POWERTRAIN DIAGNOSTICS
A MODEL-BASED APPROACH

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ABSTRACT

This paper reports on work carried out in the project Vehicle Model Based Diagnosis (VMBD), funded through the BriteEuRam III programme of the European Commission. The project aims at demonstrating the utility of model-based diagnosis for real automotive problems both in on-board and off-board situations by installing suitable systems on demonstrator vehicles. The paper presents the results obtained in three automotive drive-train subsystems which have been chosen as guiding application for the study. The paper states some of the major requirements that have been identified in these guiding applications. In particular, it is essential to solve the inherent variant problem and to reason across different

physical domains, to consider aspects of dynamically controlled technical systems and to fulfil real-time needs on-board. The evaluation provides empirical evidence for the benefit of the described approach by improving the discriminative power of automated vehicle diagnosis.

1 INTRODUCTION

It is estimated that European passenger cars have an average yearly down-time of 16 working hours due to malfunctions and maintenance. This figure is even greater for commercial vehicles. For the European Community alone this amounts to a total of over one billion hours for repair. The increased sophistication that goes along with the requirement of building safer and cleaner cars is reflected in the entire process chain: from development to service bay. In order to keep the customer satisfied, when faults occur they must be diagnosed in a timely and cost effective manner. These growing constraints and stricter performance requirements are increasing the demands on car diagnostics. Model Based Diagnostics offers itself as a promising method for streamlining the diagnostic process.

The European Commission recognised the importance of diagnostics and maintenance in the area of traffic and public safety. To push the development in this area it funded the project **Vehicle Model Based Diagnosis (VMBD)**. The consortium was comprised by a mix of car manufacturers (DaimlerChrysler – formerly Daimler-Benz, Fiat, and Volvo), suppliers (Bosch, Magneti Marelli, GenRad, Thomson Detexis – formerly Dassault Electronique) and academic partners (Universities of Turin, of Wales at Aberystwyth, and of Paris Nord). This paper outlines some of the achievements of the VMBD project, especially the results from the applications. It starts with the industrial and scientific goals (section 2), continues with a presentation of the selected guiding applications (3), the analysis of requirements (4), the achieved results (5) and finishes with conclusions (6).

2 INDUSTRIAL AND SCIENTIFIC TARGETS OF THE VMBD PROJECT

Industrial goals

Three major industrial goals can be outlined: (a) providing and integrated tool for design and diagnosis, in order to avoid the high post-development effort for diagnostics, (b) taking advantage of the re-usability of component models, and (c) reduce the time used for diagnosis. VMBD aims at a major step forward in the industrial application by evaluating the model based diagnostic technology in a realistic context, i.e. on demonstrator cars, in a set of guiding applications.

Scientific challenges

Model-Based Diagnosis is believed to play an important role:

- during the design phase, for the achievement, assessment and definition of the optimal information level (through an iteration among design actions on the system, available information and diagnostic goals).
- in performing the diagnostic task (on-board and off-board) by the optimal information management (propagation and correlation among measurements and diagnostic model variables).

- in defining a sound methodology for a comprehensive approach to diagnosis from the design phase to the field application. Defining such a methodology must be carried out with continuous reference to the guiding applications.

In the frame of the VMBD project, the research field was confronted with problems in

Modelling: having to provide model libraries that cover an entire application domain and the important features,

Diagnostic strategies: covering different goals and conditions (for instance, on-board fault identification with limited sensors for choosing appropriate recovery actions vs. fault localisation based on customer complaints for component replacement),

Methodology: providing criteria and guidelines for the choice of modelling formalisms and strategies and architectures of diagnosis systems.

3 SELECTION OF GUIDING APPLICATIONS

3.1 Application domain

It is certainly not false to assume that the drive train is the core of the vehicle. Thus, it offers itself as one of the prime candidates to apply the technology.

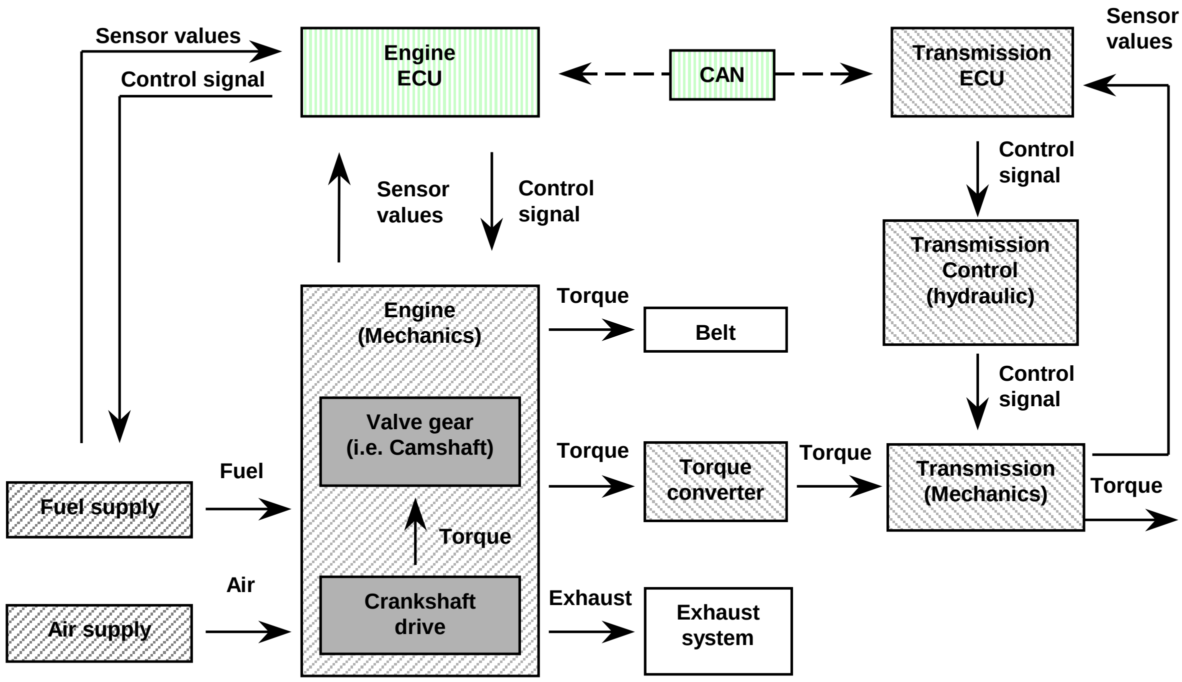

Fig. 1 Schematic view of the vehicle drive train

It would be a daunting task to start modelling everything at once, thus the industrial partners in VMBD consortium chose two different diesel injection systems (CoRa = Common Rail and DTI = distributor type injection) and one automatic transmission system (ATS) as guiding applications. Fig. 1 shows a schematic view with the elements of the injection system and those of the automatic transmission system. The shaded boxes refer to the functional units considered in the project. All three systems are complex, modular systems which consist of electronic, electrical, mechanical, hydraulic and partly pneumatic components.

3.2 Diagnostic tasks

It is usual to distinguish between on-board (i.e. on running car) and off-board (i.e. in a service station) diagnosis, as they pose different requirements on fault localization and identification and differ significantly in terms of available measurements and reproducibility of conditions.

On-board diagnosis

On-board diagnosis aims at selecting appropriate recovery actions. The injection system continuously monitors part of the sensor signals. Current on-board diagnosis can detect faults on the basis of predefined range and plausibility checks for signals. It will then perform built-in recovery actions that range from minor performance reductions to full engine stop and depend on the assumed failure and the expected failure effects. However, due to the scarcity of sensors, in most cases the control units fail to discriminate among the different possible causes that lead to the failure. Consequently, the system often applies a more restrictive recovery action than would be necessary. The goal of on-board diagnosis is to reduce the number of situations where too strong a recovery action is applied.

Off-board diagnosis

Off-board diagnosis aims at repair and, more specifically, replacement of components. In contrast to on-board diagnosis, the task is to localise the fault down to the smallest replaceable unit. Therefore, off-board diagnosis requires a different level of accuracy (granularity) for fault localisation. Off-board diagnosis can make use of more observations, using advanced service testers and human observations. Off-board diagnosis can also propose distinguishing tests, in order to partition the system, and use more information about the application context (e.g. engine load). In contrast to on-board diagnosis, where measurements "come for free" (at least at runtime), obtaining proper observations in the workshop has its, often non-negligible, price. Saving such costs for testing and, for instance, disassembly of systems, establishes a justification for using more elaborate diagnostic algorithms such as fault identification based on fault models.

3.3 Guiding application 1: Automatic Transmission System (ATS)

Structure and function

A significant number of mechanical, hydraulic and electric/electronic components act together in order to achieve the desired functionality of the ATS. An electronic control unit (ECU) receives engine revs, vehicle speed, and gear ratio data as well as information about the selected driving mode. Based on this information the ECU sends adequate control information to the hydraulic part.

The hydraulic system converts the electric commands from the ECU into pressure commands applied on the mechanical brakes and clutches. Several switching valves acting together like a tiny automaton are responsible for changing and preserving the configuration of activated brakes and clutches. Several regulating valves and hydraulic delay elements collaborate as well to control the increase and decrease of the pressure applied to the brakes and clutches. In the mechanical subsystem gear wheels (transformers), planetary gear trains (more complex transformers), brakes and clutches (coupling - decoupling function) and freewheels (transmit rotation only in one direction) are responsible for achieving the appropriate torque / speed conversion according to the desired gear.

Depending on the configuration of active clutches and brakes different "transmission paths" and conversion factors can be achieved. In a fault-free transmission there exists a fixed set of engaged and disengaged brakes and clutches for each gear. During the gear shifts this set changes and, for a short period of time, some of the brakes and clutches are in an intermediary state, i.e. they are slipping. During the slippage phase the speed of the turbine and of the engine are continuously changing until they adapt to the new gear ratio.

The whole automatic transmission can be seen as a hybrid system: several discrete and continous change steps are involved in each gear shift. The precise timing of the engaging and releasing elements is crucial to smooth shifting, which is an important determinant of the overall quality of the automatic transmission.

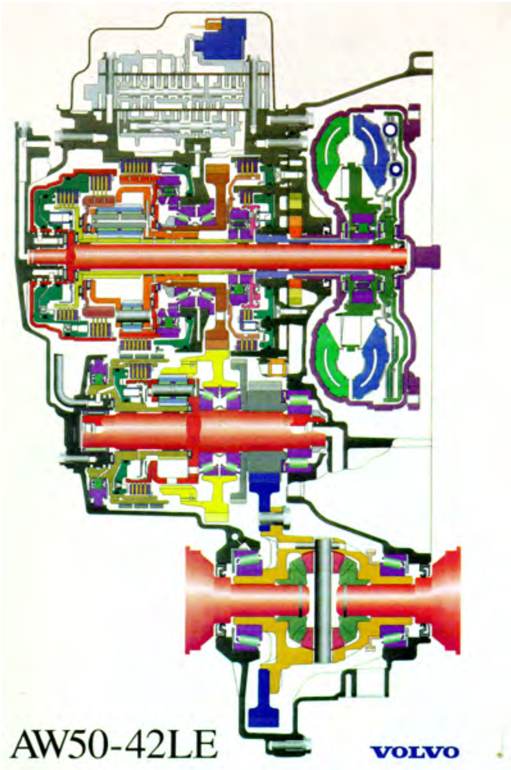

Fig. 2 Picture of the investigated ATS

Chosen fault scenarios

More than 40 single component faults in the hydraulic and the mechanical subsystems have been considered. Depending on the temporal properties of the deviations caused, one can classify the faults into:

- **"hard" faults** – They have dramatic manifestations, such as a shift not taking place, or achieving a wrong gear ratio. Faults falling into this category are: stuck-at switching valves, broken electrical connections and strongly worn brakes and clutches. More than 12 considered component faults fall into this category.
- **"soft" faults** – They affect only the shift quality, such as a shift being too hard or too soft., which is usually caused by parameter drifts and wearing. Into this category fall:

damaged regulating valves, low oil pressure, bad oil quality, clogged filters, worn brakes, clutches and freewheels, etc. More than 28 considered component faults fall into this category.

While the "hard" faults have steady-state manifestations, the faults from the second category have only temporary manifestations during the shifts. After a shift is completed the transmission works fine - it is only the timing of the switching phases, the rates of change, or the shift duration which are affected possibly resulting in a bad shift quality.

3.4 Guiding application 2: Common Rail Injection System (CoRa)

Structure and function

The Common Rail system is a flexible engine management system for passenger car direct injection diesel engines. Beside variation of fuel quantity and start of injection, it allows the choice of varying injection pressures in the range of 150 to 1400 bar, and fuel to be injected in any desired segmented delivery. Such a flexibility achieves better results in terms of performance, emissions and noise with respect to alternative fuel delivery systems.

The system works as follows. An electric fuel pump feeds fuel from a tank to a "high pressure" pump, driven by the engine, which pumps fuel into an accumulator, a *rail* which is *common* to all injectors. The ECU controls pressure in the rail through a sensor and a pressure regulator (through which part of the fuel in the rail is returned to the tank), modifying the opening or closing command to it, in order to make the pressure close to a target pressure that is considered optimal for injection given a number of other measured values regarding vehicle and engine conditions (e.g. accelerator pedal position, engine temperature).

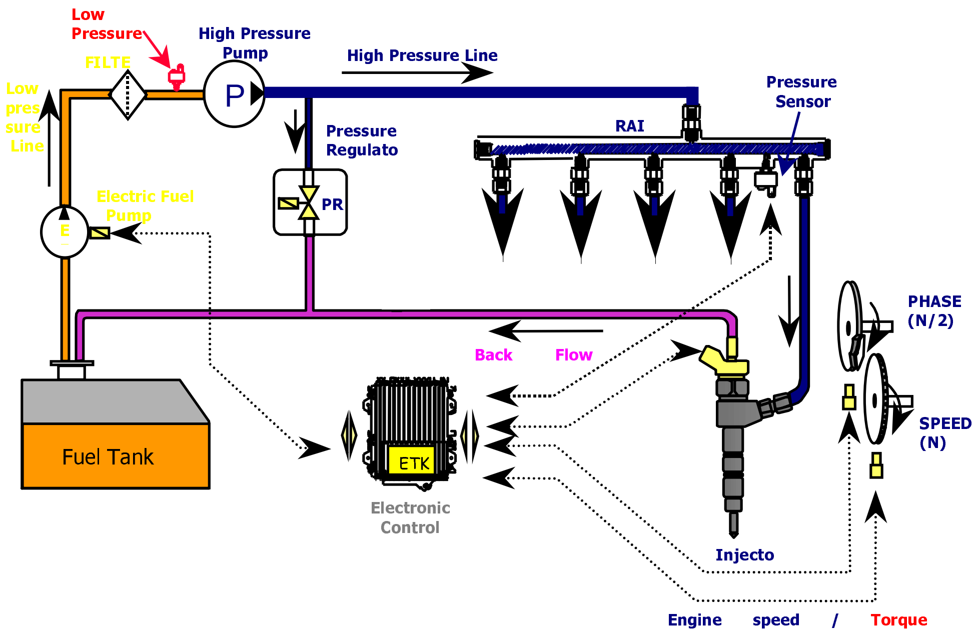

Fig. 1 Common Rail Injection System

Chosen fault scenarios

Several scenarios have been chosen from the system FMEA in order to demonstrate the diagnostic approach used in this application. The selection was done according to relevance and ease of inducing the fault; the resulting scenarios are:

- Electric fuel pump does not convey fuel
- Pressure regulator blocked open
- Injector Blocked Open (permanent injection in one cylinder)
- No injection at one cylinder

For each fault, including the four above, an appropriate recovery action should be performed by the ECU, e.g.:

- go on (but store the suspect fault)
- switch to open loop control
- limit performances (e.g. limit the maximum pressure)
- switch to a "limp home" mode
- stop the engine as soon as possible (in case of dangerous faults)

The ideal goal for diagnosis would be to identify the faults from actual measurements, or, at least, for on-board diagnosis, to perform the appropriate recovery action; if this is not possible, the action to be performed should be the safest one, given alternative possible diagnoses, while avoiding too restrictive actions such as switching the engine off if this is not necessary.

3.5 Guiding application 3: Distributor Type Injection System (DTI)

Structure and function

The other type of injection system we are concerned with is the distributor-type injection (DTI, [Bosch 96]). The main difference from the Common Rail system lies in the high-pressure hydraulic subsystem. In the DTI, there is no common high-pressure fuel reservoir for the injections. Instead, a high-pressure pump generates a certain amount of pressurized fuel individually for each injection (for a picture of DTI details cf. [Sachenbacher et al 98]).

However, more important is the fact that this system poses different requirements for diagnosis and failure analysis than the Common Rail application. Diagnosis of the DTI is focused on driver-perceivable effects related to emissions and performance. Often, such effects involve incomplete fuel combustion and increased carbon emissions, and are therefore called "black smoke" problems. A major category of failures which can lead to this class of symptoms involves faults in the air supply, which can be decomposed into the exhaust gas recirculation subsystem and the turbo control subsystem.

Chosen fault scenarios

A list of scenarios, which comprises more than 40 single component faults, has been set up for this system. An additional category consists of 4 external influences such as the quality of diesel fuel. All of the scenarios share the symptom of increased emissions, especially black smoke, and performance deterioration of the engine as their main symptoms.

The failures to be dealt with involve air leakages (intake and exhaust gas pipes or vacuum pipes), malfunctions of valves (e.g. stuck-at-open or stuck-at-closed), increased friction in bearings (resulting in a delay of actuators) and control signal disturbances due to electrical failures.

4 REQUIREMENTS ANALYSIS

The above described guiding applications provide a number of challenges for computer assisted and automated diagnosis. The VMBD choice of techniques in order to meet the requirements explained in the next paragraphs was **Model-Based Diagnosis (MBD)**.

Basis for the VMBD approach was the recognition that the most complex subsystems in a vehicle share the following **features** with respect to their function:

- there exists a natural decomposition into subsystems with only few components
- in most cases, malfunctions of the car or a system are due to some component failure
- component behaviour can be described by relations among local variables and parameters
- system behaviour is established by the behaviour of its components and their connections w.r.t. processing of material, energy or signals.

A series of problems have to be addressed:

- **Variant problem** - A remedy to the problem offers the **compositional modelling** i.e. building a system model by arranging generic component models for generating the diagnostic system (or at least a basis for it) from a structural description (like a "blueprint").
- **Phenomena from different physical domains**. The interaction of components of different physical domains (electrical, electronic, hydraulic, pneumatic, mechanic). These phenomena determine the behaviour not only of the affected components but also of the whole subsystem. This poses the problem of creating models of such components that can be used in one common framework. **Component-oriented modelling and a model library** with reusable component and aggregate models is the answer.
- **Dynamic and controlled subsystems**. All systems considered in the guiding applications have internal states depending on previous inputs, thus being an example of a dynamic system. The effects of faults may be compensated by control. Thus, failures may only be visible in a subset of the **operating modes** of the vehicle (e.g. engine start, idling, take off phase, full acceleration, etc.) or they may be only visible at transitions of operating modes of subsystems (subsystems tend to compensate for failures).
  A crucial question is whether or not diagnosis of the relevant faults demands extensive prediction of behaviour over time, i.e. some sort of (quantitative or qualitative) **simulation**. However, recent theoretical and experimental work has shown that there are conditions under which useful diagnostic results can be obtained based on "temporal snapshots" only, i.e. without performing simulation. A first application of this **state-based approach** to subsystems of the guiding applications has provided evidence that these conditions may hold for interesting classes of faults [Dressler 96], [Malik and Struss 96], [Struss et al. 97], [Struss 97].
- **Limited measurability -** Very few sensors are available in the presented guiding applications. One way of trying to compensate for the limited observability esp. on-board is to use a strong model, or more specifically, to use **fault models.** The idea behind this is

to improve fault localization by means of fault identification, which means exonerating certain components through refutation of all faults they can possibly exhibit. Fault models can also be used to appropriately model the dynamics of the system when the fault first occurs. Appropriate knowledge of this contributes to the results in [Theseider Dupré and Panati 98].

- **On-board diagnosis (real-time) needs**. Computational and memory requirements of on-board diagnosis functions must be relatively low to bring them into state-of-the art ECUs. An option to ensure this is to **precompile** selected results of model-based reasoning, especially in cases where extensive computation is needed, to be used on-board.
- **Models for diagnosis.** Many kinds of models for design, simulation and manufacturing are widespread in use, but they are not necessarily appropriate for diagnosis. A **behaviour model of the device** under diagnosis explicitly captures the knowledge about the device behaviour. This is in fact the key point for the success of an automatic diagnosis. Since any new information has a cost (implies an extra sensor for on-board diagnosis, or an extra measurement for off-board diagnosis) it is clear that redundant information is to be avoided as much as incomplete information. For example, even if faults in the **electronic control unit (ECU)** itself are not considered, the behaviour of the control unit has to be modelled in some cases, since it is part of the feedback loop comprising sensors and actuators. Nevertheless, various formalisms of the behaviour representation are possible and were investigated in VMBD. **Quantitative behaviour models** were used in the ATS application in order to get deeper insight in the fault cases and their dynamic manifestations. Furthermore this application used **interval-based descriptions** to deal with parameter tolerances and other model and measurement uncertainties. **Qualitative descriptions** reflect the nature of available observations, e.g. "black smoke" symptoms in the DTI system. By covering entire classes of behaviours, they also help to keep the library of model fragments manageable. In some cases it appears not to be relevant to reason in terms of the actual values of quantities. Rather, it can be sufficient to reason in terms of **(qualitative) deviations** from nominal values only. In addition to distinctions expressed in the quantity space of variables, it also turned out necessary to distinguish different **orders of magnitude** of the relevant physical quantities.

5 OVERVIEW OF ACHIEVED RESULTS

5.1 Diagnostic architecture

The diagnostic solutions that have been explored in VMBD, also in the context of specific guiding applications for both off-board and on-board diagnosis, can be described under several points of view.
The following Fig. 3 outlines the overall diagnostic architecture.

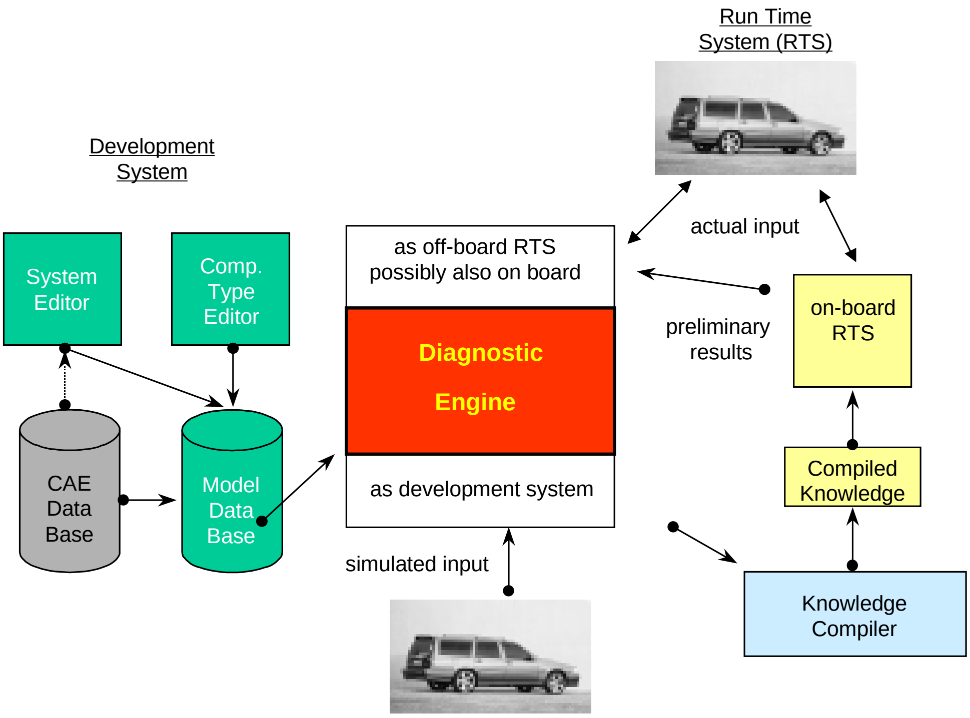

Fig. 3 Diagnostic architecture in VMBD

The standard (consistency-based) machinery of model-based diagnosis [Console et al 92] is adopted as a reference for the diagnosis engine; in a nutshell, it can be described as follows:

- **Observations** of the actual behaviour are entered.
- Based on the **device model** (from the model data base) **conclusions** are computed about system parameters and variables (observed and unobserved).
- If a **contradiction** is detected, i.e. conflicting conclusions / observations for a parameter or variable (fault detection), the set of component modules involved in it indicates which components possibly deviate from their intended behaviour. This can be determined by the diagnosis system because the device model has a structure that reflects the device constituents that may incorporate faults.
- **Diagnosis hypotheses** are generated, i.e. sets of faulty components that account for all detected contradiction (fault localization).
- Suggestions for useful **probes and tests** are generated. This is possible because the behaviour model reveals where the diagnosis hypotheses entail distinctive features of behaviour. This function can be used to reduce the costs in cases where observations are expensive and to act as a filter when the amount of information is overwhelming (see e.g. [Beschta et al 93])
- In case **models of faulty behaviour** are provided , the same approach (checking consistency of a model with the observations) can be used to discard particular faults and to conclude correctness of certain components if the set of modelled faults is considered complete.

Three diagnostic solutions have been realized based on this machinery: the MDS tool of DaimlerChrysler has been employed for the Automatic Transmisson application,; RAZ'R from OCC'M Software has been used for the DTI application; for the CoRa application a prototype has been developed which is based on the approach in [Theseider Dupré and Panati 98].

As mentioned in section 4, the contextual conditions for on-board diagnosis suggested also the exploration of the use of knowledge compilation techniques for generating the knowledge base used by the on-board run time system.

An instance of this approach is presented in [Cascio et al 99] in the context of the CoRa guiding application.

5.2 Demonstrators

Two demonstrator vehicles were available in the VMBD project, one for the Common Rail injection system (a Lancia k with a pre-series 2.4 diesel engine) and one for the automatic transmission system and for the distributor-type injection system (Volvo V70 TDI). For all three guiding applications, failures were induced in the cars, the model-based diagnosis system was run and the results were compared with the conventional diagnostic capabilities of the corresponding control units. The various failures in the demonstrator cars can be injected by switchboards from inside the passenger compartment. The pneumatic leakages for example are simulated by installing additional valves controlled by electrical switches. In some cases faults are actuated only for a fixed time interval for safety reasons.

At present, electronic control units still have rather limited computing power which does not suffice to integrate a model-based diagnosis system within the ECU software. To circumvent these restrictions, so-called application control units were used in the VMBD project. Application control units are normally used for adjustment and optimization of ECU parameters for a specific vehicle type and are equipped with special dual-ported memory chips such that in principle all variables and signals of the control unit are accessible in real time, without interfering its normal operation. The data of the vehicle is interfaced to the model-based diagnosis system, which is running on a portable PC inside the passenger compartment.

Automatic Transmission System

For dealing with the so-called "hard" faults (cf. section 3.3), such as stuck-at valves, a systematic (interval-based) modelling for computing steady states in electrical, hydraulic and mechanical systems was used. The monitoring of the transmission input-output speed ratio is sufficient for detecting and diagnosing these faults. An increased discrimination power is achieved if the diagnosis results are corroborated across several shift changes, because the set of active elements depends on the shift.

The "soft" faults raised more difficult problems. Quantitative simulation and analysis was used in order to identify measurable manifestations of the bad shift quality and to define the requirements for the component models. Two parameters of the shift transient have been chosen to characterise the shift quality, namely: (1) the time when the slippage phase begins (relative to the beginning of the shift), and (2) the duration of the slippage phase. For diagnosis we used only the qualitative deviations of the above parameters from the normal values. However, obtaining the nominal values of the above parameters has been a difficult task. For this purpose a detailed simulation model synchronised with the engine and transmission controls has been used. A significant effort has been put in the calibration of this simulation model in order to obtain acceptable estimations of the nominal parameters that reflect the (continuous) control and the various operating conditions. The qualitative deviations between the predicted and the observed shift transient properties are then used for diagnosis. During diagnosis, for each considered fault case simulation is also performed, but with a somehow simplified approach. Although the models used are relatively complex, the time required for diagnosis is within acceptable limits (e.g. not more than a few minutes).

Measurements from the Volvo V70 have been recorded for fault free and several built-in faults and for several operating conditions. The measurements included: the working hydraulic pressure, the wheel torque, the input and output transmission speed and the ECU commands. For most of the cases the fault detection provided correct answers, with the exception of some cases where the deviations are too small to be reliably taken into consideration. For the cases where significant deviations can be observed, the diagnosis results always included the real fault injected into the car. Although usually more than one fault is found consistent with the symptoms, the achieved fault discrimination exceeded our initial expectations.

We should finally note that most of the faults affecting the shift quality are not detected by the current ECU diagnostics and that the diagnosis of the shift quality is extremely difficult for the repair technicians.

Common Rail System

For demonstrating results in the Common Rail application, a Lancia k car with a pre-series 2.4 Common Rail engine has been used.

Moreover, hardware and software interfaces have been installed for data acquisition from the ECU to a portable PC. The diagnosis system runs on the PC, but, relying on a compact representation (a decision tree) it could be embedded, even if this was not in the scope of the project, into current technology ECUs and control software.

In fact, the model-based diagnosis system used in this application has been run off-line to produce decision trees suitable to be embedded on board [Cascio et al. 99]. With respect to the goals in section 3.4, the model-based approach has proven to be effective in allowing the analysis of different configurations of the hardware/software system, with possible additional sensors, to evaluate the results as regards fault identification, or at least choice of appropriate recovery actions. This is interesting for the Common Rail system, since a lot of different faults, including some that are safety critical, can lead to a pressure drop in the rail. For a more detailed description of the results see [Cascio et al 99].

Essential to these results is the fact that a model-based diagnosis system is based on reasoning modules that are independent from the specific system to be diagnosed, relying on an *explicit, modular* and *reusable* representation of the system to be diagnosed.

The on-board runtime system, other than the decision tree interpreter, includes a module for interpreting actual signals, abstracting from such data information about whether the signal is deviating (positively or negatively) from its expected value. This information is used to traverse the decision tree. We stress however that such decision tree is not developed ad hoc, but produced automatically from a representation of the system to be diagnosed and can be produced with little effort for variants of the system

Distributor Type Injection System

For the DTI system, case studies for both automated behaviour prediction and diagnosis were performed. We present results for one diagnostic scenario in more detail. One of the scenarios installed in the DTI demonstrator vehicle is a leakage in the air intake pipe between the turboloader turbine and the intake manifold. The leakage has an effect only if the pressure in the pipe (i.e. boost pressure) is significantly different from the pressure outside (i.e. atmospheric pressure), which means that the failure is not visible e.g. during idling.

The current control unit software in the DTI system is not able to detect the above failure. Diagnosis Runtime System Session for Scenario 1 (leakage in the air intake pipe). Fig. 4 shows the diagnostic results for a slowly opening leakage during stalling the engine. The diagnosis system uses only the sensor signals that are available also to the control unit (shown in the upper part of the window), and no additional sensors. The diagnosis runtime system successively detects three conflicting assumption sets, which combine to the overall result of two single fault hypotheses and a number of multiple fault hypotheses. The two single faults contain the component where the failure was actually induced.

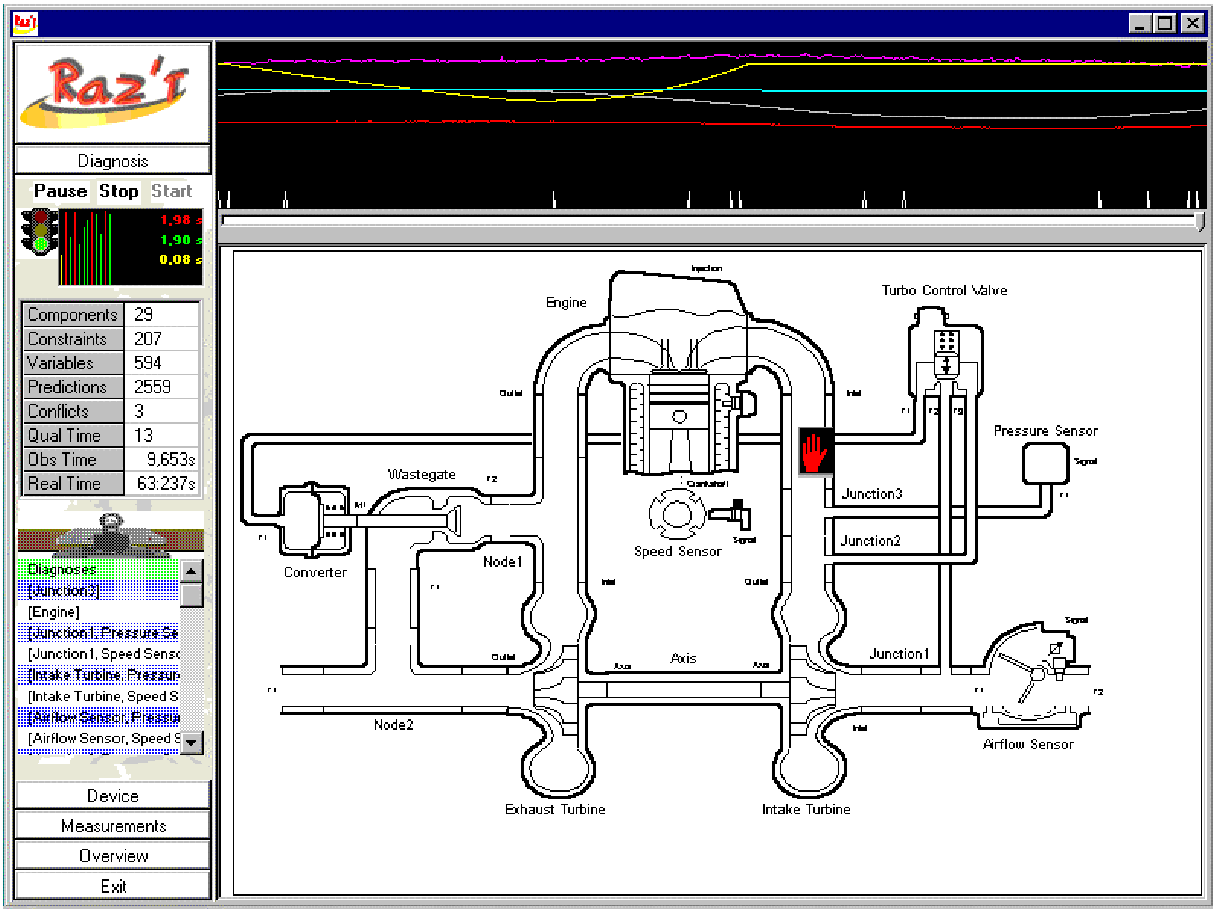

Fig. 4: Diagnosis Runtime System Session for Scenario 1 (leakage in the air intake pipe)

Similar results where achieved for the rest of the scenarios. Because some effects are noticeable only during certain operating conditions, and due to the unspecific nature of some of the faults, the diagnosis system cannot always determine a unique diagnosis, but rather yields a number of hypotheses as in the example above. In this case, fault models could be used to further constrain the set of diagnostic candidates. For the experiments, however, only models of correct behaviour have been used so far.

6 Conclusions

The component and system models described above, combined with the mentioned diagnostic architecture, and the shown results on the guiding applications provide important first steps presenting MBD in the automotive field applied to a wide range of fault scenarios. Proving the utility of model-based systems on real vehicles will be the next essential step in the industrial exploitation of our technology, not only in the car industry. Besides the technical issues, we would like to convey two important messages based on our experience:

- to managers and technical staff in industry: the technology is maturing, and becoming increasingly relevant to real applications,
- to the research community: addressing industrial applications and pursuing practical goals is a major driving force for research in the field rather than a distraction or road block.

Model building and exchange. Building the appropriate models is still carried out mostly by computer scientists or other experts with a background in engineering. However, modelling techniques should be designed so as to make them accessible to a wider class of users, in particular to engineers in industry, and they should allow for the derivation of suitable models from existing mathematical models

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REFERENCES

[Beschta et al 93] A. Beschta, O. Dressler, H. Freitag, M. Montag, P. Struss - A model-based approach to fault localisation in power transmission networks, Intelligent Systems Engineering 2(1), 1993, 3-14

[Bosch 96] Robert Bosch GmbH (ed.) 1996. Automotive Handbook, 4th Edition. Warrendale, PA: Society of Automotive Engineers (SAE)

[Cascio et al 99] F. Cascio, L. Console, M. Guagliumi, M. Osella, A. Panati, S. Sottano, D. Theseider Dupré - Strategies for on-board diagnostics of dynamic automotive systems using qualitative models, AI Communications, June 1999.

[Console et al 92] L. Console, W. Hamscher, J. deKleer (Eds.) - Readings in model-based diagnosis, Morgan Kaufmann, San Mateo, 1992

[Dressler 96] O. Dressler - On-line diagnosis and monitoring of dynamic systems based on qualitative models and dependency-based diagnosis engines. In Proceedings of the European Conference on Artificial Intelligence (ECAI-96), John Wiley & Sons

[Malik and Struss 96] A. Malik, P. Struss - Diagnosis of dynamic systems does not necessarily require simulation. In Workshop Notes of the 10th International Workshop on Qualitative Reasoning (QR-96), AAAI Press

[Price and Taylor 98] C. Price, N. Taylor - Abstract modelling for diagnosis, In Workshop notes of AAAI Workshop on Functional Reasoning, AAAI-98, Madison, Wisconsin

[Sachenbacher et al. 98] M. Sachenbacher, P. Struss, C. Carlen - Qualitative deviation models for automotive diagnosis, submitted to AICom

[Struss 97] P. Struss - Fundamentals of model-based diagnosis of dynamic systems. In Proceedings of the 15th International Joint Conference on Artificial Intelligence (IJCAI-97), Nagoya, Japan

[Struss et al. 97] P. Struss, M. Sachenbacher, F. Dummert: Diagnosing a Dynamic System with (almost) no Observations, Workshop Notes of the 11th International Workshop on Qualitative Reasoning, (QR-97) Cortona, Italy, pp. 193-201, 1997.

[Theseider Dupré and Panati 98] D. Theseider Dupré, A. Panati - State-based vs simulation-based diagnosis of dynamic systems. In Workshop Notes of the 9th International Workshop on Principles of Diagnosis (DX-98), Cape Cod, USA.

[Cascio et al 99] F. Cascio, L. Console, M. Guagliumi, M. Osella, A. Panati, S. Sottano, D. Theseider Dupré - Strategies for on-board diagnostics of dynamic automotive systems using qualitative models, AI Communications, June 1999