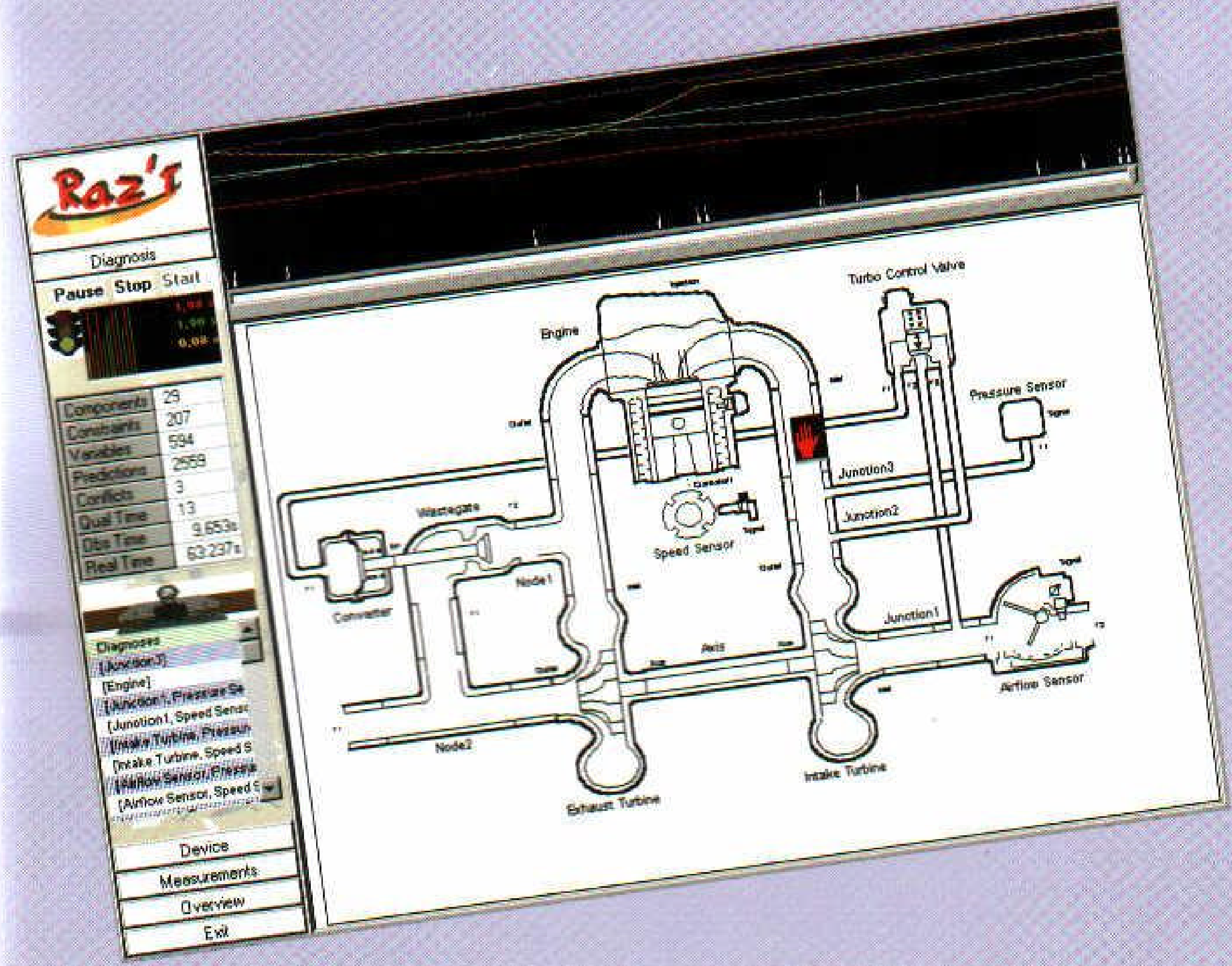
# ELECTRONIC ENGINE CONTROLS 2000

## Modeling, Neural Networks, OBD, and Sensors



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Variables 594
Predictions 2959
Conflicts 3
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# Advances in Design and Implementation of OBD Functions for Diesel Injection Based on a Qualitative Approach to Diagnosis

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## ABSTRACT

This paper reports on the application of model-based diagnosis techniques to diesel engine management systems within the Brite-EuRam project "Vehicle Model Based Diagnosis". We discuss some major requirements that have been identified in this application. In particular, it is essential to solve the inherent variant problem, to reason across different physical domains and to fulfill real-time needs for on-board diagnosis. The main foundation of our approach is to use qualitative models, especially qualitative deviation models, which serve as a coherent modeling paradigm for the different domains. In the project, this technology has been implemented and evaluated for on-board diagnosis on two demonstrator vehicles. The paper also discusses further perspectives of the technology for tools supporting the development and implementation of on-board diagnosis.

## INTRODUCTION: CHALLENGES FOR DIAGNOSIS

It is estimated that European passenger cars have an average annual 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 diagnosis and repair. At the same time, with increased environmental awareness, stricter constraints are imposed on the car manufacturers to develop clean cars, and also to keep them clean during their life cycle (see e.g. [8]). These growing constraints are reflected in increased requirements on on-board diagnostics. For diesel engine management control units, currently about one half of the software is dedicated to diagnosis, with increasing tendency.

On-board diagnosis aims at signaling alarms to warn the driver, selecting appropriate recovery actions and/or generating fault codes that can be further used in the service bays to track down a failure. The design of such diagnosis functions in a motor vehicle has to cope with a number of well-known challenges:

*Variant problem.* Automotive systems come in different variants. A supplier of automotive subsystems has to develop his products for many vehicle manufacturers and a lot of vehicle models, which all put somewhat different requirements on the base system. They may differ in the number of sensors, and redundant parts may be present or absent dependent on the specific car manufacturer. Also, the components themselves come in different constructive details. These modifications must be thoroughly handled in the diagnosis algorithms. However, generating specialized diagnostics for all variants by hand turns out to be an extremely expensive task.

*Dynamic and controlled subsystems.* Every complex automotive system has internal states depending on previous inputs, thus being an example of a dynamic system. The effects of faults may be compensated by control. For example, the control unit of the Common Rail injection system ([2]) may, to a certain extent, compensate for leakage in the high-pressure hydraulics. Therefore, 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, e.g. through changed time constants or oscillatory behavior. It becomes a problem especially in combination with low measurement quality, that is, if there are only few measurements within feedback loops over time. Determining correct diagnostics that covers these situations is a complex task, often infeasible for hand-crafted diagnostic procedures.

*Limited measurability.* Very few sensors are available e.g. for the hydraulic parts of diesel injection systems. This is especially true for the high pressure hydraulics of the Common Rail system, which contains only one pressure sensor. In addition, the context in which a car is operated in (e.g. road and weather conditions, load) is highly dynamic, uncertain and often neither measurable nor reproducible. The main consequences are noisy signals and rather qualitative symptom descriptions. Diagnosis has to be capable of processing such information.

*Real-time needs.* On-board diagnosis must come up with a conclusion before the system has to move to another state (e.g. shut off the engine) to prevent safety-critical situations or severe system damage, or to comply with legal restrictions. As a consequence, the computational and memory requirements of on-board diagnosis functions must be relatively low to bring them into state-of-the art ECUs.

*Lack of standards.* A growing interest lies in the development of standards, i.e. in the possibility to utilize the same set of techniques for all phases of the design process, e.g. for pre-design, function-design and layout of the diagnostic concept, as well as for diagnosis and fault tracing in the service bay. Since car manufacturers work with a number of system and component suppliers, there is a great, currently unfulfilled, demand for a standardized approach among the parties involved.

*Missing methodology.* At present, the development ("design") of diagnosis of electronically controlled automotive systems does not follow precisely defined methodologies or criteria and it is generally regarded as an addendum to the design of the system. It must therefore cope with many constraints and limitations sometimes impairing its efficiency.

Of course, in current ECUs there already exist routines which monitor the sensor values in order to detect failures. Current on-board diagnosis can detect faults on the basis of predefined range and plausibility checks for signals. When these routines detect a problem, built-in recovery actions that depend on the assumed failure and the expected failure effects will be performed that range from minor performance reductions to full engine stop, attempting to take the vehicle into safe operational conditions (e.g. limp-home).

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. One way of trying to compensate for the limited observability on-board is to exploit the interdependence between different signals in the electronic control unit (ECU) and to perform so-called cross-checks of signals. But currently, this is not done in a general and systematic way, leading to sub-optimal solutions. As the traditional techniques may be insufficient to fulfill the upcoming requirements, the goal of this paper is to show ways to overcome them through a more sophisticated approach to diagnosis. Especially, we describe outcomes of a European project that aimed at assessing the utility of model-based diagnosis for OBD development by experimenting with suitable systems on two different diesel engine management systems in demonstrator vehicles.

The paper is organized as follows. In the next section, the key ideas towards a model-based approach to OBD are outlined. In section 3, the paper introduces the VMBD project, which provided the framework for experimenting with this approach on two guiding applications as described in sections 4 and 5. Section 6 outlines some of the main achievements of this project. Plans for further work are described in section 7.

## KEY IDEAS TOWARDS A MODEL-BASED APPROACH TO DIAGNOSIS

In the authors' opinion, all the above-mentioned requirements on OBD can only be fulfilled in the future by a methodical, computer supported process in the design and implementation phase of diagnosis functions. The choice of a model-based approach is founded on the recognition that 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 component types
- in most cases, malfunctions of the car or a system are due to some component failure
- component behavior can be described by relations among local variables and parameters
- system behavior is established by the behavior of its components and their connections w.r.t. processing of material, energy or signals.

Therefore, we applied a knowledge-based systems approach to diagnosis which is based on the fundamental idea to separate and represent different elements of knowledge within a computer program. At its core, it consists of a declarative and modular representation of knowledge about a family of technical devices in terms of a library of component behavior models and, separated from this knowledge, a set of domain-independent diagnosis algorithms to exploit the models:

- *domain specific knowledge* is captured by a library of behavior models of components and physical phenomena relevant to an application domain,
- *system specific knowledge* appears as a structural description of the device which refers to elements contained in the model library,
- *task specific knowledge* is implemented as a diagnosis algorithm that is independent of a particular domain or type of system.

This separation allows for the re-use of the represented domain knowledge for modeling different systems for different tasks and the re-use of the diagnosis algorithm for various application domains. Furthermore, it forms the basis for features that are highly relevant to the process of modeling and creation of diagnostics:

- *automated compositional modeling:* a (mathematical) behavior model of a system is obtained by automated composition of models from the library according to the structural description.
- *automated generation of diagnostics:* a system-specific diagnosis system tailored to a particular device is generated automatically by linking the general diagnosis algorithm to the composed device model (see figure 2-1).

Apart from being compositional, the models differ from models used for numerical simulation or observer-based approaches to diagnosis in that they represent a conceptual, or physical, layer of the device which enables the diagnosis system to explicitly reason about the device, its components and faults at this level. As for the methods developed in control theory, the basic principle of the diagnosis algorithm is to derive diagnostic hypotheses as a revision of the model with the goal to remove contradictions with the actual observations of the system. Knowledge-based diagnosis, however, is not limited to a mathematical procedure (like parameter fitting or computing residuals), but exploits a logic-based algorithm that can handle assumptions about the constituents of the model, to determine type and/or location of a fault as the logically possible origins of contradictions.

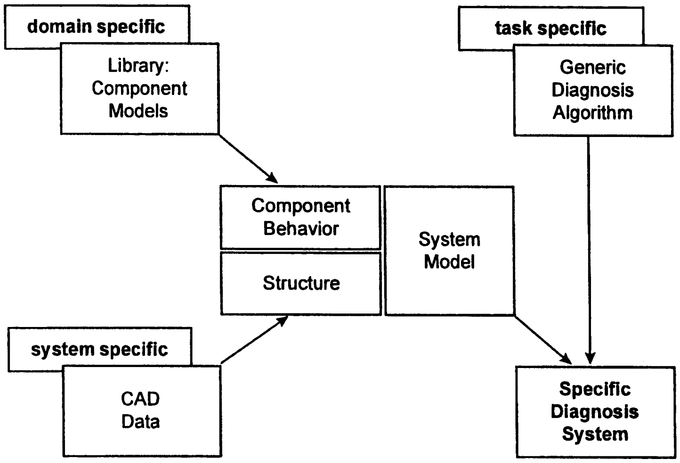


Figure 2-1. Model-based automatic generation of diagnosis systems

In a nutshell, the standard, so-called consistency-based machinery of this model-based approach to diagnosis ([6]) can be described as follows:

- Observations of the actual behavior are entered.
- Based on the device model, conclusions are computed about system parameters and variables (observed and unobserved). For each derived conclusion, 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 parameter or variable occur (fault detection), the set of components involved in it indicates which components possibly deviate from their intended behavior.
- Diagnosis hypotheses are generated, i.e. sets of faulty components that account for all detected contradictions (fault localization).
- In case models of faulty behavior 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.

Thus, a way of creating diagnostics for all variants of vehicle subsystems is obtained that is systematic as well as efficient and supported by powerful computer tools, which helps remedying the variant problem. It ensures that the correctness and completeness of diagnosis results is solely determined by of the quality and completeness of the models.

Furthermore, the knowledge-based approach is able to exploit non-numerical models: *Qualitative modeling* has developed mathematical foundations and systems for representing partial knowledge about system behavior and for computation of behavior descriptions based on this. Qualitative descriptions reflect the nature of available observations, e.g. "black smoke" symptoms in the DTI system (section 5). By covering entire classes of behaviors, they also help to keep the library of model fragments manageable. Qualitative modeling allows to cover classes of systems (with irrelevant differences in parameters), classes of symptoms (such as vague customer complaints) and classes of faults (e.g. leakage of different or unknown sizes). Where appropriate, qualitative modeling avoids the computational complexity of numerical modeling and simulation and provides efficient algorithms that even enables running of model-based diagnosis on-board a vehicle.

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. For example, it may suffice to explain why the pressure in the hydraulic system is (much) higher than it should be, regardless of the actual value of the pressure. Based on a theoretical foundation of such deviations, models have been developed that declare and propagate deviations from some nominal or reference behavior (which is possibly left unspecified), even across different domains. In particular, we use models of *qualitative deviations*, mathematical expressions which describe (directions of) changes in device variables over time or w.r.t. a reference value. This reflects the fact that diagnosis requires to detect and exploit significant distinctions in device behavior rather than arbitrary numerical differences.

The model libraries for the experiments conducted in section 4 and 5 consist of qualitative behavior models for electrical, hydraulic and pneumatic components, and a qualitative mean-value model of the diesel engine (i.e., in-cycle variations are not considered). Qualitative behavior more specifically means here that the component models consider only signs of parameters and their deviations occurring in the models equations.

## THE VMBD PROJECT

The European Commission recognized the importance of diagnostics and maintenance in the field of automotive applications. To push the development in this area, it funded the project Vehicle Model Based Diagnosis (VMBD).

To make best use of the synergy of the involved parties, the project consortium combined a mix of car manufacturers, suppliers and a manufacturer of automotive diagnostic equipment. OCC'M, a small diagnostic software firm, added knowledge to the consortium through their model based experts. The ongoing research in the field is reflected by co-operation with academic partners coming from the University of Turin, University of Wales at Aberystwyth, and the University of Paris Nord.

VMBD aimed at making a major step forward in the industrial application of model based methods by evaluating the technology in a realistic context, i.e. on demonstrator cars, in a set of guiding applications:

- 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.

Two different diesel injection systems that pose different requirements on diagnosis were chosen as guiding applications in the project: the Common Rail injection system and the Distributor-type injection system.

Common Rail (CRI) is a new flexible fuel injection system for Diesel engines ([2]). It allows, besides variation of fuel quantity and injection start, injection pressures varying in a broad range and fuel amount injected in any desired segmented delivery. These new capabilities further improve Diesel engines concerning noise, exhaust emissions and engine torque. For the Common Rail system, special attention must be paid to safety related aspects. These are mainly due to the very high fuel pressure in the rail that could cause, for example, dangerous fuel sprays in case of leakage or severe engine damage in case of blocked injectors. Furthermore this system has a "drive by wire" functionality of the accelerator pedal that could produce sudden accelerations in faulty modes. This imposes special requirements on diagnosis on-board.

In contrast, the Distributor-type Diesel injection (DTI, see [10]), is an older and already approved system that has been on the market for many years. However, more rigorous legal regulations and customer demands, especially related to emissions and performance, have lead to an increased effort to avoid temporarily irregular operations called "black smoke" symptoms.

DEMONSTRATORS – Two demonstrator cars were available in the VMBD project, one for the common rail injection system (Lancia k CR) and one for the distributor-type injection system (Volvo 850 TDI). For both guiding applications, failures were induced in the cars during various operational conditions of the engine, the model-based diagnosis system was started and results were compared with the conventional diagnostic capabilities of the corresponding control units. The various failures in the demonstrator cars could be adjusted by potentiometers and triggered by switchboards from inside the passenger compartment. The pneumatic leakage, for example, was simulated by installing additional valves controlled by electrical switches.

For the experiments, additional interfaces and devices had to be installed in both cars. Starting with the basic requirements and the following considerations:

- the present control unit and the diagnosis algorithms should work without interruption (safety reasons),
- the model based diagnostics needs (at least) the same information about the sensor signals,
- the related software runs on a separate computer (notebook), as the resources of the available ECU are exhausted,

The architecture of the measurement facilities was chosen as shown in figure 3-1.

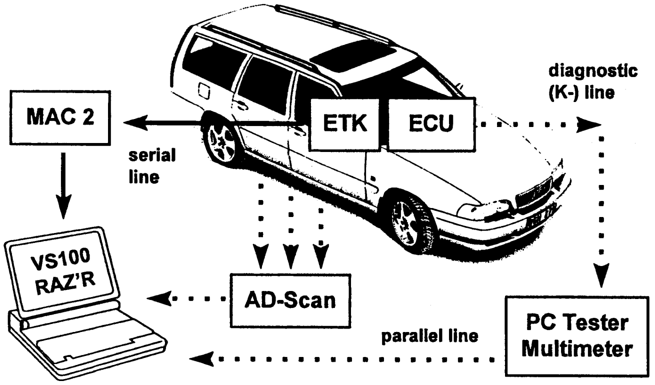


Figure 3-1. Architecture for data acquisition in the demonstrators

At present, electronic control units still have rather limited computing power which is not strong enough 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 calibration of ECU software 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.

In figure 3-1, ETK is a hardware interface closely attached to the application ECU providing access to the controller bus. MAC is a protocol conversion box which stores the information gathered from the ETK, while INCA (or VS100) is a commercial tool for acquisition, storage, interpretation and display of signal data. It runs on the same portable PC as the on-board diagnostic systems developed in VMBD. The AD-Scan device and the PC Tester allow to read in further signals from additional sensors or workshop equipment for the purpose of off-board diagnosis.

Although this means that the model-based diagnostic software is not really running on-board within the ECU, we consider this solution adequate for our case studies since it provides all important constraints except the space and computing power limitations of the ECU (which are beginning to be more and more relaxed in practice).

The VMBD diagnostic software itself includes as run-time components:

- A component for the conversion of signals (acquired by INCA/VS100) into qualitative values and qualitative deviations, as explained in section 2.
- The prototypic decision tree interpreter in the CRI application and a complete commercial model-based run-time system in the DTI application respectively, cf. the next sections.

## THE COMMON RAIL DEMONSTRATOR

COMMON RAIL SYSTEM – A pre-supply pump sucks in fuel from the tank and feeds the high pressure pump which is driven by the combustion engine and delivers fuel via the rail (an accumulator and distributor element) to the injectors of the engine cylinders. One part of this fuel is injected into the combustion chambers of the engine, a smaller part controls the injection nozzles and then flows back to the tank. The fuel in the rail is compressible and dampens oscillations initiated by the pulsating delivery of the high pressure pump and especially by the abrupt extraction of fuel via the injectors. A pressure sensor measures the fuel pressure in the rail, then its signal is compared to a desired value stored in the ECU. If the measured value and the desired value are different, an overflow orifice in the pressure regulator on the high pressure side is opened or closed taking the overflow fuel back to the tank. The injectors are opened and closed by the ECU at predefined times. The duration of injection, the fuel pressure in the rail, and the flow area of the injector determine the injected fuel quantity. The ECU controls the engine and provides information for the driver and diagnostic data for the mechanic. The driver's demand information for example is taken from the accelerator pedal, the ECU transforms this request in fuel amount taking the actual engine situation into account. For a schematic diagram and further details see [2].

SELECTED FAULT SCENARIOS – Several fault scenarios were chosen in the project VMBD to develop the diagnostic approach for this Common Rail system. The selection was done according to:

- ease of inducing the fault,
- exclusion of danger possibly caused by the induced fault,
- relevance of fault during car operation.

Such faults in the Common Rail system are for example failures of the electrical fuel pump, the pressure regulator and pressure sensor, and fuel injection problems caused by faulty injectors. All these failures can occur intermittently, making them hard to diagnose, off-board as well as on-board. The ECU currently shuts down the system in any of the above situations, although this is not always necessary. A fault in the pressure sensor, for example, could be handled by switching to open loop control of the pressure in the rail. A malfunctioning pressure regulator, on the other hand, could lead to a critical fuel pressure in the rail and, hence, really requires to stop the engine immediately (further details will be found in [5]).

DIAGNOSIS GOAL – In the on-board case, the diagnostic system must promptly react to anomalies and must take an appropriate measure to achieve safe operation of the car. This means also that the on-board diagnostics should be especially focused on performing recovery actions, rather than on the actual isolation of the fault(s). Nevertheless, keeping track of more detailed information about the fault that occurred can be an important information for the diagnostic system that will be used in the service bay in order to localize and identify the fault. In case of faults in the CRI system, such possible actions to be taken by the ECU are:

- slightly limiting the performance, e.g. decreasing the maximum value of the rail pressure (which excludes a high acceleration)
- switching to a "limp home" mode where the system variables are forced to be in idle mode. In this way the rail pressure is low, and the engine speed is kept constant, while still allowing the driver to reach e.g. a service bay.
- stopping the engine if any dangerous failure is suspected.

In one scenario even a sensor placement problem was tackled: how can less critical faults in the low pressure part of the fuel supply (like a loose contact of the electrical fuel pump power line) be discriminated from severe ones. Model based diagnosis predicted apart from a decrease of pressure before the high pressure pump also a drop in the rail pressure. The discriminative power was tested that would be gained if an additional pressure sensor was placed at this location. The set of diagnostic candidates inferred consisted of electrical faults in the power supply of the ECU and the electrical fuel pump, together with some less safety critical hydraulic faults, like an empty fuel tank or a clogged filter. None of these faults are considered severe enough to require a complete system shut down. This result indicates that in some situations, the additional sensor can enable on-board diagnosis of the Common Rail to take less restrictive recovery actions.

TEST EQUIPMENT – For the tests in VMBD a prototype Lancia car with a pre-series Common rail engine was equipped with appropriate hardware and software for data acquisition (see also section 3). The fuel delivery subsystem was modified for the induction of faults mentioned above; in particular, for switching off the electric pump in the low pressure subsystem, for switching off the PWM (pulse width modulation) command to the pressure regulator (so that it remains open), or for supplying or not supplying one injector with current, so that it remains always open, or always closed, regardless of the opening commands from the ECU. For all four described scenarios an electrical circuit for injecting the fault was designed; the fault can now be chosen by a selector and activated by pressing a button during an adjustable time period. Both the selector and the button are placed on the demonstrator car dashboard. Furthermore, a sensor in the low pressure subsystem (between the filter and the high pressure pump) was installed; it detects whether the pressure there is sufficient to deliver fuel to the high pressure pump.

The conversion from physical signals to qualitative deviation data was one of the central work-packages in both guiding applications. Though this task was not in the scope of the project, its correctness was essential for a demonstration on real data. Each observable in the system was analyzed in order to evaluate a reference value in each operational condition. The actual data were compared with this reference value. A deviation was identified if the data from the ECU - filtered to reduce noise - are higher or lower than a confidence band. This signal elaboration and conversion was implemented in C++ and the program was then compiled as a Windows DLL module, which is now part of the on-board diagnostic system in the demonstrator.

DIAGNOSTIC APPROACH – In the VMBD project, two goals came into conflict and were solved in both Diesel applications in different ways:

- to show that the model-based technology provides interesting advantages and can be exploited also for on-board applications and
- to avoid a major revolution in the hardware (and software) technologies currently used on-board.

Such considerations point out that an immediate adoption of model-based diagnosis on board generates new problems. Moreover, use of the full power of the model-based approach on board seems often to be unnecessary, as first of all the failure has to be detected and a suitable recovery action has to be taken. In conventional controllers this on-board diagnostic task is performed using simpler techniques, such as "pattern-action" rules or decision trees, because they can be easily implemented in the ECU software. Already here, the model-based approach can play a fundamental role in automatically generating a simpler knowledge base and necessary diagnostic strategies to be implemented on-board.

Therefore, for the CR application a diagnosis prototype based on the approach in [9] was developed. As the basic type of knowledge we need on-board is a set of associations between patterns of values of observable signals and the possible recovery actions, it was decided to implement such associations and the classification process for selecting the best action in a given situation as a decision tree. The choice is motivated by the fact that a decision tree interpreter can be implemented very efficiently on any hardware platform and without requiring a lot of memory. Moreover, there are well-known algorithms in order to build trees from examples (e.g. ID3 in [4]). This means that the tree can be built automatically starting from a set of examples, where each example is an association between a pattern of values of the observable parameters and the corresponding actions (and diagnoses). The exciting point is that the set of examples can be produced automatically using a model-based diagnostic engine that is directly fed from a model library of the system.

The experiments done with the Common Rail demonstrator have completely reached the desired results. The selection of the recovery actions and the fault identification was fully compatible with the expected behavior. It is worth noting that for one scenario this diagnostic approach is better than the currently used procedure, which, however, is not able to evaluate an additional sensor in the low pressure fuel system (but could use additional information such as plausibility checks concerning other internal variables in the ECU).

## THE DTI DEMONSTRATOR

DISTRIBUTOR-TYPE INJECTION SYSTEM – The second demonstrator vehicle in the VMBD project is a Volvo car equipped with the so-called distributor-type injection (DTI) system. In contrast to the Common Rail injection, the DTI is an approved system which has been on the market for many years. However, increased legislative and customer demands have lead to new requirements especially for aspects related to emissions and performance of this system.

Possible problems include, for example, incomplete fuel combustion and increased carbon emissions due to an excessive quantity of fuel injected or insufficient airflow to the engine. A major category of failures which can lead to this class of symptoms (which are often called "black smoke" problems) involves faults in the air supply. The responsible subsystems can be decomposed into the exhaust part (exhaust gas re-circulation subsystem) and the air intake part (turbo control subsystem).

The purpose of the exhaust gas re-circulation system is to return a certain amount of the exhaust gases to the intake air to decrease the oxygen rate of the intake air and thus to reduce emission levels of the fuel combustion. Depending on driving conditions, the ECU governs a converter to achieve a certain air pressure in a control pipe, which in turn sets the position of the exhaust gas re-circulation valve. The position of this re-circulation valve then determines how much of the exhaust gases are fed back to the air intake pipe.

The turbo control subsystem consists of a turbo-charger turbine, which is driven by the engine's exhaust gases, for compressing (and thereby increasing the mass of) the air taken into the engine. The ECU controls the boost pressure admitted in a certain driving situation by opening or closing the turbo control valve, which determines the position of a so-called waste-gate valve. The position of this valve determines how much of the exhaust gas drives the exhaust turbine of the turbo-charger.

In the DTI application, experiments were made to assess the potential of model-based diagnosis using qualitative component models to detect and localize failures in these subsystems.

DIAGNOSTIC SCENARIOS – The DTI control unit is already equipped with a restricted form of on-board diagnostic capabilities such that it continuously monitors part of the sensor signals and can detect a limited number of faults on the basis of predefined range and plausibility checks. We are interested in failures of the above-mentioned systems that can not be captured or are hard to capture by traditional on-board diagnosis. Such types of failures involve leakage in the air intake pipes, exhaust gas pipes or control 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. All these scenarios share the symptom of increased emissions, especially black smoke, and performance deterioration of the engine as their main symptoms. To gain a better understanding of the resulting effects, for some of these failures causal chains have been developed together with domain experts, sometimes based on reusing and refining existing failure mode and effects analysis (FMEA) documents.

One scenario consists of a leakage in the air hose between the turbine outlet and the intake manifold. The scenario was implemented in the car by installing an electric motor which opens a valve to release pressure from the inter-cooler system via a 12mm opening. If the leakage is opened, air (oxygen) mass is lost after having passed the air mass sensor. The fuel quantity calculated by the control unit which is based on this signal will therefore be too high for the actual amount of oxygen in the combustion chamber. This leads to incomplete combustion of the diesel fuel, which causes increased carbon emissions in the exhaust gas (due to non burnt particles) and reduces the torque of the engine. This effect is, depending on the driving condition, perceivable for the driver as black smoke coming out of the exhaust system.

In another scenario, a wrong flow from the exhaust gas re-circulation (EGR) system occurs due to a faulty signal or mechanical failure in the EGR valve. The real fault installed in the car consists of a switch used to control a magnetic valve that allows ingress of atmospheric pressure in the EGR valve, thus causing it to open outside its normal operating region.

The rest of the scenarios involved faults in the boost pressure sensor, airflow sensor and engine temperature sensor. These faults are injected in the car by electrically manipulating the respective signal to the control unit. Via a switch in the passenger compartment, potentiometers are connected to cause deviations of the signals.

In our experiments, we have tried these failures in various operating modes, such as idling, constant speed, full acceleration and engine stalling.

DTI MEASUREMENT SET-UP – From the control unit data available in the ETK (see section 3), the following set of signals was fed to the model for diagnosing the described scenarios:

- atmospheric pressure sensor signal
- boost pressure sensor signal
- mass airflow sensor signal
- engine speed sensor signal
- duty cycle of the turbo control valve
- current fuel quantity injected

DIAGNOSTIC RESULTS FOR THE DTI SYSTEM – Using this set-up, case studies for both automated behavior 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 was a leakage in the air intake pipe between the turbo-charger turbine and the intake manifold. The leakage has an effect only if the pressure in the pipe (i.e. the boost pressure) is significantly different from the pressure outside (i.e. the atmospheric pressure), which means that the failure is not visible e.g. during idling.

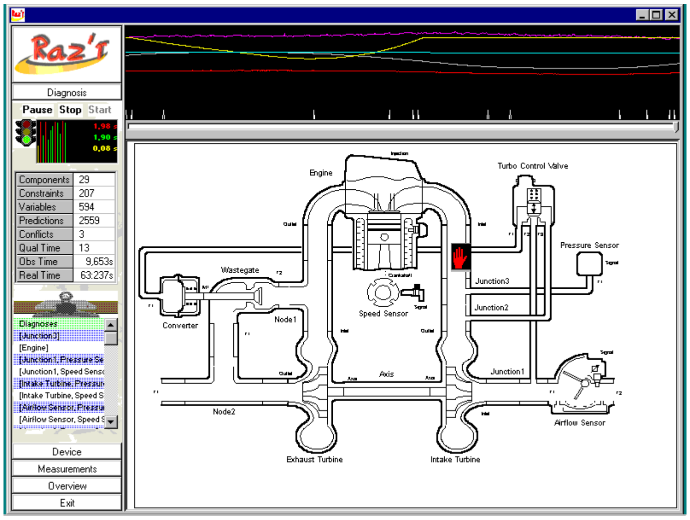
Figure 5-1 shows the diagnostic results for a slowly opening leakage during stalling the engine. The diagnosis system uses only the sensor signals that are available also to the control unit (shown in the upper part of the window), and no additional sensors. Based on these observations and the model, the diagnosis runtime system predicts values of the model variables and successively reveals three sets of conflicting assumptions:

- {Junction1, Intake Turbine, Junction3, Engine, Airflow Sensor, Junction2, Pressure Sensor}
- {Junction1, Intake Turbine, Junction3, Engine, Airflow Sensor, Junction2, Speed Sensor}
- {Junction3, Engine, Speed Sensor, Pressure Sensor}

Here, the component names stand for the assumption that the respective component is working correctly; i.e. at least one component in each of the above sets must be faulty. These conflict sets combine to the overall result of two single fault hypotheses and a number of multiple fault hypotheses:

- {Junction3}
- {Engine}
- {Pressure Sensor, Junction1}
- {Pressure Sensor, Intake Turbine}
- {Pressure Sensor, Airflow Sensor}
- {Pressure Sensor, Junction2}
- {Speed Sensor, Junction1}
- {Speed Sensor, Intake Turbine}
- {Speed Sensor, Airflow Sensor}
- {Speed Sensor, Junction2}
- {Speed Sensor, Pressure Sensor}

The two single fault hypotheses contain the component where the failure was actually induced ("Junction3", see mark in figure 5-1 within the window depicting the system structure).



| | |
|---|---|
| Components | 29 |
| Constraints | 207 |
| Variables | 594 |
| Predictions | 2559 |
| Conflicts | 3 |
| Qual Time | 13 |
| Obs Time | 9,653s |
| Real Time | 63:237s |

Diagnoses
[Junction3]
[Engine]
[Junction1, Pressure Se
[Junction1, Speed Sensc
[Intake Turbine, Pressur
[Intake Turbine, Speed S
[Airflow Sensor, Pressu
[Airflow Sensor, Speed S

Figure 1. Screenshot of the model-based run-time diagnosis prototype showing a leakage fault in the DTI turbo control subsystem

Similar results where achieved for the rest of the scenarios. Because some failure effects are noticeable only during certain operating conditions, and due to the coarse information provided by the current model, the diagnosis system cannot always determine an unambiguous diagnosis, but rather yields a number of hypotheses as in the example above. E.g. for the scenario with the boost pressure sensor out of tune, the diagnosis system yields two conflicts and outputs a list of four single faults which contain the boost pressure sensor as one possible candidate, but also three other components that could account for the same symptoms.

DISCUSSION OF THE RESULTS – The runtime for the prototype was, on average, slightly slower than real time, but sometimes faster than real time, on a Windows/Pentium PC. As opposed to the Common Rail demonstrator, no compilation of the model was performed for using it in the on-board environment. The results have been achieved using only the ordinary control unit signals, without installing any additional sensors in the car. Note that the current control unit software in the DTI system, based on the same signals, is not able to detect any of the above failures.

Relatively good fault localization could be achieved for the leakage scenario. The rest of the scenarios yields, depending on driving conditions, more ambiguous results. In these cases, fault models, e.g. knowledge about the behavior of faulty components, could be used to further constrain the set of diagnostic candidates. So far, only models of correct behavior have been used for the diagnostic experiments. At least in some cases, there is evidence that fault models could be useful to further constrain the set of diagnostic candidates.

Note also that the knowledge about the behavior of the components in the system is rather incomplete. Currently, only signs of parameters occurring in the model equations are used. The above results have shown that even these coarse models can be sufficient to detect and identify a number of faults. More accurate results could be achieved if the information about parameters used in the component models was more accurate. This means that the model and consequently the diagnostic results can be improved in a defined way incorporating information as available during the design phase of the system, or by using measurements to determine component parameters e.g. by means of automatic parameter identification. For ways how to determine such accurate models particularly for components of the air intake system, see e.g. [1].

## ACHIEVEMENTS

The major outcomes of the VMBD project were

- an agreed formalism for representing component models (leaving the particular behavior modeling language unrestricted),

- a collection of re-usable models of automotive components and systems for diagnosis (i.e. model libraries for electrical, electronic, hydraulic and pneumatic components),
- methods and techniques for creating models for diagnosis (i.e. a methodology of modeling).

The main focus in both injection systems (CRI and DTI) lay on the development of qualitative models. The papers [7], [11] and [5] discuss more details of the approach as well as the use of the models for diagnosis.

From the perspective of applying the models for diagnosis, the demonstrators proved the feasibility and the benefits of the technology in the automotive domain. In particular, it provides a basis for a systematic and cost-effective approach to creating diagnostics for car subsystems, and has the potential to improve the quality of diagnostics by handling fault situations that are not covered by current on-board diagnostics or by improving fault identification up to a point where more specific recovery actions can be chosen. Of course, such conclusions are still preliminary and have to be confirmed and exploited by further studies. Furthermore, one should keep in mind that complete fault localization and identification on-board may be:

- impossible, due to the absence of sufficient test options, which can only be performed off-board,
- unnecessary, as the main goal of the on-board system is determining an appropriate recovery action.

However, the existing results give rise to expectations of improving the diagnosis in vehicles in essentially three respects:

- in automatically generating fault candidates and decision trees for diagnosis and repair in the workshops,
- in assisting the design phase of automotive subsystems by providing methods and tools for verification, testing and design for diagnosability,
- in integrating model-based diagnosis techniques in the on-board equipment, as soon as sufficiently powerful processors in the ECU are available.

The outcomes of the project represent a major step in the transfer of model-based diagnosis technology into the automotive industry and will influence the advance in industrial applications in general. Thus, the work has created challenges and new impulse for the research field as a whole. For the industrial partners, it provides a firm set of experiments as a basis for decisions and further developments. The encouraging results have led all industrial partners to commit to the technology and undertake future efforts in further developing and exploiting it both for in-house applications and new products.

## 7. OPEN PROBLEMS AND FUTURE WORK

While the demonstrators have proven the feasibility and utility of model-based diagnosis for on-board diagnosis, more substantial work is needed in order to promote the application of the technology:

- Current models are based on representing the signs of variables and their deviations only. More fine-grained (but still abstract) distinctions are required, e.g. to distinguish different operating regions.
- Research is being carried out to derive computational solutions to determine what should be considered as a significant distinction. This applies to both the signal abstraction and modeling (for a theoretic investigation on the appropriate granularity of models for a given diagnostic task see [3]).
- More generally, it becomes necessary to generate diagnostic models from (differential equation) models that have already been developed for other purposes (e.g. simulation).
- The solutions-in-principle found in the demonstrators have to be turned into tools that support the actual work process, for instance for analysis of diagnosability, sensor placement, and FMEA. This also involves the integration with other tools, such as simulation systems and CAD tools.

Finally, despite the deep involvement of the companies, the success of the case studies in this project heavily relied on the availability of AI researchers who are familiar with the technology. For a really broad application within an industrial setting, in particular the task of modeling cannot be left to software engineers. Rather, it has to be integrated with the extensive work on modeling carried out by the engineers during different phases in the product life cycle. A coherent framework for different types of modeling and product representations is a worthwhile target, and could to a certain extent fulfill the increasing need for some kind of standard in the domain. It would also mean a lot for a cost effective approach to the total design process of complex control systems. The techniques developed in the VMBD project are considered to have the potential to become the basis for such a standard, thus making a contribution to corporate knowledge management in this area.

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## REFERENCES

1. M. Nyberg, A. Perkovic: Model-Based Diagnosis of Leaks in the Air-Intake System of an SI-Engine, SAE Paper (980514), 1998.

2. G. Stumpp, M. Ricco: Common Rail: An Attractive Fuel Injection System for Passenger Car DI Diesel Engines, SAE Technical Paper Series, 1996.
3. P. Struss, M. Sachenbacher: Significant Distinctions Only: Context-Dependent Automated Qualitative Modeling, Working Papers of the 13th International Workshop on Qualitative Reasoning (QR-99), Loch Awe, Scotland, 1999.
4. J.R. Quinlan: Induction of decision trees, Machine Learning, Vol. 1(1), pp. 81-106, 1986.
5. 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, to appear in AI Communications.
6. L. Console, W. Hamscher, J. deKleer (eds.): Readings in Model-based Diagnosis, Morgan Kaufmann Publishers, San Mateo, CA, 1992.
7. P. Struss, A. Malik, M. Sachenbacher: Qualitative modeling is the key. In Workshop Notes of the 6th International Workshop on Principles of Diagnosis (DX-95), Goslar, Germany, 1995.
8. California's OBD-II regulation, section 1968.1, title 13, california code of regulation, resolution 93-40, 1993.
9. 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, 1998.
10. Robert Bosch GmbH (ed.): Automotive Handbook, 4th edition, Society of Automotive Engineers, Warrendale, PA, 1997.
11. M. Sachenbacher, A. Malik, P. Struss: From Electrics to Emissions: Experiences in Applying Model-based Diagnosis to Real Problems in Cars, Working Papers of the 9th International Workshop on Principles of Diagnosis (DX-98), Sea Crest Resort, Cape Cod, USA, 1998.

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