin. MDS has been applied in the development of several diagnostic applications in automotive and aerospace domains, including electric, electronic, mechanical and hydraulic systems. MDS implements the ideas of consistency-based diagnosis, as presented for example in [Readings in MBD, 92] and extends and refines these concepts in order to improve applicability (e.g. to represent time using finite state machines), as described in [Tatar, 96, 97]. Besides a graphical environment for developing and debugging system models, MDS is currently offering four services to the engineer.

1. **Interactive diagnosis and test proposal.** Starting from numerical or qualitative measurements or observations, MDS detects non-nominal behaviour (if any), and guides

the user through a sequence of further measurements and useful control actions (such as opening or closing plugs), until the faulty component is localized and its fault mode is identified, or no more useful measurements are found. When proposing a measurement or control action, MDS aims to minimize the costs associated with the actions, and to maximize the expected information gain of the measurement. A simplified information entropy measure is used to assess the expected information gain. MDS keeps track of possible side-effects of control actions during diagnosis, e.g. if we switch on the power of an electrical system that contains a short, a fuse may break. Previously non-faulty components may transition into a fault mode. MDS keeps track of these dynamically introduced cascading faults.

2. **Decision tree generation**. Starting from a given set of relevant faults, an initial situation (e.g., which plugs or valves are open), and an optional sequence of previous control actions and measurements, MDS derives a decision tree that aims to discriminate, at best, between the given faults using the available measurements. The resulting decision tree is a compiled diagnostic solution. Such decision trees are useful for analyzing the diagnosability / testability during the system design, for developing on-/off-board diagnostic software, or for developing test procedures for end-of-line testing.

3. **Sensor placement**. Starting from a set of faults, an initial situation, a set of possible sensors (model variables) MDS computes the “minimal” set of sensors that can be used for the detection and identification of the given faults. MDS can explain how to use the sensors for diagnosis by presenting a decision tree that uses only the proposed sensors for diagnosing the system. As above, MDS aims to minimize sensor costs, and to maximize the information gain achieved by the sensors.

4. **Support for safety analysis**. Some currently available services allow the visualizing and comparing of faulty and normal simulation results, to generate some reports and explanations. These services will be further extended in future in order to automate the FMEA (failure-mode and effect analysis) and the FTA (fault tree analysis) of a system.

For a more detailed description of MDS, see [Mauss et al].

2.6. IDD

The European Fifth Framework project “Integrated Design Process for onboard Diagnosis” (IDD) pursues the goal of formalising and standardising the diagnostic design process, and to enable the introduction of diagnosis early in the development chain. This methodological goal has to be combined with another important objective: *giving to the designers a set of tools that can help them in evaluating and understanding the effects of each choice on the system being designed.* Model-based diagnosis (and, more generally, model-based systems) is the fundamental methodology that supports the objectives of the project.

IDD was started February 2000 with a duration of three years and involves both industrial and academic partners:

- Fiat CRF, Torino
- Magneti-Marelli SpA,
- PSA Peugeot Citroen, Paris
- Renault, Paris
- DaimlerChrysler AG, Stuttgart
- OCC’M Software GmbH, München
- Universita di Torino
- Université de Paris Nord, XIII
- Technische Universität München

The project performed an analysis of the current design process (using as test-benches some departments of our application partners), paying particular attention to the role of diagnosis-related activities (such as diagnosability analysis, Fault Modes Effect Analysis (FMEA) generation, and generation of onboard diagnostic software). Then it identified some weaknesses and analysed the consequences that such weaknesses can have on the overall design process (e.g., time delay due to re-design of some parts of the system, poor diagnosability, etc.). In particular, three major weaknesses emerged from the analysis:

- FMEA and diagnostic development are sequential activities and they are mainly performed using experience and without model-based supporting tools.

- Usually the development of FMEA and diagnostics is carried out in parallel with control design; however the two activities do not interact and if additional requirements or constraints emerge from one of the two tasks they are taken into account in the other one only when (and if!) a new design cycle is started while they could be dealt with immediately due to parallelism.

- Since FMEA and diagnostics development is carried out after component design/layout, diagnostic-related issues have an impact on system design only if the design is re-started due to some problem in the definition of control strategies. This does not often happen, and usually diagnostic issues alone are not enough for choosing this (expensive) option.

Next, the project defined a new design process in which the activities related to diagnosis are integrated into the design loops. The actual implementation of this new process requires new software environments, in which different tools are made available to the designer who can use them while designing a new system to perform different activities such as: diagnosability analysis (i.e., checking if the system is diagnosable, given the current set of sensors or asking the system which additional sensor would allow the discrimination of a given set of faults), "what-if" analysis, comparing different design choices (and the consequences of these choices from the diagnostic point of view), generation of the FMEA (this task can be partly supported by model-based systems), and generation of onboard diagnostic software. In other words, these tools can allow the designer to make different types of analysis on the system being designed and then to take more informed decisions.

The project is developing a prototype toolkit in which these activities can be carried out in an interleaved way. In such a way the toolkit can support a new design process in which all issues regarding control and diagnosis are taken into account at the same time. The project is also studying how the qualitative models commonly used in diagnostic activities can be derived (abstracted) automatically from the quantitative models used for control design and simulation (Usually models developed using Matlab/Simulink).

Same case studies (guiding applications) are being used for demonstrating the approach.

3. Extending the Scope of Applications

Model-based reasoning proved to be a very powerful technology for automotive applications, for tasks such as diagnosis, design, simulation, etc. This has been demonstrated in some recent projects mentioned in the previous sections.

In particular, the general idea is that models, and specifically, qualitative models can support several activities which are critical in the life cycle of vehicles: from analysis of the original design through on-board monitoring, diagnosis and recovery, to diagnosis and repair in the workshop. These previous experiences and projects addressed with success some problems, showing that they can provide interesting advantages but in some sense addressed only some isolated problems and parts of the process.

However, the view can be enlarged, addressing in a more thorough way a number of tasks and processes that are critical to the development of more available, reliable and safer vehicles and that are critical in the competitiveness of European car manufactures and suppliers of automotive technologies.

In particular there is a need for the development of a set of tools, centred around models, that can support various phases of the life cycle of a vehicle (from its initial conception to the market and the customers). Moreover, the projects aim at creating a framework for the integration (and standardization) of these tools.

The tools should provide designers, engineers and technicians with a set of facilities which can support the improvement of the vehicle safety, reliability and availability. Moving from the experience of previous projects (tools for diagnosis and for integrating diagnosis in the design process – FMEA generation, diagnosability analysis), the projects aim at filling in gaps in the current life cycle, providing support for activities that are currently not fully or completely supported (or even not supported at all).

The need for these tools stems from the increasing complexity of vehicles (especially as regards electronically controlled systems). In parallel with this increasing complexity also the expectations of customers have increased, forcing manufactures and suppliers to develop new products frequently (the life of car models has reduced significantly in the last decades), and each new product must be more technological and complex, but also more reliable and safer than the previous product.

These needs require the availability of tools for speeding up the design and development of a new vehicle, guaranteeing at the same time that the quality of the vehicle is very high from the very beginning (the very first car which is sold must already be “perfect”, without teething problems).

The adoption of models and the possibility of studying and simulating the new components or subsystems of a new vehicle in a virtual environment are therefore very critical. Previous experience showed that different types of models are needed at different points in this process, from mathematical models (commonly used by engineers) to qualitative models. However, currently only a few phases are supported by model-based tools. Thus, new tools need to be developed for supporting critical tasks (currently unsupported) and for creating a framework that supports the life-cycle as a whole.

In the project(s) we propose to concentrate on some tasks that are considered the most critical and urgent ones by experts in automotive and supplier companies; in particular:

1) Tools for Knowledge management of technical knowledge via models. Managing the know how of companies is a critical problems, especially as regards know how on technology. Models can provide an interesting opportunity, especially qualitative ones that can provide a very clear and understandable knowledge content and that could allow for the design of tools for knowledge maintenance and retrieval (at a semantic level). The tools should support the construction of a Model warehouse and Model maintenance, selection and use across the work process (models as interfaces between processes and tools), the re-use of models across multiple projects; integrated environments for modelling. This can lead to the definition of international standards for model representation and interchange between companies.

Moreover, the standards and the model warehouse should support the use of models for training and tutoring engineers and technical people.

2) On-board systems; integration of control and diagnosis; software solutions for the deployment of model-based diagnosis on-board. Model-based approaches to meet on-board diagnostic requirements and to meet requirements for improving safety and for controlling conditions that can lead to abnormal emissions. The possibility of having model-based tools for these tasks would allow the rapid development of these software systems, cutting the time and cost currently spent on these activities.

3) Model-based testing. Testing a new component or sub-system (or even vehicle) is a critical and time consuming activity. Models can provide a means to support and speed this activity in several ways. First of all testing can be done on the models first. Second, tools based on models can provide suggestions on how to test a system, analyzing critical aspects for on-board systems. This is particularly important for on-board software, for which the tools should provide support for formal specification and verification and testing.

4) Preventive diagnosis. Preventing faults is a major goal of car manufacturers. This problem may arise in several contexts. During the design, support should be provided for analyzing the reliability and fault tolerance of a system and to generate guidelines for the maintenance of each subsystem (given models of the components characteristics as regards their behaviour in time, wearing, etc.). Moreover, the tools should support the introduction of indicators for preventative maintenance.
After market, the tools could be used in workshops (possibly with a remote connection to the vehicle) to analyse the vehicle state. Again, the use of models, in conjunction with statistical analysis should provide support for preventive maintenance and anticipation of faulty and possibly dangerous situations

These tools could be the topic of integrated projects with a common coordination, which imposes common standards, languages and also common software platforms for the integration of the tools.

The development of the methodolgies and tools can have important benefits for the competiveness of European Automotive Companies (car manufatures and suppliers), impacting on at least the following aspects:

- More reliable and safer vehicles, thus more customer satisfaction thus better position on the global market
- Reduced time and cost during the whole life cycle, the tools developed in the project, supporting several activities in the life cycle can lead to shortest time for developing new products. This means shortest time to market better products.
- Improved reliability and safety can have a significant impact on environmental issue, with the ability to control emissions and prevent problems with emissions.
- Better management of technical knowledge and know-how; improved conditions for the sharing of knowledge and training/tutoring of young technical staff and engineers.
- Standardization of interfaces between tasks and of modelling primitives.

The recent projects and systems showed that the technology and the know-how in European Companies and Research Institutions is sufficiently mature to achieve this goals. Actually, this is an area of excellence for European companies and the aim of the projects is to maintain and improve this excellence level, which can have a positive impact of the competitiveness of European companies.

The companies which participated in this exercise manifested a potential interest to participate in the proposed projects (similarly, other companies, which we cannot list in this document, supported the proposal). Similarly, several research centres and University, with many years of experience in model-based reasoning and in automotive applications declared their interest in participating in the project(s) in this proposal.

Universities and research centres could provide methodological support as well as support in the design of the tools. IT Companies and suppliers could provide know how for the design and development of prototype tools. Automotive manufactures could be the final users, providing requirements, specifications and concrete case studies to experiment and demonstrate the tools.

Clearly, the final two groups of partners are those that could benefit the most from the exploitation of the results of the project(s)

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5. Document History

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