# MONET2

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# Automotive Technological Roadmap (Version 1.0)

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# 1 Introduction

## *1.1 Purpose of this Document*

This document presents a Technological Roadmap for the application of model-based systems and qualitative reasoning techniques in the automotive industry. The techniques and trends discussed are relevant to all powered land vehicles and to a greater extent, to other forms of transport such as aeroplanes and ships, especially where they share the characteristics of increasing complexity and reduced development time, which is discussed later in the document.

There are trends in vehicle development that are not included in this document, such as better battery technology. Changes in technology over the next ten years have been included or excluded in this document on the grounds of whether model-based reasoning can assist in the aim of supporting the development of such technologies. Where that is not the case, the technology is not included in this roadmap, however significant it might be to the automotive community in general.

## *1.2 Scope*

The structure of this document is:

- Section 2 contains a brief introduction to model-based reasoning and a snapshot of some of the model-based applications currently deployed in the automotive industry.
- Section 3 contains a graphical representation of a roadmap for model-based technology in the automotive industry. It is explained in more detail in the following sections.
- Section 4 considers the relevant drivers of the technology over the next ten years. It discusses the demands on automotive companies from customers, and the ways in which automotive companies themselves expect to respond to those demands.
- Section 5 considers the ways in which model-based reasoning might assist automotive companies in reaching their goals and the research and development that will be needed in order for that to occur.
- Section 6 summarises the document.

# 2 State of the Art in Model-Based Reasoning

The automotive industry was the first to promote the development of applications of model-based systems technology on a broad scale and as a result, has produced some of the most advanced prototypes and products. This section contains a brief introduction to model-based reasoning and a snapshot of some of the model-based applications currently deployed in the automotive industry. For a full and comprehensive view of the State of the Art please see MONET Automotive Task Group Deliverable A1 ‘Model Based Systems in Automotive Domains’, available on requests from the MONET Office or online at: http://monet.aber.ac.uk:8080/monet/docs/tg_minutes_and_reports/automotive/a1_report.pdf

## *2.1 Model-Based Developments in the Automotive Industry*

Cautiously stated, the majority of car manufacturers and suppliers are at least exploring the potential of model-based systems, either through purchasing and evaluating commercially available tools, or by building prototypical solutions and carrying out feasibility studies. A number of manufacturers and suppliers are already deploying solutions in industrial work processes and on vehicles.

The EC-funded Vehicle Model-based Diagnosis (VMBD) and Integrated Design Process for On-Board Diagnosis (IDD) projects brought together several European manufacturers (FIAT, DaimlerChrysler, Renault, PSA Peugeot-Citroen, Volvo), suppliers (Bosch, Magneti-Marelli), and OCC'M Software as a supplier of AI technology. BMW and Volkswagen are actively working to move diagnosis technology on-board. The Mercedes S has a diagnostic control unit whose database is generated with the support of models. Truck companies also face diagnostic challenges, in particular under the requirements of emission-related on-board diagnosis (OBD 93). DAF runs a project (together with Siemens and Click Software) on supporting after-sales diagnosis by models generated from Failure Mode and Effects Analysis (FMEA). Scania is working towards a model-based diagnosis running on a Power PC on the trucks. There is a demand for commercial AI software in this area: R.O.S.E., OCC'M Software and FirstEarth Limited provide tools for modelling and building model-based systems. Ford recommends FirstEarth's AutoSteve software as part of its C3P suite of tools for designing vehicles.

This list of European automotive manufacturers and suppliers interested in model-based technology illustrates that this technology is relevant to solving some of the challenges presently facing the automotive industry, as discussed in Section 3. Firstly, we should discuss the technology in greater detail.

## *2.2 What is Model-Based Reasoning?*

Model-based systems are based on a separation of the problem solving algorithm from the model of the domain and on the compositionality of this model. Once a library of appropriate component models has been established, only a structural description of the respective device (e.g. obtained from design data) is required to automatically generate a system model and based on it, a problem solving system dedicated to this device. Figure 1 illustrates this idea for the production of a model-based diagnostic system.

Since vehicles are assembled from standard components and the behaviour (and misbehaviour in the case of a fault) emerges from the behaviour of these components, establishing a model library is feasible and entails collecting models of (correct and faulty) behaviour of such standard components. This is important: this kind of model-based reasoning cannot be performed if the overall behaviour of the system cannot be composed from the behaviour of the components and the way in which they are linked.

Model-based systems enable the support of common engineering analysis tasks at early design stages because they are based on first principles and do not require experiential or empirical data from a physical prototype. This is in contrast to rule-based, case-based, or machine learning approaches, where experiential knowledge is needed. They provide well-founded algorithms for automated problem solving which provide the guarantees for coverage and completeness of solutions required for safety critical applications.

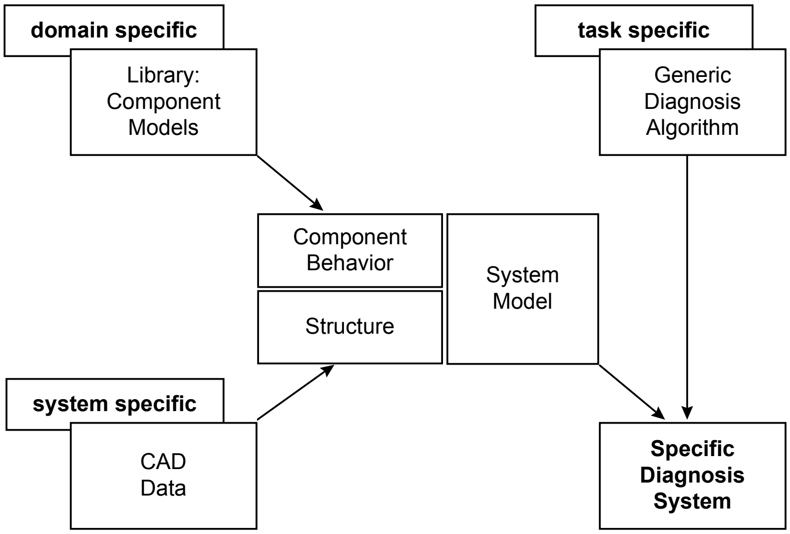


**Figure 1: Automated Generation of Model-based Diagnostic Systems**

Engineering analysis tasks addressed by this technology include:

- Design for diagnosability: has the system and in particular, the placement of sensors, been designed in a way that allows the detection, localization and discrimination of faults?
- Failure modes and effects analysis (FMEA): what is the impact of each possible failure of a system component?
- Sneak circuit analysis: are there states of a designed circuit that lead to an unintended (de)activation of certain functions?
- Creation of on-board diagnostics: design and implement algorithms that generate diagnostic hypotheses based on the sensor values available to the control units on the vehicle.
- Workshop diagnosis: create diagnostics that guide and exploit tests performed on the vehicle in a workshop.

Models and a model library capture a considerable portion of the knowledge and information underlying various work processes during the life cycle, such as the ones listed above. Hence, model-based systems provide a means for explicitly storing corporate technological knowledge and sharing and communicating it between different work processes (‘horizontal integration’). This knowledge becomes accessible independently of time, location and people.

The reusable nature of the knowledge and the guarantees of coverage of the algorithms, promise reductions in design costs, a shortened product development life cycle and reductions in time-to-market for new products.

Engineers generally work with numerical models, but in this type of work the capability to exploit qualitative models (Forbus 88) turns out to be crucial for several fundamental reasons:

- In particular in early design phases, only a partial specification of components and parameters is available, which prevents the use of numerical techniques.

- Many tasks, such as FMEA or the generation of diagnostic manuals, aim at statements about classes of (fault) behaviour and of symptoms rather than specific instances. For example, the effect of a leakage of any size has to be predicted, rather than just a leakage of a specified size.
- Faults are defined as qualitative deviations from normal functioning (e.g. flow through pipe is reduced), rather than arbitrary discrepancies with respect to precise values (e.g. flow is 4.12 gallons/minute, but should be 6.73 gallons/minute).
- Precise values often do not exist because the vehicle is operated in a noisy and widely unmeasurable environment, and only incomplete data is available (e.g. about properties of the road surface).
- Qualitative models provide an appropriate level of abstraction for modelling complex systems and processes where standard mathematical models do not exist or are not tractable (consider the combustion process or communication among the control units).
- They enable an intuitive representation and presentation of knowledge and information to the users.
- Where more detailed models are needed in order to produce precise answers, the qualitative models provide a way of focusing the numerical modelling on the answers that are needed.

The qualities outlined above mean that qualitative models often provide appropriate answers for a wide range of systems with incomplete knowledge. This enables automation of reasoning about the complex systems found in modern vehicles, early identification of safety and reliability issues, and generation of good diagnostics. This can be done for many different vehicle variants with little extra effort.

In the following sections, we will illustrate the features and benefits of model-based systems and qualitative modelling by two application systems that were developed in the automotive industries to support on-board diagnosis and design analysis. These example systems are representative of a range of such model-based systems in the automotive industry.

## *2.3 Examples of Deployed Applications*

### 2.3.1 Diagnosis - the VMBD Project

Modern passenger vehicles contain a growing number of processors. This could be in excess of one hundred for a high-end limousine. This computational power, originally used mainly to control the normal operation of various subsystems, such as the engine, the anti-lock braking system, airbags, beams and air conditioning, is more often now also used to run software that deals with faults and abnormal behaviour. Such software has three aims:

- Detection of faults. This is, for instance, required for emission-related problems by US regulations [OBD 93].
- Triggering so-called recovery actions, i.e. a different control scheme for a subsystem that allows for its continued, though limited operation under fault conditions, for instance by limiting certain performance parameters.
- Providing information for subsequent fault localization in the workshop. This usually happens by storing a fault code which represents a symptom (e.g. ‘open circuit’) rather than a particular component fault and hence, is only a starting point for further testing.

The pressure on car manufacturers to improve on-board diagnostics is high. It is needed to achieve compliance with legal restrictions, to avoid overly restrictive recovery actions, to avoid customer dissatisfaction and to reduce after-sales costs by providing a narrower focus for maintenance in the workshop. In particular the latter aspect is crucial for the world-wide operation of car companies, since it is close to impossible to guarantee the requested high and up-to-date skills and information level of maintenance staff all over the world.

Model-based systems provide a new methodology and new software solutions that are needed to address the requirements for both reliable and efficient diagnostics of vehicles and the systematic and economic processes for generating them. This is why there has been a strong interest of European car industries in this technology and why the VMBD project was initiated in 1997. VMBD involved Fiat CRF, DaimlerChrysler, Volvo Car Corporation, Robert Bosch GmbH, Magneti-Marelli SpA, GenRad, OCC'M Software GmbH, and several universities and was funded by the Commission of the European Union in the BriteEuRam III program (Project No., #BE 95/2128), see [Bidian et al 99].

The goal of VMBD was to run model-based diagnosis on-board real demonstrator vehicles. In the following, we present one of these case studies (More details are given in [Sachenbacher et al. 00]. Another on-board demonstrator is described in [Cascio et. al 99]). Since increased legislative and customer demands have led to new requirements for aspects related to emissions and performance of the system, the case study was focused on effects that involved incomplete fuel combustion in a Diesel engine due to an excessive quantity of fuel injected or insufficient airflow to the engine, resulting in increased carbon emissions (called ‘black smoke’ problems). The experimental environment was provided by the turbo control system of a Volvo 850 TDI demonstrator vehicle that was used in the project.

A schematic of this system is contained in the screenshot of the demonstrator system in Figure 2. The air is taken in and the airflow measured on the bottom right part of the structure. The intake turbine compresses the air (with the pressure measured by a sensor) and feeds it to the combustion chamber of the engine (top middle). The exhaust gases exiting to the left drive the exhaust turbine which is connected to the intake turbine. Its speed can be influenced by the waste gate valve which is controlled by the pressure-driven converter. This pressure in the control pipe is in turn determined by the turbo control valve (top right), an actuator controlled by the engine ECU.

Types of failures which can lead to black smoke symptoms involve leakages in pipes, malfunctions of valves (e.g. stuck-at-open or stuck-at-closed), increased friction in bearings (resulting in a delay of actuators) or signal disturbances due to electrical failures. The demonstrator vehicle included facilities to create some of these failures. For instance, it had a valve installed in the air hose between the turbine outlet and the engine intake manifold that could be opened in order to simulate a leakage. If such a leakage is too large to be compensated for it will lead to insufficient oxygen supply to the engine and hence, the potential of incomplete combustion.

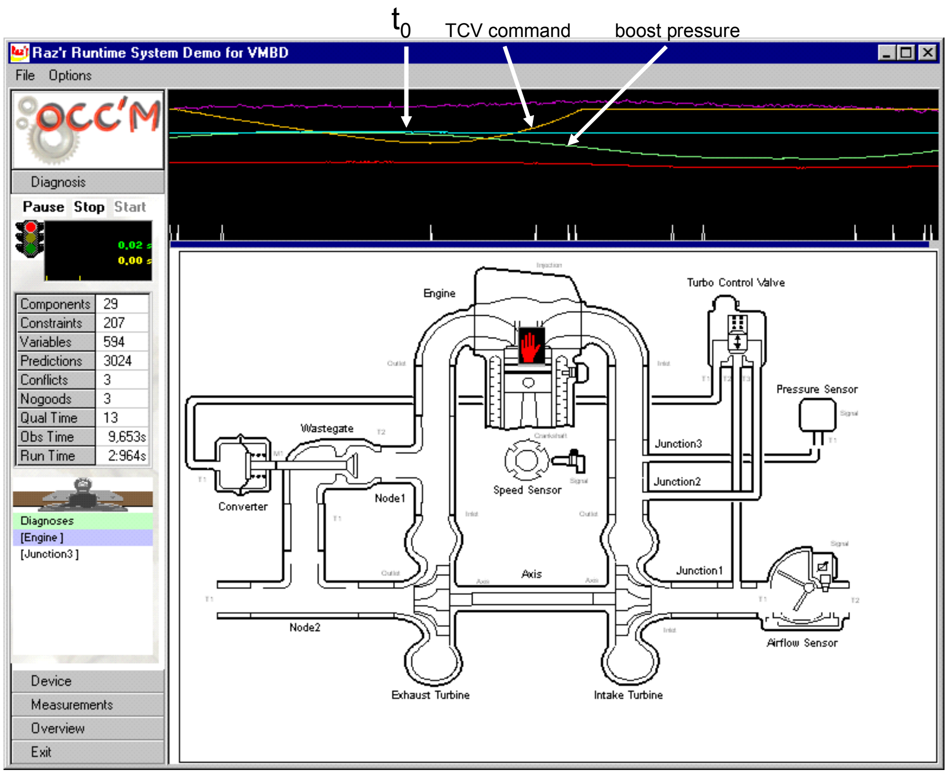
The on-board diagnosis prototype was to use only signals available to the standard ECU without additional sensors. These were signals from the boost pressure, airflow and engine speed sensor, as well as the actuator signals indicating the amount of fuel quantity injected and the position of the turbo control valve.

This application imposes a number of requirements that are typical for on-board diagnosis of a broader class of subsystems:

- The system has a dynamic behaviour described by continuous variables.

- There are relatively few observables, some of which are very noisy signals (see the signals displayed in the upper window of the screenshot in Figure 2).
- Real-time performance has to cope with a high frequency of signals (with data coming in roughly every 10 ms, this is one of the fastest processes on a vehicle).

The solution produced in the project was based on a compositional qualitative model of the turbo control system and its exploitation in a so-called consistency-based diagnosis system. Technical details are provided in; Moving Forward - Model-based Systems in the Automotive Industry. Peter Struss and Chris Price - to appear in AI Magazine, 2003.



| | |
|---|---|
| Components | 29 |
| Constraints | 207 |
| Variables | 594 |
| Predictions | 3024 |
| Conflicts | 3 |
| Nogoods | 3 |
| Qual Time | 13 |
| Obs Time | 9,653s |
| Run Time | 2:964s |

Diagnoses
[Engine ]
[Junction3 ]

**Figure 2: Screenshot of the Model-based Run-time Diagnostic Prototype for the Turbo Control Subsystem**

The diagnostic runtime system was provided by RAZ'R, a commercial system of OCC'M Software [RAZ'R 03] which is an implementation of consistency-based diagnosis [de Kleer et al. 92; Dressler and Struss 96].

This technique considers diagnosis as a search for device models that are consistent with the given observation about the actual behaviour. Based on the given observations and the device model, conclusions are computed about system parameters and variables (observed and unobserved). For each derived prediction, the set of component models involved in it is recorded. This information can be determined by the diagnosis system because the device model has a structure that reflects the device constituents. If a contradiction is detected, i.e. conflicting conclusions for a variable occur (fault detection) the set of components involved in it indicates which components possibly deviate from their intended behaviour. Based on this information, diagnosis hypotheses are generated, i.e. sets of faulty components that account for all detected contradictions (fault localisation).

As an illustration; consider the scenario of a leakage at the engine intake manifold (Junction3 in the schematic of Figure 2). The plots of the signal in Figure 2 show that, due to this leakage (the open valve) the sensed value of the boost pressure starts to drop at $t_0$. The ECU responds by changing the position of the turbo control valve (until a certain limit) which should counteract the pressure drop, but fails to achieve this. To us, the qualitative characterisation of the signals in conjunction with the qualitative understanding of the intended functioning of the components leads to the conclusion that at least one of the participating components must be faulty. The same result is obtained by the model-based diagnosis system on the basis of the qualitative deviation model and an appropriate abstraction of the signals.

The demonstrator system uses a signal abstraction component that transforms each incoming vector of signals to the qualitative level at which the model is stated. Only if this abstracted signal vector represents a new qualitative state, it is entered to the diagnosis system. The resulting reduction of input and hence, of diagnostic inferences is immense, as illustrated by the fact that instead of more than 1000 numerical vectors, only 12 qualitative ones (indicated by the peaks at the bottom of the signal window in Figure 2) have to be processed.

One of these qualitative vectors states that the boost pressure drops while all other signals (including the turbo control valve position) do not change. This is in contradiction to the deviation model which predicts a constant pressure from the steadiness of the valve position and the engine speed. The set of components whose models are involved in this prediction comprises the control path (turbo control valve, converter and waste gate valve) and the feedback loop from the intake turbine via engine and exhaust turbine. One component in this fairly large set must be broken. The localisation of the fault can be confined by combining evidence from several detected discrepancies: for instance, an increasing airflow signal contradicts the decreasing boost pressure, yielding a different conflict set of components.

It is worth noting that the above inferences use only models of correct component behaviour and no description of possible faults. If, in addition, models of faulty behaviour are provided, the same technique (checking consistency of a model with the observations) can be used to discard particular faults (fault identification), or to conclude correctness of certain components if the set of modelled faults is considered complete.

The VMBD system was realised on a notebook that received the actual data from the ECU via a serial line while the vehicle was stalled, simulating full load conditions. Figure 3 shows the installation on the demonstrator vehicle.

The screenshot in Figure 2 shows the diagnostic results for a slowly opening leakage during stalling the engine. The measurement runs for 9.75 seconds and yields 1064 quantitative observation vectors. The signal transformation module reduces them to only 12 qualitative observation vectors. The two single fault hypotheses generated by the system (displayed in the bottom left section) contain the component where the failure was actually induced (‘Junction3’). The run time for the example was 2.87 seconds (on a Windows/Pentium PC). Similar results were obtained for the other failures that could be induced on the car (but, due to the available sensors, not always with a comparable quality of the fault localisation). This means that for the considered subsystem and scenarios, the performance of the on-board system is in the order of magnitude of real-time.

**Figure 3: View of the Volvo 850 TDI Showing the Notebook Connected to the ECU. The Glove Compartment (Behind) Contains the Switchboard for Controlling the Built-in Faults.**

The results of VMBD achieved their goal of providing evidence for the feasibility of using model-based systems and qualitative models for on-board diagnosis and strengthened the interest of the companies in the introduction of this technology.

### 2.3.2 Design Analysis - AutoSteve

Design analysis such as Failure Modes and Effects Analysis (FMEA) or Sneak Circuit Analysis (SCA) is typically carried out once in the lifecycle of a product. This is likely to be late in the lifecycle, when all design information is available and the design is stable. The drawback of this is that problems discovered at this late stage can be very expensive to fix. On the other hand, performing the analysis earlier might miss some problems because they only become apparent once all information is available. Repeating such analysis as the design evolves is impossible without automated assistance, because the amount of time needed to manually perform the analysis is prohibitive.

AutoSteve is a suite of design analysis tools based on qualitative model-based reasoning for assisting engineers in performing design analysis early, and efficiently repeating it whenever the design changes or extra information becomes available. Technical details of AutoSteve are available in [Ward & Price 01].

These tools enable the engineers to identify potential problems as soon as they become apparent, while also identifying the implications of any design changes, without tedious and expensive repetition of analysis by experts. AutoSteve assists engineers with the following design analysis tasks:

*What-if investigation*: As soon as the schematic has been designed, the engineer can alter inputs to the system within AutoSteve, interactively flicking switches and activating sensors, and see the results of the simulation illustrated on the schematic. A good example of a what-if investigation occurred recently. The European Commission is introducing legislation to make day-time running lights (DTRL) mandatory for all new vehicles. There are a number of issues to take into account when meeting this legislation - negative effects on charge balance cycle, negative effects on headlamp warranty, extra costs for relays, resistance wires, interpretation of the homologation permitting optimisation to offset these problems, etc. A headlight schematic without DTRL was modified to add it, and the simulation and visualization were used to run many different scenarios. Answers were found with AutoSteve in a few hours to problems that might have otherwise taken weeks to solve.

This kind of investigation could previously only be carried out by bread-boarding a physical prototype. This virtual bread-boarding can save significant time and effort for the engineers. The tool also allows us to ask what-if questions concerning destructive tests that may not be possible on a physical breadboard or real vehicle. In high-power circuits like electric windows, front-screen de-icers, etc, very large fault currents can flow. The cost and danger of testing these in real life rule them out. AutoSteve can use the numerical simulator Saber to carry these tests out virtually. It can verify wire temperature and fuse relationships, failure mode management, etc, and make design revisions accordingly.

*Failure mode and effects analysis* (FMEA)*:* AutoSteve is able to simulate operation of the schematic when one or more components have failed. A textual FMEA report is produced which gives the effect of each possible failure of each component in a schematic on the functioning of the whole circuit. These are presented to the engineers in a standard FMEA report format. Figure 4 shows an undoctored example row of an FMEA report produced by AutoSteve for a central door locking system.

| Item/Fn | Potential Failure Cause | Potential Failure Mode | Potential Failure Effect | Sev | Occ | Det |
|---|---|---|---|---|---|---|
| (23) | The component UNLOCK_RELAY has failure switch stuck at contact2. | For the first time, the “doors unlocking” function was achieved. Finally, regardless of any event change, the “doors locked” function was never achieved, and the “doors unlocked” function was always achieved. | Doors started unlocking unexpectedly. Doors unlocked unexpectedly. Doors failed to lock. | 6 | 3 | 2 |
| (24) | The component DEADLOCK_RELAY has failure coil blown. | When DRIVER_KEY_SWITCH was set to lock (3) the “doors locked” function was achieved unexpectedly. Also, when DRIVER_KEY_SWITCH was set to neutral (4) the “doors locked” function was achieved unexpectedly. | Doors locked unexpectedly. | 6 | 2 | 4 |

**Figure 4: Example Output Produced by FMEA Tool**

An example of the kind of problems that have been highlighted by this tool occurred in a lighting subsystem. Stop-lamps were driven by a lighting ECU module and powered by the stop-lamp fuse input. The stop-lamp switch fed positive voltage to the ECU module when pressed. If the fuse failed, the ECU module would detect that braking was required but no power was available to supply the stop-lamps. It would alert the user that the stop-lamps were not available. In an early version of the lighting system, the FMEA software detected that when the stop-lamps did not work, no warning was issued. On examination, it turned out that this was because the stop-lamp switch was spliced to the fuse feed. When the fuse blew and the brake pedal was pressed, the ECU detected that there was no fuse feed, but did not detect that the brake pedal had been pressed, and so gave no warning. The software detected this early in development and so saved a lot of money and cycle-time.

*Assistance for FTA*: One of the uses of Fault Tree Analysis (FTA) is to compensate for the shortcomings of manual FMEA. It is used to highlight all of the combinations of failures that will make a particular unwanted event occur. For example, such an event might be a vehicle’s airbag firing when it should not. Alternatively, it might be to identify when the airbag will fail to fire. It is then possible to calculate an overall figure for how likely the unwanted event is to occur. Engineers calculate the dependencies in the fault tree by hand. The automated software can perform multiple failure FMEA. This provides all of the information that is needed to decide what combinations of failures can cause the unwanted event to occur. In addition, as vehicles become more complex, with ECUs programmed to mitigate the effects of known failures, it is likely to calculate the true effects of a combination of failures more accurately than an engineer mentally simulating circuit operation.

*Sneak circuit analysis*: In complex electrical systems, the interaction of several subsystems can cause further systems to be activated unexpectedly. A classic example is given in [Savakoor et al. 93] and illustrated in Figure 5, of the cargo bay doors of a particular aircraft design, where operating the emergency switch for the cargo doors can cause the landing gear to lower unintentionally. Typically, such problems are caused when a wire, which was expected to provide current in one direction, is used in the opposite direction, causing a *sneak path*.

Sneak Circuit Analysis (SCA) is the process of identifying and eliminating such sneak paths where they might occur. Where a wire is allowing current to flow in an unexpected direction, this can often be prevented by the addition of a diode to the design, but cost considerations mean that extra diodes should not be added to the circuit unless they are really needed.

AutoSteve includes an automated sneak circuit tool capable of detecting classic sneaks [RAMS - Price & Hughes 02]. The functions of the system will have already been declared for FMEA. It is necessary only to declare the combinations of inputs, which should activate each function. All combinations of inputs can then be tried in simulation in the circuit by AutoSteve and if unexpected functions occur for any combination of inputs, then they are due to a sneak.

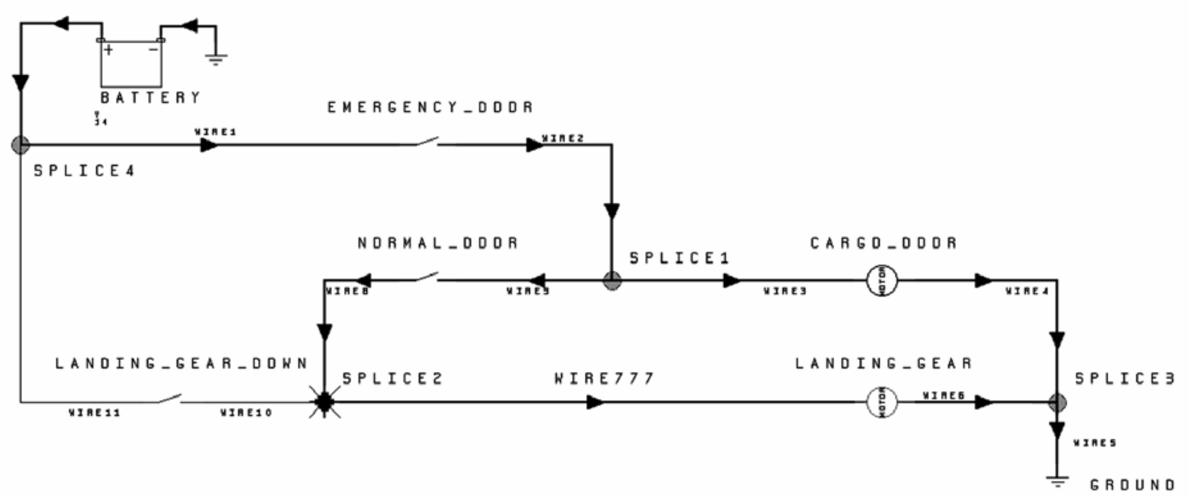
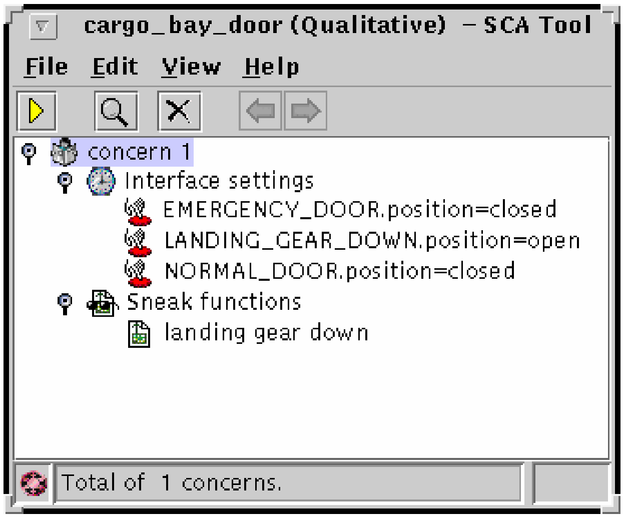


**Figure 5: Illustration of Cargo Door Sneak Path**

Unlike several other sneak circuit tools, it is not necessary to declare the direction in which current should flow through each wire (impossible for many wires in circuits such as central door-locking circuits, where current is allowed to flow both ways in many wires). Neither does the algorithm produce spurious sneaks. Figure 6 shows the results generated by AutoSteve for the classic cargo door sneak problem.

Ford's adoption of AutoSteve as part of its C3P recommended development toolset provides some indication of the value of this technology. The group of engineers at Ford who pioneered the use of AutoSteve were recently awarded a Ford European Technical Achievement Award for their contribution to advancing electrical design analysis within Ford. One of the award winners stated: "The benefits of AutoSteve are important. We can test and debug electrical systems before we ever wire them up for tryouts, so that confidence is close to 100% that the first prototype will be right first time. The automated FMEA's will have



concern 1
Interface settings
EMERGENCY_DOOR.position=closed
LANDING_GEAR_DOWN.position=open
NORMAL_DOOR.position=closed
Sneak functions
landing gear down

Total of 1 concerns.

**Figure 6: AutoSteve Sneak Report for the Cargo Door Example**

already confirmed adequate robustness of the design. This saves time in the development cycle with lower engineering resources and development costs. In fact, the pressure of program work is becoming so great that electrical Computer Aided Engineering CAE simulations will soon be the only way we can handle development and signoff of some subsystems."

# 3 Overall Graphical Roadmap

**Drivers**

## Market

Efficiency / Environmental Considerations -- Safety -- Customer Satisfaction -- Cost of Ownership

| Now | | 2 Years | | 5 Years | | 10 Years |
|---|---|---|---|---|---|---|
| | durability | biometric systems | interaction with intelligent infrastructure | fleet management | driver DNA | personalisation of vehicles |
| | increased security | | safety issues (convenience issues traffic info) | tailor made morphing (characteristics of vehicle in software) | small production runs (output geared to market) | |
| | | | reduced emissions | | | |

## Business

Complexity -- Development Improvements -- After Sale Improvement

| Now | | 2 Years | | 5 Years | | 10 Years |
|---|---|---|---|---|---|---|
| keeping engineerng knowledge | variant problem | significant reduction in need for late engineering changes | managing complexity of software | conditional maintenance | design for disassembly | fuel cell technology |
| | high cost of testing and maintenance | drive by wire | optimisation of control (distributed) | doubling of electronics | using knowledge of world for safety and efficiency | variant problem worse |
| | adaptive cruise control | | virtual assembly / repair training | remote monitoring | small production runs (output geared to market) | |
| | | | | integration of systems e.g. ABS / Engine management / ESP | | |

| | Now | | 2 Years | | 5 Years | | 10 Years |
|---|---|---|---|---|---|---|---|
| **Products** | diagnosability tools | automatic generation of garage based diagnostics | automatic generation and checking of tests | knowledge management of model libraries | on board repair - better fault mitigation | World model-based vehicle efficiency (e.g. gear shift with terrain knowledge) | distributed diagnostic systems (localised intelligence) |
| | FMEA | automatic generation of off board diagnosis | automatic software test generation (guaranteed coverage) | MBS Shell | | automatic generation of emission reduction systems | robot diagnostician --> |
| | SCA | integration of models over lifecycle of vehicle | software verification | monitoring tools for efficiency and lower emissions | | | vehicle personalisation tools --> |

| | Now | | 2 Years | | 5 Years | | 10 Years |
|---|---|---|---|---|---|---|---|
| **Technology** | models for performing diagnosis | hybrid modelling (across domain plus different model types) | standards for modelling tools | plug and play model based systems for different applications | modelling vehicle environment | driver modelling | |
| | models for simulation in electrical and hydraulic | derivation of Q models from design models | better models of software (not UML) | model maintenance | hybrid reasoning systems | model data warehouse | |
| | | model of complex dynamic, time varying and continuous systems | automated modelling from data | model conversion | integration of reasoning technologies | | |

| | Now | | 2 Years | | 5 Years | | 10 Years |
|---|---|---|---|---|---|---|---|
| **Resources** | training of PhD/Ms in technologies | exchange between industry and academia | FP6 projects | forums for industrial exchange | | | |

# 4 Technology Drivers for the Next Ten Years

This section considers what the relevant drivers of this technology may be over the next ten years. It discusses the demands on automotive companies from the market and the ways in which automotive companies expect to be responding to those demands.

## 4.1 Market Demands on Manufacturers

Many of the key market demands on manufacturers are due to pressures which exist at present and which will continue over the next ten years. They will lead to improvements in technology and in processes. These key issues are:

*Efficiency / Environmental Considerations*. Some of the demands in this area are being driven by legislation. The EC target for reduced $CO_2$ emissions over the next ten years is an average of 120g/km. Both customers and legislation (indirectly) are exerting pressure for reduced fuel consumption.

*Safety*. Customers are beginning to select vehicles on safety features, with improved safety test results being seen as an important marketing point. Legislation will also demand improved safety equipment as time goes on.

*Customer Satisfaction*. Customer expectation of vehicle features is increasing over time, with demands in the area of increased security, performance, ride comfort, and decreased maintenance. Target for increased availability of transport is a reduction of downtime by 40% over next ten years [Foresight Vehicle 02].

Other market drivers of technology that will feature in vehicles over the next ten years are:

*Durability*. Components will become more reliable and last longer. The average planned lifetime of a vehicle needs to increase.

*Increased Security*. Preventing theft and improper access to a vehicle is becoming more of an issue and the average time needed to break in to new vehicles is gradually increasing (from a very low base figure). We will see more complexity of vehicles as security systems get more robust.

*Biometric Systems*. One type of security system being contemplated is the use of driver identification systems such as iris or fingerprint recognition systems to enable identification of allowed drivers.

*Interaction with Intelligent Infrastructure*. The ability of a car to receive and interpret information from road and environment infrastructure (road type and condition, weather, traffic, etc.) will improve. This information will be used in order to adapt its behaviour to these conditions. This might involve operating on the car control system in order to guarantee optimal behaviour, safety, limited environmental impact, efficient routing.

*Safety Issues*. We can expect more complex systems for improving safety, both active and passive.

*Reduced Emissions*. The need to significantly reduce emissions with respect to the EURO4 standard, towards the Zero Emission Vehicle.

*Fleet Management*. The possibility of managing a fleet of vehicles in an optimal way (e.g., a fleet of urban buses or the fleet of a company or car rental agency), as regards monitoring, diagnostics and maintenance.

*Tailor Made Morphing*. (Characteristics of vehicle in software). The ability of a car to adapt its behaviour to the behaviour of the individual user. Adaptation of control strategies (e.g. sporty gearbox or suspension) according to the driving style of the user and in order to achieve optimal behaviour

*Driver DNA*. This brings together biometric recognition and tailor made morphing. When it is possible to recognise a driver and to record their preferred driving characteristics, then you can record those preferences, and load them into any vehicle. This may be particularly significant if individual car ownership reduces, and shared car pools increase. When a driver gets into any car, then it adapts itself to their preferences.

*Personalisation of Vehicles*. The possibility for a customer to personalize the vehicle as regards electronic controls and components, type of behaviour (Software control).

## 4.2 Business Drivers of Technology

Many of the key market demands described above contribute to the three business issues that dominate the development concerns of the manufacturers.

*Complexity*. Because of the above demands, there is a further expected doubling of electronics in the vehicle over the next ten years, at which point electronics will make up 20% of the vehicle [Foresight Vehicle 02]. This increase in electronics is matched by an increase in the complexity and amount of software in the vehicle.

*Development Improvements*. Target for improvement of development period: 18 months to develop a completely new vehicle, 12 months where using an existing vehicle platform [Foresight Vehicle 02]. Target for reduction in costs: 35% reduction in the cost of developing a new vehicle [Foresight Vehicle 02].

*Cost Reductions*. In order to remain competitive, costs are being relentlessly driven down by the manufacturers. This is explored in greater detail in some of the drivers in the list below.

These three issues mean that the manufacturers are being called upon to design and deliver more complex systems, more cheaply and in less time. One solution to this is to increase the amount of automation in the development processes, and it is in this area that model-based systems and qualitative reasoning can provide the greatest help.

Other important issues for the manufacturers raised by the market demands are:

*Keeping Engineering Knowledge within the Company*. There is a need to maintain knowledge bases (models) inside a company and to have access to these models; and the possibility of using them for training and for new projects. There is a need for tools for knowledge and content management and for standards for knowledge storing and exchange.

*Variant Problem*. There is a need for dealing with many variants of the same system or subsystem. It may be variants in the design of systems with the same function; or variants across time; or variants for different versions of a vehicle. This means that much of the design work presently has to be repeated even though the analysis done for each version of the system is very similar. Economic ways of dealing with this problem are needed; especially for monitoring, control and diagnosis. In the future the number of variants of a system will increase yet further, especially with the needs of customised / personalised solutions.

*Adaptive Cruise Control*. There is a need for solutions for intelligent and adaptive cruise control; taking into account the environment, the driver and the car conditions. This will lead to greater complexity in the operation of the vehicle.

*Significant Reduction in the Need for Late Engineering Changes*. Late engineering changes are very expensive and may lead to delays in product time-to-market. These changes should be minimised or even eradicated by good early design analysis.

*Drive by wire*. There are an increasing number of X-by-wire solutions inside a car. They are producing a need for solutions ensuring efficient reliable design of control systems.

*Managing Complexity of Software*. Software systems for monitoring, control and diagnosis are becoming very complex and the complexity will increase in the next decade, with new problems arising from the interaction between the controlled systems and their software. There is a need for reliable techniques for software development, testing, maintenance and versioning (interaction with the variant problem).

*Optimisation of Control (Distributed)*. There is a need for solutions for distributed control and multiplexing of control functions (in order to reduce the number of ECUs, moving from specialized ones – one for each controlled system – to a few generic ones). There is a need for strategies for distributed control and for control of interacting systems.

*Virtual Assembly / Repair Training*. Techniques and solutions are needed for training engineers and workshop people; especially for dealing with the increasing complexity of vehicles and with the rapid changes of many features of the vehicle. Traditional training techniques would cost too much and require too much time.

*Conditional Maintenance*. There is a need for changing the maintenance scheme from a time-based one (every year or every 15,000 kilometres) to a model where maintenance is performed only when needed. This should reduce the cost for maintenance, reduce the unnecessary replacement of components or materials that are indeed OK and thus lead to a reduction in the down time of vehicles.

*Doubling of Electronics*. The number and complexity of electronic systems (or electronically controlled systems) is increasing significantly and will continue to increase similarly in the next years.

*Remote Monitoring*. The possibility of monitoring a vehicle from a remote station (using some communication channel such as an internet connection). Possibility of performing bi-directional exchange of information in order to reduce the need of vehicles to go to a workshop.

*Integration of Systems* e.g. Anti-Lock Braking Systems (ABS) / Engine Management / ESP. Responsibility for the development of control systems is often handed to the tier 1 suppliers. However, an ongoing issue is the need for better integration of controls (especially as regards interaction) between the various electronically controlled systems, especially in particular or potentially dangerous conditions.

*Design for Disassembly*. The possibility of easily disassembling a vehicle (or some components) for facilitating recycling of car components and subsystems.

*Using Knowledge of the World for Safety and Efficiency*. Using information from the environment to improve safety (e.g. information about the road status, weather, traffic, presence of pedestrians, etc.)

*Small production runs (Output Geared to Market)*. Improved manufacturing processes and adaptability should make production of small quantities of a vehicle economically feasible.

*Fuel Cell Technology*. There is a need to move from traditional Internal Combustion engines to new technologies such as fuel cells.

# 5 Model-Based and Qualitative Solutions to the Needs of the Automotive Industry

This section discusses some answers and solutions that the model-based system community can provide in the next ten years to achieve the market and business requirements discussed in the previous sections.

The presentation will be centred on the products and tools that could be produced by the MBS community, for which the graphical roadmap provides an estimate of the expected deployment time.

We then provide a definition of the function of each one of the products / tools and we link it to the other dimensions in the graphical roadmap. More specifically, we list the requirements (drivers) that can be achieved by the product / tool and we list the technologies that will be needed in order to implement the product / tool itself.

In this way this section provides a picture of what the MBS technologies can do for the automotive domains and thus the vision of what can be achieved in the next decade. It also links such a vision to the basic research and technological issues that must be achieved in order to enable the implementation of the products and tools and thus to respond to the market and business drivers.

The description will be schematic in order to make it easier for a reader to immediately grasp the connections between basic technologies, products and drivers.

## *5.1 Automatic Generation of Garage Based Diagnostics / Automatic Generation of Off-board Diagnostics*

DEFINITION

- A tool for generating automatic diagnostic procedures for supporting the work of the people in the workshop (long term evolution → robot diagnostician)

NEEDED FOR

- The need to improve after sales services
- The complexity of systems is increasing and the systems change very rapidly so that it becomes more and more difficult to train workshop people in order for them to deal with these systems
- Many variants of a system so that it becomes more difficult for workshop people to have knowledge and experience on all the systems

TECHNOLOGIES NEEDED TO IMPLEMENT IT

- Models for building diagnosis
- Hybrid modelling across different domains
- Better models of software
- Models of complex dynamic, time varying and continuous systems
- Derivation of qualitative models from design models

## *5.2 Integration of Models Over Life-cycle of Vehicle*

DEFINITION

- Use of models and model-based tools to support the whole lifecycle of a vehicle, from design to after-sales service

NEEDED FOR

- The need to improve the development of a vehicle, with regards to both market and business drivers
- The need for shorter time to develop and market a vehicle
- The need to improve the quality of the vehicle (as regards safety, environment impact) to achieve customer satisfaction

TECHNOLOGIES NEEDED TO IMPLEMENT IT

- Hybrid modelling across different domains
- Better models of software
- Models of complex dynamic, time varying and continuous systems
- Derivation of qualitative models from design models

- Modelling tools and environments

## *5.3 Knowledge management of model libraries*

DEFINITION

- Tools for storing, managing and accessing models (a long term evolution model-data warehouse which is automatically filled in when a new component/system is designed)
- The tool should be used along the whole life cycle of a vehicle to support designers, workshop people, training, etc

NEEDED FOR

- Keeping engineering knowledge inside the company
- Supporting an MBS shell with a library of models to be re-used in the analysis of new systems or subsystems
- Need for support system for training in virtual environments

TECHNOLOGIES NEEDED TO IMPLEMENT IT

- Standards for modelling tools
- Hybrid modelling across different domains
- Better models of software
- Models of complex dynamic, time varying and continuous systems
- Derivation of qualitative models from design models
- Modelling tools and environments
- Model maintenance
- Model conversion

## *5.4 MBS Shells*

DEFINITION

- Tool for creating model-based applications for different tasks;
  - design
  - diagnosis
  - monitoring
  - control
  - planning
  - FMEA support
  - lifecycle support

NEEDED FOR

- Improving the development of new systems and their control, monitoring and diagnostic aspects
- Need to cope with complex systems due also to the increase of electronics
- Improving the quality of vehicles and thus their duration and customer satisfaction
- Improving after sales service

TECHNOLOGIES NEEDED TO IMPLEMENT IT

- Standards for modelling tools
- Hybrid reasoning systems
- Integration of different reasoning technologies
- Standards for modelling tools
- Hybrid modelling across different domains
- Better models of software

- Model of complex dynamic, time varying and continuous systems
- Derivation of qualitative models from design models
- Modelling tools and environments

### *5.5 Monitoring Tools for Efficiency and Lower Emissions (for Conditional Maintenance)*

DEFINITION

- A set of tools for supporting the maintenance of a vehicle in order to guarantee efficiency, low emission levels and availability
- Supporting the efficient management of fleets of vehicles

NEEDED FOR

- Implementing conditional maintenance
- Achieving low emission goals for operational vehicles (not only at regular checks)
- Achieve the goals of controlling a vehicle from a remote station
- Reducing down-time of vehicles, thus increasing customer satisfaction

TECHNOLOGIES NEEDED TO IMPLEMENT IT

- Hybrid reasoning systems
- Integration of different reasoning technologies
- Reliable, efficient and inexpensive bi-directional communication with the vehicle

### *5.6 World Model-based Vehicle Efficiency / Automatic Generation of Emission Reduction Systems*

DEFINITION

- A set of tools controlling the vehicle in order to achieve maximum efficiency given the environment and driving conditions (e.g. avoiding the need to shift to a higher gear if the road ahead will soon force a shift to a lower gear)

NEEDED FOR

- Improving the efficiency of the vehicle
- Improving safety
- Reducing fuel consumption and emissions
- Making the interaction with intelligent infrastructure feasible, i.e.
  - intelligent roads
  - intelligent traffic
  - management
  - intelligent collision systems for collision prevention

TECHNOLOGIES NEEDED TO IMPLEMENT IT

- Modelling the external world and reasoning on world conditions
- Modelling the driver
- Hybrid reasoning systems
- Integration of different reasoning technologies

### *5.7 Vehicle Personalisation Tools*

DEFINITION

- A set of tools supporting the design of a personalised vehicle (as regards the combination of electronically controlled systems and as regards control / control strategies)

NEEDED FOR

- Vehicle personalisation
- Customer satisfaction
- Making production of small quantities feasible

TECHNOLOGIES NEEDED TO IMPLEMENT IT

- – Modelling the external world and reasoning on world conditions
- – Modelling the driver
- – Hybrid reasoning systems
- – Integration of different reasoning technologies

### *5.8 Automatic Generation and Checking of Tests*

DEFINITION

- Future levels of system complexity increases the difficulty of testing using traditional methods

NEEDED FOR

- Reducing the high cost of testing and maintenance
- Drive by wire and similar technologies

TECHNOLOGIES NEEDED TO IMPLEMENT IT

- – Automated model generation from data

### *5.9 Automatic Test Generation for Software (Guaranteed Coverage)*

DEFINITION

- Increased amounts of software in many systems make testing difficult
- Test generation for such software will need both improved and automated methods
- Systems have many operational modes, internal states and interactions with other systems

NEEDED FOR

- Managing the complexity of software
- Drive by wire systems where the software becomes critical

TECHNOLOGIES NEEDED TO IMPLEMENT IT

- – Models of software that are executable and can support automated reasoning (Existing models such as UML are not suitable and models of the software that have characteristics associated with model-based reasoning are needed)
- – Conversion of models (i.e. converting source code to a form which can support reasoning)

### *5.10 Software Verification*

DEFINITION

- Ensuring the correct operation of software in all modes of operation is problematic as the complexity of the software increases and the level of interaction between systems becomes greater

NEEDED FOR

- Managing complexity of software

TECHNOLOGIES NEEDED TO IMPLEMENT IT

- Models to represent system specifications and requirements
- Combined qualitative / functional models

## 5.11 On-board Repair and Better Fault Mitigation

DEFINITION

- Systems can be made to detect and cure / compensate for faults while maintaining major functionality. Fault mitigation allows a lower level of functionality to be achieved using alternative means
- As more of the functionality is software based, failures of individual sensors or actuators will be compensated for by the software

NEEDED FOR

- Remote monitoring
- Conditional maintenance (minor degradation can be compensated for until service schedule leading to less unnecessary replacements)

TECHNOLOGIES NEEDED TO IMPLEMENT IT

- Model conversion (to allow fault mitigation strategies to be automatically generated from design models)
- Integration of reasoning techniques
- Functional modelling

## 5.12 Distributed Diagnostic Systems with Localised Intelligence

DEFINITION

- Inexpensive embedded microprocessor technology enables the trend towards smart sensors and smart actuators
- These devices may contain their own diagnostic capabilities and alternative modes of operation
- Diagnostic systems will need to work at a number of levels and also be aware of and integrate with other related systems

NEEDED FOR

- Integration of systems for example ABS, ESP, Engine and drive train control
- Optimisation of control

TECHNOLOGIES NEEDED TO IMPLEMENT IT

- Standards for model representation and model meta knowledge
- Standards for diagnostic knowledge representation and distributed mitigation protocols

## 5.13 Robot Diagnostician

DEFINITION

- On board repair and fault mitigation cannot deal with all faults and eventually a fault will need to be fixed. The robot diagnostician has the ability to perform diagnosis, disassemble and repair faulty parts.

NEEDED FOR

- Customer satisfaction
- After sales service cost reduction for the industry

TECHNOLOGIES NEEDED TO IMPLEMENT IT

- Hybrid reasoning systems (multiple ontologies)
- Automatic model selection
- Integration of a number of reasoning techniques
- Planning (disassembly and reassembly)
- Vision / recognition / tactile / manipulation of old and broken parts
- Automated modelling from data (system identification)
- Hybrid and integrated modelling in all domains i.e. electrical, mechanical and hydraulic
- Model warehouse to allow knowledge of the variants present for diagnosis

# 6 Conclusions

In this Technological Roadmap we have discussed the potential impact that MBS&QR technologies can have in the automotive sector over the next ten years. We presented a vision of the set of products and tools that could be built, responding to requirements provided by market and business drivers. We have also discussed the basic technologies that will be the basis for the implementation and deployment of these solutions, placing them on a time scale according to how far they are from what is currently possible.

With respect to the graphical roadmap; we can now analyse the resources that will be needed in the next decade, but especially in the next few years, in order to guarantee the conditions enabling the steps above.

Using a schematic view again, we can group these requirements as follows:

- From a research point of view, a lot still has to be done in order to develop the enabling technologies according to the schedule in the roadmap. This will need projects with the co-operation of academic and industrial partners (both automotive end users and providers). Not only should these projects provide the basic methodologies and technologies but they should also show their applicability with prototypes on real domains and applications. In the near future, this will mean the creation and funding of several FP6 projects or IP's on applications of MBS&QR to the field of surface transports.

- From an application point of view, manufacturers and providers should be involved in the development of applications, starting from State of the Art technologies (which have already proved to be useful in several case studies). This will require, on the one hand, a stronger support for SME involvement in the design and marketing of model-based solutions and on the other hand, forums for a wider penetration of the technologies in end user companies.

- The work of the MONET Network, with regards to the automotive domains, has been very important in the last few years, by supporting the activities in the items above and involving several companies (car manufacturers and providers). This is also a very important activity for the coming years in order to guarantee a fundamental leap to disseminate widely the technologies and their potential, especially at the level of medium and high management of end users. This means that the efforts for the next decade should go more and more in the direction of presenting the technologies and the applications that have been and will be developed at events and forums dedicated to managers and decision makers.

- From an academic point of view there is a strong need to train students on the methodologies and technologies. This has been done, with strong support from the network, mainly at the post-graduate level. In the future we need to move to lower education level in order to guarantee that the next generation of engineers and computer scientists are familiar with the technologies and can bring them to the companies in which they will work. This form of dissemination, from the bottom - up, is a fundamental one for generating a long term and stable knowledge base in companies.

- The item above does not exclude, however, the adoption of new measures for information dissemination to companies, supporting the various forms of continuing industrial training and education of people working in those companies. This will also include the organisation of events for the industrial exchange of technology and know-how transfer from basic to applied research.

In conclusion, MBS&QR can have a strong impact on the automotive (or more general in the transportation) domain and it can provide solutions to the problems that this sector will face in the next decade(s). The drivers in the graphical roadmap coincide with some of the technologies and research directions for the next generation of vehicles (see for example the [Foresight Vehicle 02]).

The applications that have been built so far and the interest of manufacturers and providers (demonstrated by their presence in these projects and, even more important, in the Network and Task Group) show that the vision is realistic and that indeed the products and solutions in the Roadmap can be achieved, provided that the enabling conditions for the development of the technologies are met.

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# 8 Document History

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