Executive summary:

In the commercial vehicle industry, service contracts are of prime importance both for dealers and customers. Selling service contracts impose to the dealers to guarantee the best level of services when it comes to maintain customer vehicles. Dealers must avoid, as far as possible, unplanned stop to happen and consequently guarantee to the customer an optimal availability of his vehicles. For the vehicle manufactures to ensure a certain level of vehicle uptime, it is necessary to have precise knowledge of the vehicle health state and to minimize the immobilization time in case of a breakdown.

Thus, the project maintenance on demand (MODE) aims to increase transport competitiveness by increasing the vehicle uptime, optimizing the maintenance service time and reducing the failure time by following means:

- Dynamic maintenance planning: The ordinary maintenance plan is updated with the new event, i.e. the vehicle continues as planned but will have a service stop earlier then first planned.
- Maintenance-on-the-fly: A component needs service immediately, i.e. the vehicle interrupts its mission to find a convenient place for the maintenance service
- Repair on the fly: A component breaks down and causes an immobilization, i.e. the vehicle interrupts its mission and waits for the spare part to arrive.

In order to enable maintenance-on-demand and maintenance-on-the-fly concepts, MODE objectives are to adapt and combine new enabling technologies such as condition monitoring and SHM concepts, wireless communication and advances in data management allowing the proof of feasibility of above mentioned concepts. Currently, many concepts for a 'Condition Monitoring' are being develop and validated for the detection and diagnosis of premature damage in a structure or failures in electronic components and for the prevention of hazardous failures in the case of damage. Basis for the development of such systems are integrated sensor and partly actuator systems which are also being developed for smart structure technologies. At the same time, methods and procedures from the structural durability point of view are currently being developed allowing an even more accurate prediction of the remaining life-time of damaged or aged structures. Today, the adaptation of above mentioned new enabling technologies to support commercial vehicles Maintenance-on-Demand concepts is a real breakthrough.

With this, MODE technologies increase the competitiveness of vehicle product manufacturers as well as vehicle owners. MODE will impact a market of several billion euros for new product and maintenance by enhancing the capability to provide an uptime oriented offer which targets 15 to 30% increase in efficiency. On a warranty cost reduction perspective, will lead to 10 to 15% reduction of warranty costs by early detection of damages on the vehicles.

Following main results has been achieved within MODE:

- Validated detection of damages or detoriation on dampers, injectors and in oil
- Sensor network system for measurement system condition monitoring with three sensor nodes, three routers, one coordinator and central PC
- Modular back-office service platform with Web 2.0 capabilities

- Transmissibility concept for damper condition monitoring & correlation based CM technique for vehicle suspensions
- Self-monitoring concept for sensor systems
- Modified FMEA evaluation towards a selection of reliability-relevant failure MODEs;
- Advanced MODEls for life-time evaluation & dynamic maintenance MODEl
- Demonstration suite including a support tool for the selling of transport solution, a vehicle us-age tracking tool and a cost-based maintenance scheduling optimization tool
- Reduction of maintenance costs (up to 25%) when adopting an optimized maintenance strategy
- Repair spot locator developed

Project context and objectives:

In the commercial vehicle industry, service contracts are of prime importance both for dealers and customers. Selling service contracts impose to the dealers to guarantee the best level of services when it comes to maintain customer vehicles. Dealers must avoid, as far as possible, unplanned stop to happen and consequently guarantee to the customer an optimal availability of his vehicles. On a customer perspective, the service contract is a guarantee that he will keep a constant level of performance when using his vehicle in his day-by-day business. Moreover, it also represents an important source of expenses. For the vehicle manufactures to ensure a certain level of vehicle uptime, it is necessary to have precise knowledge of the vehicle health state and to minimize the immobilization time in case of a breakdown. New researches results in the field of condition monitoring and prediction of remaining life time of vehicle components will give an accurate image of the vehicle health status.

This information can result in the following actions:
- Dynamic maintenance planning: The ordinary maintenance plan is updated with the new event, i.e. the vehicle continues as planned but will have a service stop earlier then first planned.
- Maintenance-on-the-Fly: A component need service immediately, i.e. the vehicle interrupts its mission to find a convenient place for the maintenance service
- Repair on the fly: A component breaks down and causes an immobilization, i.e. the vehicle interrupts its mission and waits for the spare part to arrive.

Currently, many concepts for a 'Condition Monitoring' are being develop and validated for the detection and diagnosis of premature damage in a structure or failures in electronic components and for the prevention of hazardous failures in the case of damage. These methods, indicated as 'health' monitoring methods, aim at controlling and reducing the life-cycle costs in safety-critical components of cars, commercial vehicles, trains (such as wheels, brakes, power trains), and civil structures (such as cable-stayed bridges). Improvement of the life-cycle costs is achieved by reducing product maintenance costs and improving product availability and reliability. Basis for the development of such systems are integrated sensor and partly actuator systems which are also being developed for smart structure technologies. At the same time, methods and procedures from the structural durability point of view are currently being developed allowing an even more accurate prediction of the remaining life-time of damaged or aged structures. Combining these fields would allow Maintenance-on-Demand bringing down the overall life-cycle costs of a product. The latter is one of the key factors in the MODErn design of structural components. Already foreseen in the aeronautics or for wind power plants, where more and more composite materials are used, these techniques need to be introduced also to other transport MODEs such as commercial vehicles to increase the safety and to reduce life-cycle costs.

Consequently, maintenance-on-demand (MODE) aims to adapt and combine new enabling technologies such as condition monitoring and SHM concepts, wireless communication and advances in data management to realize maintenance-on-demand and maintenance-on-the-fly concepts. The maintenance-on-demand and maintenance-on-the-fly concepts and services will be developed on basis of the three test cases

- damper system with position sensor,
- injector of a diesel engine,
- oil quality sensor.

The MODE-scenarios

Currently, a vehicle dealer sells maintenance contracts which are focused on using static maintenance information; i.e. information is issued when the vehicle is sold. The vehicle's communication to the infrastructure is coming up using a centralized database to collect information dynamically. Those data are not only concerning service but also vehicle environment and operating conditions.

The expectation is to provide tailored services to the customers in close relation to the vehicle con-figuration and mission work scope. These services shall enable the customer to reach his business objectives by minimizing loss of time when the vehicle cannot operate in the nominal way. It is also allows a new approach of selling vehicles with an uptime based perspective. Within this 'Maintenance-on-Demand' scenario, the dealer asks the client what his needs are in terms of the transportation solution. The client shall define vehicle usage and mission constraints in order to establish the vehicle configuration profile and requirements on the uptime level. Thus, the selling process shall consider both customer needs but also limitation factors (e.g. small or big fleet). Like vehicle con-figuration, services shall also be customizable as far as possible; i.e. 'On Demand'. This shall increase the ability to schedule and optimize planned vehicle stops. Moreover, the capacity to adapt the services to the mission taking into account the vehicle configuration shall be dynamic; i.e. shall be modified if the vehicle's operating conditions and/or environment evolves.

Furthermore, when a breakdown or failure occurs, an on-board system warns the driver. Then, he has to phone the call center in order to get his vehicle repaired. If the vehicle is equipped with navigation system and this information is communicated to the call center, it is easier to locate where it is immobilized. However, it is still hard to figure out what the problem is and to ensure that the right parts are delivered at the right place. Moreover, for many components of the vehicle which are subject to failure, it is not obvious to find spare parts in any workshop. This matter of fact also in-creases repair time. Consequently, the Maintenance-on-the-Fly scenario aims to increase the efficiency of the 'on the roadside' repair process. The vision is to replace progressively a roadside immobilization by a 'on the fly' maintenance. On board condition monitoring together with estimation of remaining lifetime are support information. Using these tools to detect in advance failures would really have the benefit to gain time in order to enhance repair actions. Thus, when a failure or damage is pre-detected on the vehicle, the information can directly be sent to the back-office system. This triggers the corrective procedure starting with locating the vehicle, reporting about the failure and finding the most suitable workshops. Computations from remaining lifetime or condition monitoring system give an idea about remaining vehicle driving distance. A central system tries to find all the workshops that are located in the area described previously. Stored information concerning these workshops leads to figure out the most suitable one in that particular case: are the spare parts needed available? Finally, driver can receive information from the system on which location he should go. However, it will not be possible to reach any workshop in many cases. In that case, the system delivers a 'best location to stop' in order to minimize 'meeting time' (both minimizing vehicle distance and workshop time to deliver based on location). The concept of 'mobile workshop' is here addressed here: the assumption is that some workshops can have the ability to repair on the roadside with special resources. The system shall ensure the needed spare parts are available and inform the workshop about failure type and pre-diagnostic data. The proposed 'meeting' location is decided on both downtime minimization and safety criteria; any parking could be used instead of keeping vehicle on the roadside.

Benefit of maintenance-on-demand

Proposing a global uptime based transport solution will help to maintain vehicles at their optimal condition. However, the ability to provide such an offer to the vehicle owners relies on the capacity to follow-up vehicle's usage and trace maintenance history. Analysis of vehicle usage and follow-up of components status will generate better inputs in order to tailor services and maintenance solutions toward customer business expectations. Usage of remaining life time information will allow extension of service interval. The service time will also decrease by optimization of maintenance planning tools. Furthermore, scheduling maintenance operations based on actual component degradation will benefit to spare parts consumption. Vehicle uptime also depends on our ability to decrease the 'failure' time. Even if part of the 'failure' time is dedicated to service done by the technicians, the other part mainly concerns wasted time (wait for diagnostic technician, wait for parts, wait for payment procedures…). Providing the right information (i.e. failure cause description, vehicle location) will suppress the major part of this wasted time. Moreover, indirect consequences could be the reduction of congestion and accidents (by avoiding long period of immobilization on the roadside).

With this, MODE technologies increase the competitiveness of vehicle product manufacturers as well as vehicle owners. MODE will impact a market of several billion euros for new product and maintenance by enhancing the capability to provide an uptime oriented offer which targets 15 to 30% increase in efficiency. On a warranty cost reduction perspective, MODE could lead to 10 to 15% reduction of warranty costs by early detection of damages on the vehicles.

Project results:

System requirements

The objective of system requirements (WP 1) is to identify the impacted key stakeholders and actors in the process and to analyse their needs. The beginning of the project focused on a detailed analysis of the specific requirements and targets of the business scenario behind MODE as well as a risk assessment in order to select and assess the best solutions provided by the enabling technologies at hand within the consortium.

General specifications

The participating industrial partners and end-users Volvo and DHL worked together to define the project general specifications. The general specifications document aims at:
- Breaking down objectives per project work packages
- Provide a general work flow for the project
- Present the high level end-user requirements work from Volvo and DHL as industrial end-users

Each project end-user requirements has been then allocated per work packages. A list of foreseen project stakeholders has been depicted. To conclude a general project use cases view has been proposed.

Project business scenario

The target of the project business scenario is to present the overall project business (also called 'end-users') requirements. An analysis of the expected business processes becoming available due to the Maintenance on Demand concept was proposed. A complete list of project business requirements were collected and detailed based on the proposed analysis proposed.

The business requirements have been structured around 4 key areas:
- Economic Requirements
  Expresses the economical view of the MODE project; i.e. how such an offering shall be proposed to a commercial vehicle customer
- Technical Requirements
  Technical requirements are only high level requirements on technical project aspects from a end-user perspective.
  This is a list of requirements that the MODE offering shall fulfil in order to secure a progressive integration of the functionalities into day-by-day operations
- Service Incident Communication
  Service incident communication section provides a set of requirements on the project communication chain.
  It highlights that all MODE service benefits can be challenged if the communication and data management enablers are not robust enough.

Finally, this section also describes the required level of the interaction between the Maintenance on Demand actors/stakeholders to guarantee the operational feasibility of the concept.
- Maintenance And Repair Scenarios
  This section describes how the different service incident shall be handled from a Maintenance on Demand service perspective

In order to fulfil all the proposed requirements, a general business scenario is provided. This business scenario is composed of 10 different business processes which composed the complete project scope. Each business process is depicted as a series of combined activity/decisions gates.

All business processes are broken down into business use cases which are pointing out:
- Process trigger: activity/decision which launched the process,
- Process support system/information: what are the required information/system to support the business process,
- Process inputs: the set of necessary information (either inherited or developed in the MODE project) which are required to perform the action,
- Process outputs: the expected results of the described process

To conclude, a mapping between the complete list of business requirements and the proposed business processes is provided. This mapping aims at securing that all business requirements are covered by the project overall process.

Identify, list and prepare follow-up of system requirements

The task has been conducted based on the results of the previous sections. The work aims at identifying the project breakthroughs to be investigated by the different work packages. A list of 13 breakthroughs is proposed, each one connected to one or many project work packages. The primary conclusion is that the most challenging issues raised by the project are:
- Condition Monitoring techniques and their implementation on-board the vehicles,
- The remaining life time estimation/algorithms.
Those two areas are really drivers for change and key success factors for the Maintenance on Demand supported vision.

A list of system requirements is finally proposed. They express all the requirements on MODE operational solutions from an end-user perspective. A total of 74 system requirements were presented. Each system requirements which relies on a breakthrough has been identified.

Sensor Technologies

To detect degradations and failures of damper systems, different sensors (acceleration sensor and a level sensor) and methods (measuring the transmissibility, random decrement method and correlation factors) have been under consideration. The in-depth analysis in the first project years ended in the decision to use accelerometers and the method based on correlation factors. Using COTS accelerometers and an open-source microcontroller framework, Smart Sensor Nodes using the abovementioned method have been build up and programmed. Those have successfully been tested regarding their usability under driving conditions.

Starting point was a feasibility study whether available sensor technologies can be adapted for the use for condition monitoring sensor systems with series-production status (off-the-shelf) were evaluated for damper system condition monitoring. The main idea was a sensor signal comparison of test drive data for different damper conditions (OK…NOK) and identification of changes where applicable.. For this feasibility study the following three series sensor products were used:

- chassis acceleration sensor BSZ04
- axis/wheel acceleration sensor BSZ04
- level sensor (Mercedes Benz standard)

As MODEl system for evaluation of sensor performance a passenger vehicle was chosen due to availability and local capability, e.g. car lift, to support damper changes and perform test drives. The test vehicle used was a Mercedes Benz C-class MODEl. Additionally to acceleration and level sensor signals steering angle and car velocity information are recorded.

Due to better accessibility and easier exchangeability the test vehicle's rear axle dampers were investigated. In order to evaluate the damper system two test cases were defined, first a monotonic non-dynamic excitation and second a high impact excitation of the damper system

- motor way (Autobahn) at approximately constant velocity, typ. 80 km/h to 100 km/h
- aluminum sleepers (lateral aluminum bars on the street)

Additionally, damper inspection was performed at a public test service point (GTUe).

Three test series were performed using manufacturer modified dampers with damper set-up. Offline spectral analysis of axis acceleration test drive data shows corresponding changes of a low-frequency resonance peak around 18 Hz due to modification of the damper. A spectral shift of 1.5 Hz of the resonance peak towards lower frequency occurred for the intentionally damaged damper. This experimental result was confirmed by both cross-change of OK/NOK damper and application of two OK dampers with respect to the rear axis.

Furthermore, experimental and operational modal analysis has been performed in order to evaluate the reliability of the sensors data and its usefulness for the desired monitoring. The chosen passenger car, properly instrumented by using laboratory and adapted in-vehicle sensors, has been tested upon two different experimental approaches and with two shock absorber configurations to proof the abovementioned condition monitoring concepts. An impact test (as input for an Experimental Modal Analysis (EMA)) took place in the laboratory and a series of operational tests were performed mostly on public roads (see also above). The last-mentioned tests allow for the identification of the vibration behaviour of the vehicle in real operating conditions through an operational or output-only modal analysis (OMA).

The complete sensor layout consisted of 16 measurement points whereas eight sensors have been fixed at the car body (respectively 4 at the rooftop and 4 at the bonnet sides) and eight sensors have been used for the characterization of the four suspension systems (two sensors per suspension system - one at the strut mount and one at the wheel hub). Additionally eight in-vehicle sensors, developed by Continental for the real time diagnosis and life time estimation of the component, have been closely located to the laboratory sensors at each suspension system. In this way a direct comparison of the performance of the laboratory equipment and the in-vehicle sensors was possible.

While the signal trend is similar in the two scenarios, the signal-noise ratio decreases slightly for the in-vehicle sensors (Continental BSZ04). The in-vehicle sensors have been properly developed in order to satisfy the specification requirements for a real-time condition monitoring of shock absorbers. They have to guarantee a low cost (to be produced on large scale) but, at the same time, good performances in terms of accuracy, limited mass and dimensions, high measuring range and so on. Additionally, robustness and environmental conditions protection (waterproof and dusty protection) are other peculiar tasks to be usable in all road conditions and over long term utilization so that a lower signal quality can be justified.

Regarding the injector system structural damages in injectors are assumed to come up at the nozzle. Therefore, a commercial injector system has been artificially damaged in two steps, first in a slight and afterwards with a deepened cut near the nozzle. To identify these 'failures', the measuring of the Electromechanical Impedance (EMI) was chosen. The Electromechanical Impedance (EMI) method allows for the monitoring of local parts of a structure. Therefore, a piezoelectric transducer (PZT), a tiny piezo patch, was surface bonded to the injector. Once the transducer is subjected to an alternating electric field, it excites elastic waves within the host structure. At the same time, the electric impedance of the transducer can be measured. However, in the case of a PZT bonded to a structure, the mechanical impedance of the structure is coupled to the measured electrical impedance. Measurements in the three states 'undamaged', 'first cut' and 'deepend cut' show that the method is feasible to detect presence and growth of defects in injector's nozzles. It has been deduced, that a damage can be detected in every frequency band, however, the band 0-100kHz turns out to be most sensitive.

Wireless sensor network

The main goal of the work package was to perform sensor data acquisition and processing on the sampled data along with a reliable transmission of the analysed data at a central location.

In order to distribute computationally intensive tasks of the condition monitoring process, the low-power microcontroller available on the wireless sensor node has been extended with a co-processing unit. This core was developed on an FPGA, as an intermediate layer between the sensor interface and the wireless communication interface. A generic architecture was first developed in order to improve the energy-efficiency and the performance of the system. The processing unit was then tailored to handle maintenance-specific tasks as they were defined in the frame of MODE. This includes mainly pre-processing of the sensor data, extraction and processing of features as condition monitoring indicators and for sensor fault detection, supports tasks for reliable and secure wireless communication such as encryption and forward error correction. These functionalities were successfully ported to the MODE sensor node and tested in a vehicle. This setup demonstrated the possibility to efficiently combine high-bandwidth sensing (accelerometers) with a low-bandwidth wireless communication protocol. Without a co-processing unit, it would have been difficult to wirelessly transmit the complete sensor data to a central unit for centralized processing.

The challenge arising from the integration of these extensions was to keep the usage of hardware resources low while sustaining a high efficiency, performance and accuracy. This issue was addressed with the utilization of the technology of coarse-grained dynamically reconfigurable hardware. Based on functional units reconfigurable at the operator level, the reconfigurable architecture could be modified at runtime to implement different processing algorithms in a time-multiplexed manner. Thanks to short configuration bitstreams, the function of the processor extension could be changed in a very short amount of time. In addition, a large amount of functions could be stored in the embedded memory, giving a large choice of processing algorithms that could be dynamically loaded.

A configuration software has been additionally developed. The parameters of the processing unit as well as single elementary operations can be adjusted using a Graphical User Interface. The software can then automatically generate binary configuration data that can be loaded into the database of the co-processing unit.

The objective of realizing a maintenance-specific processor extension to the wireless sensor node using reconfigurable signal processing has then been achieved. The co-processing unit is able to handle multiple sensor data processing tasks of condition monitoring processes with high efficiency and an architecture enabling several levels of reconfiguration with short delays and high efficiency was developed. The system has been demonstrated and shown working in real time at the dissemination conference in Galway Ireland in July 2012. Avonwood has successfully produced a universal RF platform that can be used in various applications and on different types of vehicle.

The feedback from end users requiring MODE has been toward safety systems so the first trials of the system was with DHL on fork lift trucks. The basic platform was interfaced to a low frequency field that detected a transponder that warned the driver of a person in a dangerous position from vehicle movements. All information gathered by the DSU has been successfully sent to the web server and viewed by the back office system.

From the basic platform Avonwood has produced a new product that is being launched in the marketplace called ZoneSafe.

Furthermore in the work package the impact of sensor failure on the prediction and analysis of the conditions of the vehicle has been researched. For these specific works the usage of sensor monitoring to detect a failure of sensors has been evaluated.

The results of the self-monitoring showed the following sensor test results:
- Cable breaks can be detected with high reliability and CPU load is low.
- Detection of cable shorts need processing resources and its reliability depends greatly what the resistance between shorts is.
- Clipping of the sensor value can easily be detected and CPU load is very low.
- Detection of the sensor, in which the output value is stuck, is simple and processing resources are low.
- Typical outliers are outside of the normal distribution of sensor signal values and they can be detected. Computing can be easily implemented with microcontroller.
- Rolling was detected and CPU load was at the same level as outlier detection.

It can be concluded that all results obtained during the time of the MODE project were very promising and show great potential for future use.

Data management

Within the context of MODE, data management stands for the definition and implementation of a software hub where vehicle data are gathered, processed and stored. Data Management (WP 4) is therefore the integration point of output data from WP2 and WP3, the communication link between the vehicle and the software platform, and the computing platform for WP7, WP8 and WP9. By the end of the project, WP4's intended goal is to demonstrate how a given vehicle's uptime can be maximized by both measuring its usage and MODElling and monitoring the degradation of its critical parts.

Developments overview

The MODE platform as released is both the convergence point of all MODE-defined vehicle data, the computation platform for the project's algorithms and degradation simulation modules, and an accessible and manageable platform by means a full-featured web portal.

Main achievements

Task 1 (On Board system data management) has been successfully completed by using the existing Volvo Telematics Gateway. On the field testing proved the solution to be fully functional.
Task 2 (Data Transfer) was successfully completed as well, as demonstrated by the subsequent use of vehicle data for maintenance scheduling and monitoring purpose on the back-office platform. The resulting maintenance planning could be reviewed and be updated at user request on MODE's web portal.
Task 3 (Database) was reported as complete after high-level integration tests demonstrated the platform's ability to acquire, process and later retrieve both vehicle-originated and computed data from the platform's database.
Task 4 (Web Services). The initial proposal of using web services to integrate other WPs into the platform dataflow was mostly discarded after it turned out that web services were not as efficient a solution as embedding the third-party computational units into MODE-compliant software 'bricks'.
Task 5 (Integration and Validation) was successfully led by means of real-life-compliant test cases run on the Back-Office platform. The most visible proof of achievement was the computation of optimized maintenance scheduling based on a given vehicle's usage and maintenance plan configuration data.

As described above, the Task by Task validation testing of WP4's platform proved it in accordance to the initial project expectations, with all WP4 deliveries meeting expected deadlines. Unfortunately though, WP4's platform had to use simulated data to compensate for the absence of a hard-wired Wireless Sensor Network (that is the sensors, the wireless network and its gateway to Volvo's Telematics box) in the tested configuration. The following section illustrates MODE's achievements through on-the-field use of the platform's web portal.

MODE showcase

A live connection is established with the test vehicle through Volvo's Telematics Gateway on the vehicle side and specific software components on the back-office side. This connection allows the transmission of instant runtime data such as vehicle faults, positioning, and speed or engine statistics.

The most relevant and comprehensive overview of the MODE platform is arguably given by the maintenance scheduling tool, as optimizing the vehicle's immobilization periods' distribution relies on MODE's component degradation monitoring, component remaining useful lifetime computation, usage analysis and eventually all maintenance scheduling algorithms.

The vehicle and contract data are filled in, after which the initial Maintenance planning is computed. Later re-calculation of maintenance occasions is performed as needed based on the vehicle's usage. Any update on the chosen date seen as economically viable will be integrated to the planning by re-dispatching maintenance actions; otherwise the date will be discarded and the planning unchanged.

Condition monitoring

Condition monitoring (WP 6) encompasses single and multi-channel signal processing, feature extraction, comparison with expected values or operational limits, and alert-generation. These condition monitoring concepts have been developed for the selected vehicle components, properly instrumented using the adapted sensor technologies developed in WP 2. The selected algorithms have been adapted allowing implementation on the WP 3 hardware. Next to in-vehicle use, the measurement data needs to be transferred to the back-office servers. This allows running much more sophisticated condition monitoring algorithms that take into account historical data of the vehicle and compare multiple vehicles within the fleet. Data-driven statistical approaches have been developed for this purpose. The results of condition monitoring were further used in WP 7 to assess the remaining lifetime of the structural component.

The development of monitoring and fault detection methods for vehicle components required preliminary experimental studies. Since all proposed methods are using the information coming from in-vehicle sensors during normal road operation, a test vehicle has been properly instrumented by using laboratory sensors (acceleration sensors mainly). Different damper settings have been considered for the semi-active suspension system equipping the car and two different kinds of tests have been performed for the assessment of the suspension performances: proving ground tests and laboratory four poster rig tests. For the outdoor tests, only the response data are measurable and not the actual loadings coming from the road excitations. Hence, the system identification has to be based on output-only data. By using Operational Modal Analysis (OMA) techniques, an experimental identification of the vehicle vibration behavior in real operating conditions is allowed. The experimental results relative to different damper level scenarios have been compared so that a good indication has been obtained with regard to the sensors layout and the analysis methodologies to be adopted for the development and the implementation of real-time condition monitoring strategies.

In the following step, additional experimental tests have been performed in order to evaluate the usefulness and reliability of the sensor data. In this case, the test vehicle was properly instrumented by using laboratory sensors and adapted in-vehicle instrumentation. Two different experimental approaches have been adopted to proof the monitoring concepts. An impact test took place and a series of spectral tests performed mostly on public roads. Both kinds of tests have been performed in two different shock absorber configurations (the testing vehicle was equipped with passive suspension systems at both axles). Firstly, four undamaged shock absorbers have been used while in the second test session one shock absorber (mounted at the rear-left suspension system) was replaced with a time-worn one. The EMA (Experimental Modal Analysis) and OMA results obtained with the two shock absorbers scenarios are compared in order to check the influence of the component life time on the vehicle's dynamic behavior. Due to different reasons, no significant changes in the eigenfrequencies or dampings could be detected using the data from the acquisition and analysis methods described. Therefore, two new methods using operational data and longer averaging intervals have been examined.

The first monitoring methodology uses the transmissibility as a function of the damping ratio and the forcing frequency ratio so that it is directly affected by the excitation frequency. Moreover transmissibility depends on the spring stiffness value (that can be considered as constant for a vehicle conventional passive suspension system during vehicle life), vehicle mass (which changes with vehicle loading condition changing) and damping value associated to the shock absorber. This last factor changes due to aging, wear or malfunction of the shock absorber. Because of this dependencies, monitoring the transmissibility function values in the frequency domain yields indicators of the shock absorbers' condition.

An alternative structural hearth monitoring method is represented by the Random Decrement technique. This is mainly based on an averaging process of the time data series measured on the system (so-called Random Decrement signature) when random input loads are acting and a given trigger condition is fulfilled. Using properties of the statistical vibration process, those RD signatures can be transferred to correlation functions and used for frequency domain based operational modal analysis, namely the algorithms of frequency domain decomposition (FDD). Both of two shock absorber monitoring methods have been tested using time data acquired from the above mentioned passenger car and they seem suitable for the future implementation on the WP3 hardware.

A critical assessment of the strengths and weaknesses of these methods led to the finalization of the CM concepts Transmissibility- and correlation based CM concepts have been elaborated (Task 1), implemented and validated (Task 3). In addition, a suitable strategy of computation distribution related to each of these concepts was defined (Task 2).

In Task 4 an extensive experimental database of damper characteristics was created. In addition, also sensor node data quality assurance algorithms have been implemented. Within Task 5, a self-monitoring system for the measurement system was developed.

Logistics

Within MODE also integrated logistics support solution were developed which enables vehicle manufacturers to offer both 'Maintenance-on-Demand'- and 'Maintenance-on-the-Fly' services to their customers on a pan-European level. In line with user expectations and the phase-in strategy agreed upon, the state of the art solution has been identified as a networked, multi-layer warehouse set up. This set-up allows a reduction of the part references available for delivery in 24h (a potential cost saving of the advanced planning the 'Maintenance-on-

Demand' service would deliver) whilst at the same time dramatically increasing the number of parts references available in under 2,5h (target response time for a 'Maintenance-on-the-Fly' service). Since the services developed in the 'maintenance-on-demand' project will not be available on all vehicles in operation for several years after the project end, it has been decided to develop / follow a phase-in strategy for the logistics solution.

The three scenarios reflecting this strategy has been identified:
- Scenario 1: SC optimization - no technology available;
- Scenario 2: Advanced pre-planning - improved Advanced Maintenance Planning.
- Scenario 3: Full MODE optimization - MODE technology available on the entire fleet.

Assuming a full Maintenance on Demand vision (technology & process-wise) is deployed, the improvement in diagnostics & maintenance planning results in a drastic reduction of the number of routes to deliver spare parts to workshops by avoiding unplanned orders. However up to 5 drops per day would still be required as by default an unplanned event can happen any time. Maintaining up to 5 deliveries per day would however lead to high underutilization of the vehicles resulting in a prohibitively high cost per part. Nevertheless, warehousing costs would be reduced by about a half. Taking also into account that the number of kilometers driven per day can be most likely reduced by optimizing routes in line with actual demand pattern as well, alternative fuel driven vehicles can be introduced on a larger scale to reduce the CO2 foot print of the logistics of spare parts.

Evaluation of the system reliability

Within MODE, an analytical investigation of the reliability of a transport vehicle damper was performed. This was achieved by the means of a failure MODEs and effect analysis (FMEA) with respect to the vehicle dampers. As a second step the results were used to set up methods and procedures to determine the remaining life-time.

For MODE the failure analysis was carried out on the basis of a system structure and function analysis according to the regular scheme. The collection of the failure MODEs was conducted regarding typical failure phenomena with regard to the components and their functions. The failure causes are examined at the component level and further investigated concerning assumed consequences on the operation of the hierarchically superordinated subsystem. For that purpose, the component topology, loads and interactions with other components or media were examined as to which extent a certain deviation from the functional state may lead to a specific effect on the vehicle dynamics. Finally the possible end-effects concerning dysfunctional effects of the vehicle in use are determined. Especially those influences which negatively affect the safety or some of those that reduce the comfort of the vehicle are of interest for a monitoring concept. Another methodological approach to MODEling a system´s possibility to enter a failure-state can be implemented with the help of bayesian networks. It mainly follows the principles of the FMEA-procedure to a large extent except from the last step of optimization and risk reduction measures. Additionally, the possibility to quantitatively assess the failure-cause-and-effect-relations provides more detailed information when evaluating the failure MODEl. Moreover, a differentiation of the likelihood of root-causes to occur with respect to the load-intensity due to different usage scenarios can be realized.

In the failure analysis with bayesian networks a component can be represented as one node in the network. Similar to one basic node in a hiearchical FMEA-Structure also here in the BN-FMEA one node contains a list of the mutually exclusive failure MODEs together with one state representing the component´s state of an operation as specified. Each of these failure MODEs is being appointed its estimated likelihood of the failure state to occur. The likelihoods of the operational- and failure-states complement on one, since the component necessarily has to be at one of the possible states. In accordance to an FMEA, in the BN-FMEA the failure MODEs at component level are also investigated regarding possible failure effects and consequences. In contrast to the common FMEA-method, however, the likelihood of occurrence of the effect is regarded. This means that an expert judgement is deployed whether an effect will occur with a likelihood ranging between 0 and 1. This allows a quantified evaluation of the system´s cause-effect-MODEl. In the regular FMEA-Method, no probabilistic differentiation is made between the variety of possible consequences of one single failure cause. That means, that it is generally assumed that each of the consequences results from a specific failure cause without any probabilistic relation. But not all of the possible effects for one specific failure cause are equally likely to follow its occurrence. Therefore the BN-FMEA offers a higher precision of results since the probabilistic conditions are determined and included in the evaluation scheme.

As a further enhancement of the features of a BN-FMEA described above, conditional load sets can be attached to differentiate the evaluation of the MODEl concerning influences on the root-causes regarding characteristic types of use by adding another network MODEl which represents relevant influences onto the components. Such a network of external influences serves to MODEl characteristic operational loads due to its individual operation. This connection includes an estimation of the likelihood of the failure MODE to occur regarding different load profiles. As an example, a variation of the load-intensity acting on the vehicle suspension may adversely affect the reliability of some of the components as for example gaskets, bearings or elastomer support of the bearing.

In a comprehensive failure analysis like an FMEA, a variety of different types of failure MODEs are collected. These include functional conflicts, inappropriate dimensioning or design as well as qualitative inadequacy. In MODE emphasis was put on aspects contributing to the system reliability. Therefore a diversification of the failure data into different categories was undertaken.

The collected failure data were assigned to three different regions of the usage cycle represented in the MODEl of the so-called 'Bathtub-Curve' which represents a generic MODEl of a systems failure rate over its lifetime:
- Region 1: failure causes due to unqualified design that occur mainly at the beginning of the system's operation
- Region 2: ad-hoc-failures occurring step-wise under certain circumstances or randomly at any point in the system´s lifetime
- Region 3: degradation failures with gradually or progressively increasing probability during usage of the system; relevant for monitoring and maintenance strategy

The failure MODEs of the damper found in the previous section were classified by occurrence along the lifetime and assigned to the typical regions of the bathtub curve. The failure MODEs assigned to region 1 and 2 are typically not correlated to the systems operational state and are therefore not suitable to serve as a basis for a monitoring concept. The most relevant region for monitoring concepts is region 3 ranging at the right end of the 'Bathtub-Curve', since the occurrence of the assigned failure MODEs is strongly connected with the specific physics of failure of the components. These wear-out failures lead to gradual change in the system's properties which can be detected by means of a suitable monitoring system as soon as a defined threshold value is exceeded.

In correlation with the monitoring- and lifetime-prediction-concepts the method for failure analysis can contribute to establishing a monitoring concept as far as the following properties are concerned: Possible root-causes of failure states are identified deviations from the specified functional states and properties are deduced systematically which provides a database to identify monitoring requirements. Further the effects on the system operation with respect to its usage purpose are concluded which can support the development of a monitoring algorithm.

The further decision of how to design a dedicated monitoring system is one following task beneath setting up a failure database. Depending on factors as for example the system topology, cost targets or monitoring purpose and others the appropriate technological basis and therefore an appropriate strategy and conception can be elaborated. For the scope of MODE it can be concluded that its definition and implementation can be supported by the failure analysis.

Prediction of the remaining life-time

Furthermore the MODElling of the life-time of systems has been considered. For this stochastic (random) deterioration MODEls were selected suitable for the remaining lifetime assessment of the applications. These were improved to fit in with variable environment loads and on-line information, and to optimise pro-active condition based or predictive maintenance decision rules at the component/system level based on stochastic (random) remaining lifetime and intervention costs.

Regarding the deterioration-based lifetime MODEls and integration of covariates, several generic deterioration based lifetime MODEls were investigated. The advantage of these MODEls for the problem at hand in MODE is that they are able to explain the failure of the system by its deterioration: the system is assumed to fail as soon as its deterioration level exceeds a threshold (they are also called 'deterioration threshold failure MODEl'). These MODEls make it possible to link the deterioration level of the system, its failure and its reliability. They are thus well adapted to online reliability estimation and residual life prognosis of monitored components, i.e. components whose deterioration can be measured online. Among others a Gamma process, Wiener process, and General path MODEl were considered and some extensions developed. Additionally other failure mechanisms such as shock were taken into account. Actually some components fail when the deterioration level exceeds a failure threshold. But a failure can occur due to traumatic event or shock. The MODEls considering these two kinds of failure mechanisms are called the Deterioration Threshold Shock (DTS) MODEls.

In order to MODEl the changing operating MODEs and usage patterns of the vehicle and the impact of these changes on the components/system deterioration, deterioration MODEls with covariates were introduced. These 'covariates' are exogenous variables that represent the 'environment' (either the operating MODEs, usage patterns, environment of use, etc.) changes. Once introduced in the MODEl, they allow MODElling the deterioration changes in response to the environment changes.

Besides, the inverse problem was addressed as well, how to detect a change of the usage conditions given the monitored data. Actually, a commercial vehicle could be used in different usage classes (from long distance to distribution profiles) and the environment changes influence highly the system deterioration. The knowledge about the usage change is then useful to predict accurately its remaining useful lifetime and to schedule the maintenance time. Algorithms were developed considering known, partially known or completely unknown parameters of the process in the new usage conditions.

The MODEls were applied to specific cases such as the damper and the oil deterioration. The main idea for the damper system is that the transmissibility of the damper can be assessed which can lead to a deterioration indicator. If this indicator value can be evaluated over time, it can lead to the assessment of the remaining lifetime after fitting a suitable deterioration MODEl and a failure threshold. Concerning the oil deterioration, available data were processed and a deterioration indicator developed using statistical methods. Also a deterioration MODEl for oil for the 'normal' and 'stressed' usage as well as a method to assess the RUL was derived.

Based on the studied deterioration/failure MODEls, dynamic maintenance policies MODEls for deteriorating components were developed. In the proposed 'dynamic maintenance' framework, the maintenance actions are not triggered on a periodic calendar basis, but it is rather the condition (i.e. its deterioration level or health status) of the component that triggers a maintenance action. The aim of these developments has been to show how the prognosis information can be integrated in the maintenance decision to improve the maintenance performance. Among several studied cases, a case with maintenance opportunities and environment impact on the deterioration was considered. The information on the maintenance opportunities and the environment are assumed to be known only a finite rolling horizon. The aim was to show how to use the time-limited information and the prognosis to improve the maintenance decision making. This problem corresponds to a vehicle used in different conditions impacting the deterioration of a critical monitored component that can be repaired is some specific workshops. The knowledge about the vehicle usage can be limited in practice, the reason for which we considered the finite visibility horizon.

The developed maintenance policies were compared with more classical age-based and condition-based policies using simulation data. The results showed better performances of the predictive developed policies. Some of the algorithms were integrated into an interface that allows updating the remaining lifetime assessment of a monitored component and proposing a predictive maintenance policy. This interface allows choosing between different cases (degradation MODEl, processes parameters, workshops position, etc.) and between an automatic maintenance scheduling and a manual scheduling (by the fleet manager) given the information on the component state and some computed indicators.

Maintenance-on-Demand & Maintenance-on-the-Fly

Regarding Maintenance-on-Demand and Maintenance-on-the-Fly scenarios, innovative 'uptime management' based services were developed to increase transport solution competitiveness and demonstrating 'uptime management' services. In this category, two kinds of pricing are identified:
- Cost-based pricing: this pricing takes only account of the product cost, the product volume and the price elasticity
- Market-based pricing: this pricing considers the market and the competitors to be competitive in addition to the 'cost-based' components.

Nowadays, most of truck's manufacturers are positioned at these types of selling strategy and pricing. The next step is the solutions selling based on the value-based pricing. The main goal is to integrate the customer's process into the manufacturer's selling process. Moreover, many services are packaged to enhance the solution offer's value. Thus, the total benefit and cost ownership are estimated to assess this value.

In the future, many industries would probably develop the consultative selling. This strategy assumes that the customer and the manufacturer work together and share the gains but also the pains. A better knowledge of the customer's activity and needs is required in order to reduce the potential risk.

The first step is to analyze the customer profile. It aims at understanding the customer technical and business needs. According to the technical requirements, the optimal vehicle configuration is identified. The customer can even modify or add other vehicle equipment. Then the customer can choose the additional interesting services. According to the vehicle configuration and the chosen services, a computation tool evaluates the values of ownership: total cost and uptime level. To complete this kind of services, some technologies are developed as the vehicle usage estimation and the optimized service planning.

The vehicle usage estimation aims at estimating the current operating usage from the vehicle data namely the GPS data. The vehicle usage is described via the Global Truck Application parameters, used and defined in the Volvo Group. The GPS data are matched with a digital map to retrieve the interesting attributes which qualifies the Global Trucks Application parameters.

The optimized service planning tool developed in MODE project gives some innovative features and allows:
1) the use of several maintenance policies as :
- Type 1: Fixed interval date
- Type 2: Maintenance intervals based on the current vehicle usage profile, specified in terms of time, mileage or engine hours.
- Type 3: Maintenance intervals based on statistical failure analysis
- Type 4: Maintenance intervals dynamically computed based on RUL estimation
2) the optimization of the service planning based on vehicle real time usage:
- When a change in usage is dynamically detected via the Global Truck Application parameters, the usage profile is automatically recalculated and the service planning is updated accordingly.
- The uptime will increase up to 30% thanks to this functionality.
3) the reduction of operating costs:

- The service planning computation algorithm aims at minimizing customer's costs, considering both maintenance operation (+ set-up) costs, and immobilization costs.
- It can save 25% of the maintenance cost.

4) some flexibility from the customer's point of view:
- The system allows the customer to suggest time slots when vehicle immobilization is more convenient.

Potential impact:

The MODE project aims to increase transport competitiveness by increasing the vehicle uptime. Proposing a global uptime based transport solution will help to maintain vehicles at their optimal condition. But, the ability to provide such an offer to the vehicle owners relies on the capacity to follow-up vehicle's usage and trace maintenance history. By using the increasing potential of wireless communications systems, vehicle data could be transferred on a regular basis to a central system. The analysis of vehicle usage and follow-up of components status will generate better inputs in order to tailor services and maintenance solutions toward customer business expectations. The MODE project applies state of the art research results in condition monitoring and remaining life time of components to optimize the maintenance service time and reduce the failure time. The usage of remaining life time information allows the extension of service interval whereas the service time decreases by optimization of maintenance planning tools. Furthermore, scheduling maintenance operations based on actual component degradation can benefit to spare parts consumption.

Vehicle uptime also depends on our ability to decrease the 'failure' time. Even if part of the 'failure' time is dedicated to service done by the technicians the other part mainly concerns wasted time (wait for diagnostic technician, wait for parts, wait for payment procedures…). Providing the right information (i.e. failure cause description, vehicle location) will suppress the major part of this wasted time. Moreover, indirect consequences could be the reduction of congestion and accidents (by avoiding long period of immobilization on the roadside).

Impact on competitiveness

The evolution of fleet maintenance strategies is really clear: fleet are more and more interested in getting a business solution including both hard (vehicle) and soft products (services) in a same package. However, the possibility to provide such offers relies on a complex combination of technical information:
- Vehicle configuration: addressing the choice of most relevant vehicle components which is connected to,
- Vehicle usage: addressing the description of how the vehicle is expected to be used (including environment and usage by the operator) and,
- Vehicle services: which shall address the best set of services taking into account the two previous topics and customer expected revenues,
Solving this 'trade-off' will move the mindset from product offers toward 'uptime' offers, including product and services, thus supporting European transport 'mobility' vision. By using 'uptime' offers, most of the vehicle owners (fleet operators, logistics …) can focus on their core business: 'just in time' goods delivery. Uptime offers will increase the competitiveness for both dealers and customers. The MODE project will also impact a market of several billion euros for new product and maintenance. MODE targets uptime by enhancing the capability to provide an uptime oriented offer which targets 15 to 30% increase in efficiency. Currently, when a fleet company buys a vehicle, return on investment requires several years. However, expected revenues will decrease due to vehicle ageing. MODE proposal aims to support vehicle owners keeping operating cost as constant as possible. It potentially increases the competitiveness of fleet companies.

Supporting the development and demonstrate feasibility of R&D innovative competencies is one of the MODE objectives as well. Condition monitoring shall support automotive industry with high level algorithms. The ability to detect as early as possible faults and potential vehicle damage is very important for vehicle uptime management. Moreover, work on data quality insurance would be beneficial to ensure higher reliability of the system. Assessing the remaining useful is a key in order to leave the old schemes and establish tomorrow's way of achieving competitiveness. MODE gathers competencies in the field and tends to demonstrate how this could be used to increase European competitiveness in the road transport field. Ability to assess the remaining useful life of vehicles component would probably lead to guarantee of higher product and services values. That R&D work will positively impact both vehicle users and vehicle operators.

Environment

MODE objectives have a substantial direct and indirect impact on CO2 emission reduction. By providing systems and supporting decision based on quality ensured information about vehicle state of health, the MODE proposal will also create added value in the CO2 area.

MODE direct contribution on CO2 emission will be addressed thanks to a more relevant monitoring of vehicle components health status and remaining life time. This obviously includes some important engine and transmission items. Indeed, oil quality and injector performances state of health impacts fuel consumption. Thus, extending the oil drain interval will generate higher viscosity levels which could then be considered as a resistant engine torque. For injectors, faulty injection quantity directly impacts engine performance leading to poorer combustion efficiency.

MODE indirect impact on CO2 emission will be mainly generated by the opposite effect of the optimization of vehicle service intervals. The vehicles service is planned on regular periods of time whatever their component state of health is. Optimizing on components actual health status would lower the amount of stops at workshops in most of the cases. The less the vehicle is stopped for service, the less you need vehicles on the road for the same mission.

As unplanned stop on roadside directly creates risks of accident by immobilization of massive vehicles, it is important to avoid such a situation as far as it is possible. Whatever, immobilization also contributes to create congestion along the road. By partial blocking of the road, immobilized vehicle directly affects the traffic fluidity and increase the chance of bottlenecks. In the two situations described above, MODE directly or indirectly contributes to save CO2 emissions. Indeed, immobilization required either another vehicle to pull to stopped one or repair actors to drive till the location place. This leads to non-productive fuel consumption.

Congestion

Freight movements too have grown with rising incomes and because just-in-time logistical arrangements often require smaller but more frequent deliveries. Commercial truck travel has doubled over the past two decades, the same rate as highway travel as a whole, but remains a relatively small share of total vehicle miles travelled (about 7.5 percent). Like all vehicles in the traffic mix, trucks add to congestion and are affected by it. Their contribution to congestion is more dramatic in certain places-near intermodal terminals, on long inclines, and on two-lane roads, to name a few. Thanks to the development of early breakdown detection based on powerful vehicle monitoring abilities, MODE intends to reduce the commercial vehicle contribution to road congestion. Especially in case of incident, finding a 'safe' and more appropriate place to repair the vehicle would lower risks for congestion in potential risky and already crowded areas. Moreover, the capacity to provide exact information on breakdown prior to it from the vehicle to the repair centre would decrease back and forth trips from the repair team as well as less needs for roadside towing.

Safety

This pressure to save costs may incite some road operators to poorly comply with rules on road safety and social standards. While it can be assumed that the large majority of road companies operate in good faith, the record of infringements in several Member States indicates the existence of a number of negligent or even rogue operators. The compliance rate is also uneven between Member States. For every 100 working days checked, European enforcement agencies detect on average 2.9 offences against driving time rules, but the variation is high: in some Member States the detection rate is over 5, while in others it is less than 1. Lastly, compliance rates differ between undertakings operating outside their establishment country and those operating in their home country. The Vehicle and Operator Services Agency in the UK has found that heavy goods vehicles on international journeys have a higher rate of non-compliance than those engaged in purely domestic journeys (e.g. as regards roadworthiness, 31% of non-GB vehicles are non-compliant compared to 25% for GB vehicles). It also found that vehicles on international journeys are disproportionately more often involved in incidents which can lead to closure of lanes and severe congestion.

Low compliance rates have a negative effect on road safety and congestion since failure to comply with rules may create accidents or incidents in the network (lane closure). Heavy goods vehicles are involved in 10% of the total number of accidents with injuries. Although this figure is decreasing slightly, the seriousness of these accidents is two to three times higher than that of other accidents and 20% of road fatalities are caused by accidents involving heavy goods vehicles. The second negative effect is on market efficiency. The uneven level of monitoring and controls creates distortions of competition between operators committed to be fully compliant, and therefore to bear the corresponding compliance cost, and those inclined to deliberately exploit the disparities mentioned above.

Dissemination and exploitation

Besides the project website, major means of dissemination were participation in conferences, work-shops and expert groups of European interests groups such as EUCAR and ERTRAC. E.g. progress of MODE was regularly reported in the EARPA working group on materials & manufacturing from which the project originated. Altogether, more than 20 presentations and 25 publications were made addressing the scientific community and potential end-users of MODE technologies. Furthermore, Partners of MODE submitted a proposal to the transnational call 2011 of the mnt-era.net which did not pass the evaluation. Additionally, a MC-ITN proposal related to condition monitoring of mechanical systems has been submitted with MODE and external partners. In view of Horizon 2020, the MODE network intends to continue with its cooperation.

Besides, a general brochure and a 5min video have been produced for the general public and potential end-users promoting the technologies of MODE. After official project end, the MODE project received the DHL Innovation Award 2013 in the category 'Best customers solutions' a publically announced award. A detailed list of dissemination activities can be found in the MODE Dissemination and Use Plan as well in the following sections.

List of websites:

http://www.fp7-MODE.eu