Remote Diagnostics Tools and Services - ReDi2Service

Project within "FFI - Transporteffektivitet"

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Content

FFI in short

FFI is a partnership between the Swedish government and automotive industry for joint funding of research, innovation and development concentrating on Climate & Environment and Safety. FFI has R&D activities worth approx. €100 million per year, of which half is governmental funding. The background to the investment is that development within road transportation and Swedish automotive industry has big impact for growth. FFI will contribute to the following main goals: Reducing the environmental impact of transport, reducing the number killed and injured in traffic and Strengthening international competitiveness. Currently there are five collaboration programs: **Vehicle Development, Transport Efficiency, Vehicle and Traffic Safety, Energy & Environment and Sustainable Production Technology.**

For more information: www.vinnova.se/ffi

1. Executive summary

The project aims were to explore and develop a new approach to vehicle fault detection and diagnostics, including possible digital services to be designed around this. There are two main reasons to provide Remote Diagnostics Services. First is to increase vehicle availability by avoiding unplanned breakdowns. Second is to decrease the cost of maintenance by better scheduling, faster diagnosis, better parts availability and the possibility to bundle service and repair to reduce the number of workshop visits. The key technology idea in this project was to use the streaming data on board a fleet of vehicles, detect deviations by comparing data across a fleet, and do data mining on this by combining on-board data with Volvo off-board databases, for example vehicle repair and maintenance records.

The technical side of the project corresponds to a paradigm shift in how fault detection and maintenance prediction is done on board vehicles. Instead of defining potential faults beforehand and designing and implementing fault detection algorithms for each fault, the approach here was to observe what signal deviations that actually occur in the field and match these to repairs and to use one algorithm for all faults.

The project included developing hardware and software for on-board data monitoring with remote re-configurability capabilities, plus off-board software for communicating with the vehicle, as well as analysing and presenting the data. It also included the development of algorithms for fault detection and diagnostics, with a demonstration on a real-world pilot study: a fleet of city buses operating in Kungsbacka. Furthermore, it included an analysis of services connected with remote diagnostics, based on interviews and case studies. The resulting recommendation is to start supplying remote diagnostics solutions as an integrated tool in the already existing service contracts.

Within the project we designed and produced the VACT (Volvo Analysis and Communication Tool) system. It continuously monitors signals on board the vehicle and can either log them or produce and transmit compressed representations of the data to a back-office application. We have demonstrated, on several real events, how our approach can detect emerging faults weeks or months before they are discovered using existing solutions, in particular for a number of issues that ultimately lead to serious problems.

Examples of such faults include jammed cylinder, worn NOx sensors, malfunctioning cooling fans and worn compressors. Those are faults that are either infrequent or not critical for vehicle operation, and therefore difficult to motivate specific fault detection algorithms for. With our method we have shown that with single hardware and software, we can monitor many subsystems at the same time, without specifying what particular fault to look for. We have shown that it is feasible to use a low complexity system, with no additional sensors, based on a stream data mining approach to build up a knowledge base that can describe many different faults and monitor many components for which no commercial diagnostic solutions exist today.

We have also analysed how to integrate remote diagnostics system with Volvo customers' current operations. Deviations and maintenance needs must be communicated efficiently with various stakeholders, e.g. the customers' fleet managers, in order to properly schedule maintenance. It is necessary to handle all of this information in a comprehensive fashion, also incorporating error reporting from e.g. drivers and cleaning staff. It is vital that the information is available and transparent to everybody involved in planning and executing maintenance. Studies on current procedures used by bus operators reveal that this information tends to be noted on paper and kept to too few actors.

2. Background

The ReDi2Service project was started as a result of very promising findings in a previous smaller project. It was shown that by mining data streams on board vehicles and compressing them to linear relations it was possible to detect faults that had been injected. The detection results were better than the available (and feasible to install in a vehicle) commercial systems for data based deviation detection. These results were based mostly on data from a single truck running on a specific route with a fixed load.

In order to apply the method in real scenarios, more knowledge was needed regarding the variability of data between vehicles in normal traffic. It was also discovered that more investigation was needed on how to build services around remote diagnostics, to motivate the costs to install monitoring systems and maintain an off-board analysis tool.

3. Objective

The ReDi2Service project started with the specific aims to study the issues mentioned above. The expected results, as stated in the application, were:

- A new method for remote diagnostics that had been tested on real vehicles and that could be shown would lead to increased vehicle reliability and more efficient transports.
- Technology transfer and knowledge transfer to product units within Volvo.
- A concept pilot together with a third party transport operator.
- A concept demo for dissemination and education.
- One PhD (industrial) with expertise in methods for vehicle diagnostics in general.
- A product prototype for the on-board system (hardware and software) and a back-office application for remote diagnostics, based on the technology developed within the project.
- An identified service built around remote diagnostics and predictive maintenance.

- Process description that demonstrates how the technical solution together with the service offer affects the customer's business process in a positive way.
- Three academic theses; two licentiate and one PhD.
- A number of scientific publications.
- A plan for implementing the method and other results within Volvo's product units.

4. Project realization

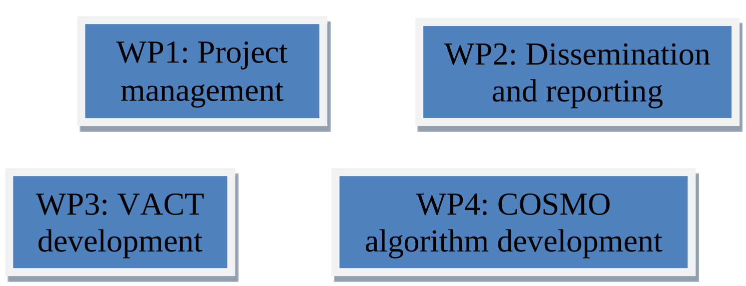
The project constitutes of a service part and a technical development part. The latter supports the first with the necessary solutions while the service development investigates how these can be packaged into products and services that increase Volvo Group revenue.

In the technical part we developed a fleet-based fault detection and diagnostics framework. It enables remote monitoring of vehicles using a distributed approach. The approach consists of on-board hardware as well as data analysis algorithms, and has been tested on a fleet of busses. The VACT on-board tool monitors the individual vehicles and communicates with a central back-office system. There the vehicles are compared with each other and deviations are tracked.

The back-office system also augments the discovered deviations with information from other Volvo internal sources, such as the service history, that can be used to provide additional context. A self-learning scheme, applied to the combined data, allows matching the deviation history with patterns of workshop operations. In this way the characteristics of certain faults can be discovered. This knowledge is later used in explaining and predicting a fault when the same deviation is found in another vehicle.

The service part investigated how Remote Diagnostic Services (RDS) can create value for the customers of Volvo. This was done by developing concepts for business models and services that incorporate technologies such as the technical framework developed in the project. Topics addressed include maintenance strategy, services enabled by RDS, selling RDS and business case models. For example, the maintenance strategy covers how to balance corrective and predictive maintenance and how to optimize the service intervals for various components, as well as the influence of the prediction accuracy of the maintenance needs.

The following work packages were included in the project:



WP5: Log data acquisition | WP6: Service development | WP7: Proof of concept

Work packages 1 and 2 were about management, reporting and communication. The dissemination activities are described in detail in Section 6.1.

Work package 3 was about developing the VACT hardware and software that enabled logging of data on-board vehicles as well as communication to a back-office portal. Through this portal, individual vehicles could be configured with regards to what signals to log and what algorithms to run.

Work package 4 was about analysing the on-board data, testing and developing a methodology for fault detection and isolation (based on the COSMO concept). The project also analysed data from off-board sources, such as vehicle service records, usage statistics and vehicle configuration databases, in particular to understand what additional knowledge is necessary for improved uptime services.

Work package 5 was about management and maintenance of the VACT operation, regular collection of data on USB sticks from the vehicles and interaction with the external partner, the bus fleet operator. This work package resulted in data collected for a period of over two years, from late 2011 until the end of 2013, on a fleet consisting of nineteen city buses.

Work package 6 was about investigating how the technical developments of the project can create value for our customers and for the Volvo Group by developing concepts for business models and services that incorporates technologies such as ReDi2Service that can be applied within the Volvo Group.

Work package 7 was about system integration and creating a proof of concept. Here work was performed to understand and annotate the on-board data and service records in order to get a top-level picture of the vehicles' operation and the problems they encountered. This was critical to show the potential that exists in the life-long learning concept on a fleet of vehicles.

5. Results and deliverables

5.1 Delivery to FFI-goals

We have contributed to the following FFI goals:

- New business opportunities created

The transportation industry is undergoing a transformation towards a service industry, where the OEMs will offer transportation enabling services instead of selling vehicles as such. The key to success here lies in risk handling, which is partly facilitated by precise predictions of maintenance needs. The project developed and evaluated a technology for automatically discovering anomalies that can lead to increased knowledge about vehicles, also beyond the warranty period. In addition, the business case analysis is crucial for finding out how to introduce such a disrupting technology into the market.

- <u>Decreased travel- and transportation times through fewer disturbances and increased throughput</u>
  The technology and services developed in the project will decrease the number of unplanned stops and thus lower the risk of delayed transports and traffic congestion. We have shown that the self-monitoring concept offers early warnings in case of several problems that today often result in unplanned downtime or increased fuel consumption.
- <u>Increased competitiveness for Swedish vehicle industry</u>
  Precise maintenance predictions means better risk handling for the OEM, which leads to better price estimates, for example of service contracts, and therefore for more competitive offers for the customers. In addition, a number of patents have been created for Volvo's account of the underlying technology.
- <u>Improved service, maintenance and improved products and services</u>
  The method developed increases the diagnostic precision and enables better workshop planning. This reduces the number of re-visits to workshops, as well as waiting time at the workshops.
- <u>Increased competence in the area</u>
  A licentiate degree is planned during 2014, two PhD dissertations are planned for the end of 2014. The project has resulted in several publications as well as several Volvo internal workshops and reports.

5.2 Project Results

It is necessary to balance between keeping the maintenance and repair costs low and the vehicle availability high. Vehicle maintenance and repair can broadly be categorized as either *corrective* or *preventive*:

- Corrective maintenance is based on run-to-failure maintenance approach. The vehicle is driven until it breaks, then it is fixed.
  - Pros: no throwing away components that still have some useful life in them.
  - Cons: the vehicle will frequently break down and stand still; also, problems tend to get larger and more expensive to fix if not solved early.
- Preventive maintenance requires planning and taking actions before actual failure occurs, where some parts are replaced based on e.g. experience or early wear symptoms.
  - Pros: increasing the availability and performance of the vehicle.
  - Cons: the risk of costly over-maintaining of the vehicle.

All vehicle manufacturers have chosen a mix of the two above methods. The service plan is used to schedule replacement of some parts preventively (e.g. filters and oil), while other components are replaced correctively as they break (e.g. turbo and air compressors). The approach in this project tries to, as shown in Figure 1 below, find the optimum level of preventive (green line) and corrective (red line) maintenance and repair to keep the total cost of operation (yellow line) to a minimum.

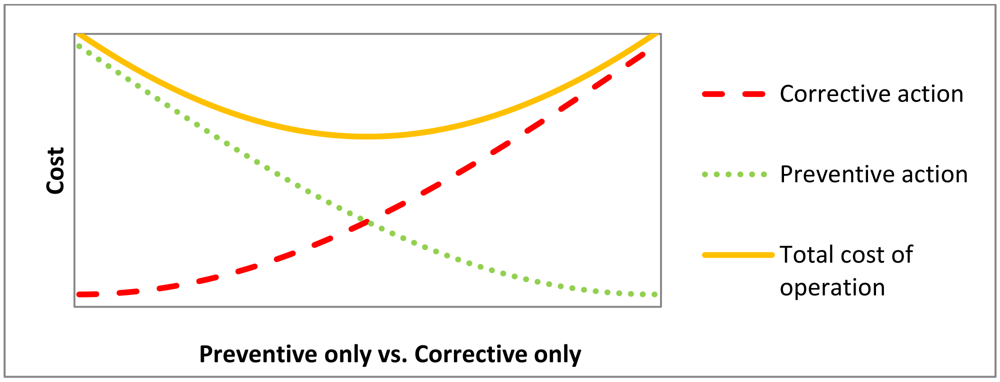
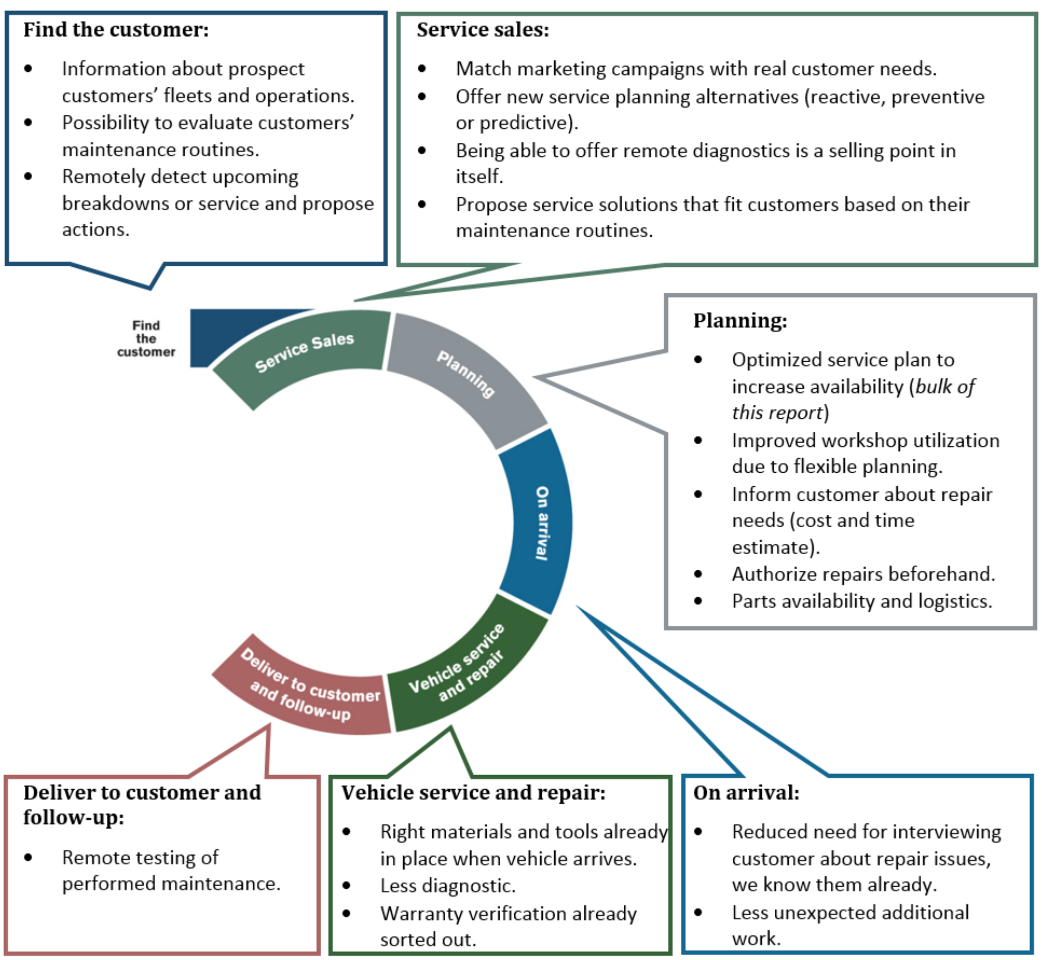


Figure 1 - Preventive vs. Corrective

The information provided by technologies developed in this project can be packaged and used for many different applications. While the main focus was on detecting component deviations and optimizing the service planning and vehicle availability, there are several secondary cost saving possibilities. We have used the Genuine Volvo Service (GVS) process to illustrate where RDS can contribute.



The different Volvo businesses (Trucks, CE, Buses, and Penta) today have two main aftermarket business models. One is of a transactional basis, where a vehicle is sold and then they hope to sell spare parts and maintenance labour during the lifetime of the vehicle. The other is based on service contracts, where a vehicle comes with maintenance and repair plan for a specified number of years. The revenue streams from the service contracts are usually in the form of monthly fees. In some of those contracts, e.g. for the new FH truck in Europe, Volvo adds an “uptime promise,” where the customer is compensated for any downtime exceeding a predetermined level. There are distinct differences and even conflicting requirements between the two business models.

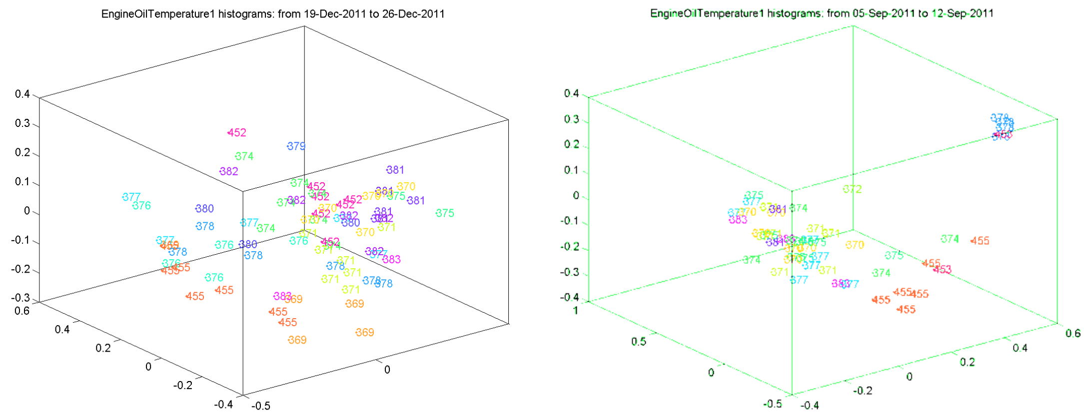
From an internal engineering perspective it is reasonable to believe that it is easier to make a positive RDS business case for the service contract model. To make it profitable in the transaction based business, we would need to either increase the price of the truck, spare parts, and labour rate or sell RDS as a standalone service. It is possible to do, but it takes effort to convince the customers about its value.

However, the information obtained via the analytical procedure in RDS can also be sold to bus operating companies who have their own workshops. As they will not sign Volvo’s regular service contracts, a special agreement needs to be prepared for providing RDS. When bus operating companies sign it, Volvo takes the responsibility to monitor their buses and report possible emerging faults and maintenance needs to them. It is necessary to send detailed information regarding the predicted fault, as well as about what the technicians should do as the next step.

Another problem is that a lot of money is currently spent on over-maintenance. Parts are replaced routinely that, once extracted and examined, show no or little signs of wear. The bus maintenance staff estimates that 20% of the maintenance activities are unnecessary. This is both uneconomical and a waste of resources from a sustainability perspective. Based on our findings, customers would be willing to pay for a service that helps with some of the above issues. The business model can be a prescriptive model, where a long term contract would be signed in order to see the value over time.

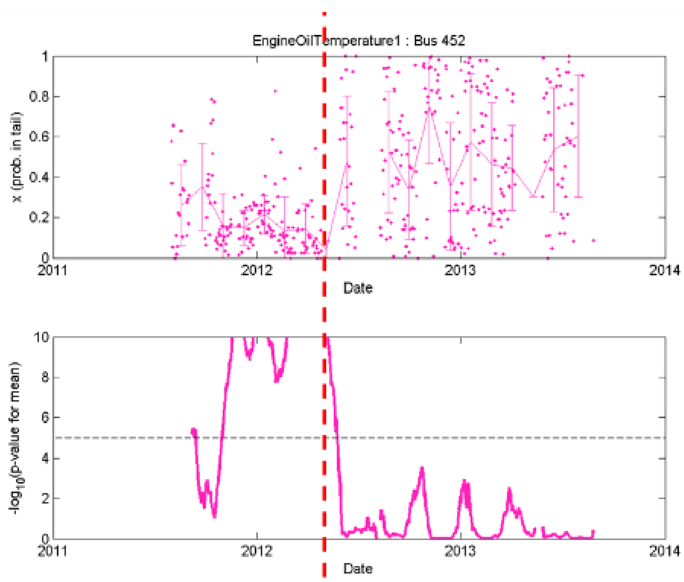
Unplanned stops for heavy vehicles are particularly problematic. Not only are the repairs more costly if they have to be carried out away from appropriate facilities, but they also often result in extra costs such as additional damage to components, failures to meet delivery deadlines and possibly loss of confidence among clients. Last but not least, the effects on the traffic flow could be devastating. It is also known that many vehicles operate for long periods of time in conditions that are far from perfect, since customers usually only visits workshops once problems render trucks or buses unusable. In this project we have observed examples where smaller faults are present for weeks or even months, causing fuel consumption and CO_2 emission levels to increase by several percent on the fleet level, and/or eventually leading to serious breakdowns.

The figure below shows an example of the data collected for one of the signals, the Engine Oil Temperature. Using a visualisation technique called *multidimensional scaling*, we have presented the variation in the data across the whole fleet over two one-week periods. On the left plot the data looks as expected, with no particularly interesting structure. Each point represents a single day for one vehicle, coded with colour and bus



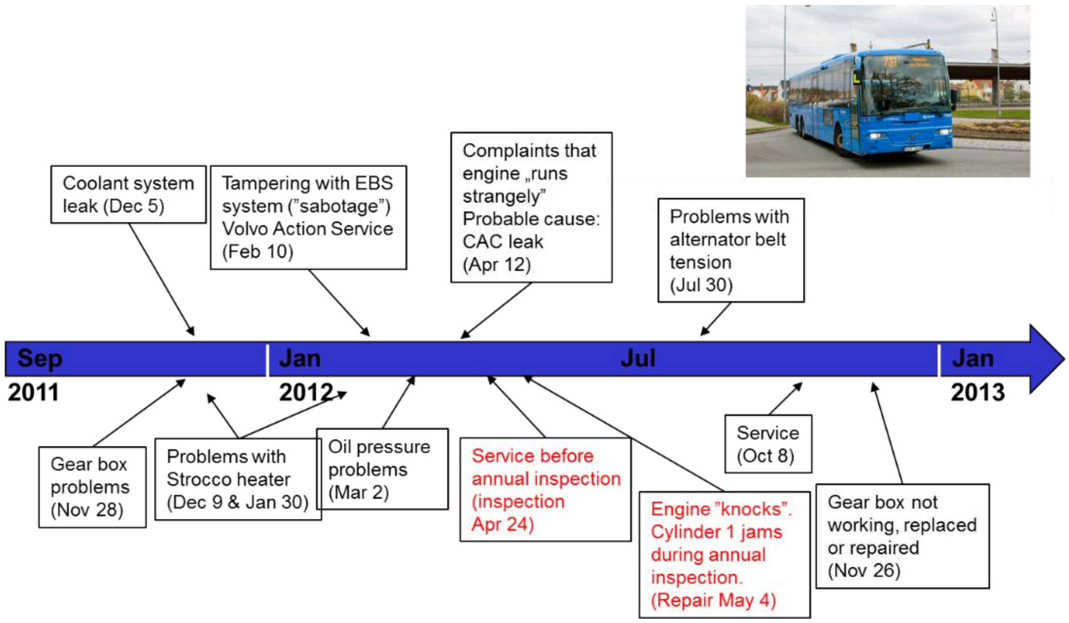
number, and while an individual is typically more similar to itself than to others, there is no reason to suspect any faults here.

To the contrary, on the right plot one bus is significantly deviating from the group. This is an example of a situation that is abnormal and should be communicated to the workshop or fleet operator so that it is analysed further. Our method is capable of finding this automatically. It allows also tracking the progress of the deviation over time:



In the top plot of the above figure we show the probability that a given histogram from a specific bus belongs to the 5% *tail* of the fleet distribution. Over time, if the vehicle operates as it should, those probabilities are expected to follow a uniform distribution. As can be seen, in this particular data there is a clear deviation that starts in late 2011 and lasts until May 2012. After that things go back to normal. The bottom plot shows a measure of how significant the deviation is.

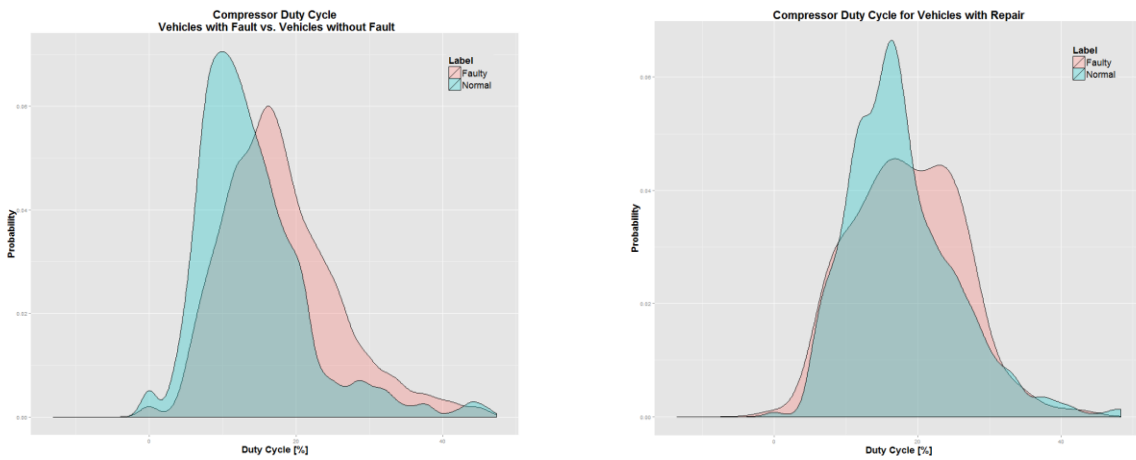
A tool that lets customer and workshop know about abnormalities in their vehicles is useful in itself, but the next step is figuring out the reason for those deviations. It can be either done automatically, based on historical data, or in a supervised manner, taking advantage of expert knowledge. In this particular case, an explanation can be found by looking at the repair history in early May, i.e. at the time when the deviation disappears.



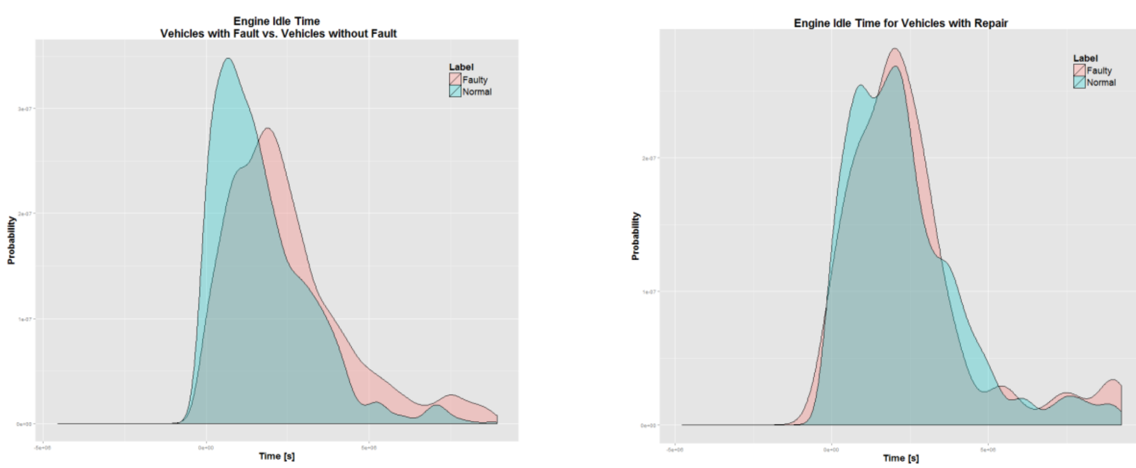
It turns out that there was a problem, probably lubrication, with one of the cylinders on this bus that eventually led to a jamming and required full engine renovation. Even despite customer complaints in April, the workshop was not aware of the issue and was not prepared for such a serious operation, which led to a significant delay (3 weeks) on top of an already lengthy repair. On the other hand, our method flagged the problem more than 20 weeks before it became a serious issue.

In the project we have also investigated the use of existing data sources, since most vehicles on the roads today are not equipped with continuous data logging capabilities. In particular, we have looked at which of the statistical usage parameters that are currently collected during workshop visits can be used to predict failures of various components.

We have been able to distinguish between two different ways in which parameters can be related to faults. The first type captures symptoms of the wear or damage. For example, vehicles with compressor failures have a different distribution of "compressor duty cycle" parameter than the ones without that fault (the red and blue plots, respectively, on the left figure below). Moreover, this distribution also differs between faulty vehicles long time before the fault (blue plot on the right figure) and the same vehicles shortly, i.e. less than 20 weeks, before the fault (red plot on the right).



The second type of relation corresponds to different usage patterns, instead. Keeping with the same example, vehicles with compressor failures have a different distribution of “engine idle time” parameter than the ones without that fault (the red and blue plots, respectively, on the left figure below). However, there is no significant change between faulty vehicles long time before the fault (blue plot on the right figure) and the same vehicles short before the fault (red plot on the right).



Over the time of pilot study in Kungsbacka we have detected multiple different problems, including cylinder jam, ECU fault resulting in cooling fan overuse, wear of compressors, issues with NOx sensors, as well as broken wheel speed sensors and modulators.

6. Dissemination and publications

6.1 Knowledge and results dissemination

Several workshops and project presentations have been held. We had one final workshop, for invited people from all over Volvo, on June 24th 2013. There we presented the results so far both from the service developers and the technical part of the project.

As our results from analyzing the logged data started to show, we required more in-depth information about components in the electrical system of the vehicles. When meeting the experts, we took the opportunity to present our project, the results and how our method would affect their area of responsibility. By doing so, our project has been presented to a wide spectrum of potential stakeholders within Volvo.

We started to cooperate with a bus operator in Kungsbacka in 2011 that let us collect data from their fleet of buses. We have had some presentations and workshops with them to get a deeper understanding of their operations, needs and future wishes.

This autumn we have had two major presentations for Volvo Product Planning teams. The latter one, a team dedicated to diagnostics and data logging. They showed great interests in our results, even though there are some platform related obstacles to implement our findings in the real market. More work is needed to justify hardware modifications to the current electrical architecture to get access to more data, but there are ongoing projects that look at how to handle these issues.

Finally, we have had a "technology readiness level" (TRL) assessment presentation for a handpicked number of persons responsible for Volvo's global diagnostic platform. They have judged our technology to be mature enough to start product project building upon our results, i.e. we have reached TRL level 4.

It should also be mentioned that "InnoMerge", another project sponsored by FFI program, is building upon some results from ReDi2Service, including using a modified version of VACT tool. A new FFI sponsored project "In4Uptime" is also taking advantage of the results from ReDi2Service.

6.2 Publications

Patents:

Granted: J. Hansson, M. Svensson, T. Rögnvaldsson, S. Byttner, "Remote diagnosis modelling", US Patent 8,543,282 B2. Granted Sept. 24, 2013. (International filing date: May 14, 2007. Publication date for application: Nov. 20, 2008). *Note that this patent was applied for before the project started (and was mentioned in the application). However, the patent was granted in the US during the project time.*

Applied for but not yet granted: S. Byttner, S. Nowaczyk, R. Prytz, T. Rögnvaldsson, “A method for monitoring the operation of a sensor” (Filing date Oct. 4, 2013), application number PCT/EP2013/002983.

Scientific papers from the technical part of the project:

[1] G. Vachkov, S. Byttner & M. Svensson (2013). Detection of Deviation in Performance of Battery Cells by Data Compression and Similarity Analysis. *International Journal of Intelligent Systems*, 29 (3), s. 207 - 222.

[2] S. Byttner, S. Nowaczyk, R. Prytz & T. Rögnvaldsson (2013). ”A field test with self-organized modeling for knowledge discovery in a fleet of city buses”. *IEEE Int’l Conf. Mechatronics and Automation (ICMA 2013), Kagawa, Japan, August 4-7, 2013.*

[3] R. Prytz, S. Nowaczyk, T. Rögnvaldsson & S. Byttner (2013). ”Analysis of Truck Compressor Failures Based on Logged Vehicle Data”. *9th Int’l Conf. Data Mining (DMIN’13). Las Vegas, AZ, July 22-25,2013.*

[4] S. Nowaczyk, R. Prytz, T. Rögnvaldsson & S. Byttner (2013). ”Towards a Machine Learning Algorithm for Predicting Truck Compressor Failures Using Logged Vehicle Data”. *12th Scandinavian AI conf. (SCAI). Aalborg, Denmark, Nov. 20-22. 2013.*

[5] S. Nowaczyk, S. Byttner & R. Prytz (2012). ”Ideas for Fault Detection Using Relation Discovery”. *27th annual workshop of the Swedish Artificial Intelligence Society (SAIS), Örebro, Sweden, 2012.*

[6] G. Vachkov, S. Byttner & M. Svensson (2012). ”Battery aging detection based on sequential clustering and similarity analysis”. *6th IEEE Int’l conference on Intelligent systems. Sofia, Bulgaria, 2012*.

[7] N. Karginova, S. Byttner & M. Svensson (2012). ”Data-driven methods for classification of driving styles in buses”. *SAE World Congress 2012, Technical paper 2012-01-0744. Detroit, MI, 2012.*

[8] M. Svensson, T. Rögnvaldsson, S. Byttner, M. West & B. Andersson (2011). ”Unsupervised deviation detection by GMM - A simulation study”. *8th IEEE Int’l Symposium on Diagnostics for Electrical Machines, Power Electronics and Drives (SDEMPED). Bologna, Italy, September 5-8, 2011.*

[9] R. Prytz, S. Nowaczyk & S. Byttner (2011). “Towards relation discovery for diagnostics”. *First International Workshop on Data Mining for Service and Maintenance, San Diego, CA, 2011.*

[10] S. Byttner, G. Vachkov & M. Svensson (2011). ”Incremental classification of process data for anomaly detection based on similarity analysis”. *IEEE Symposium on Computational Intelligence. Paris, France, April 11-15, 2011.*

[11] A. Mosallam, S. Byttner, M. Svensson & T. Rögnvaldsson (2011). ”Nonlinear relation mining for maintenance prediction”. *IEEE Aerospace conference. Big Sky, MO, March 5-12, 2011.*

[12] S. Byttner, T. Rögnvaldsson & M. Svensson (2011). ”Consensus Self-organized MOdels for Fault Detection (COSMO)”, *Engineering Applications of Artificial Intelligence, 24(5), pp. 833-839.*

[13] S. Byttner, M. Svensson & T. Rögnvaldsson (2010). ”Finding the Odd-One-Out in Fleets of Mechatronic Systems using Embedded Intelligent Agents”. *AAAI Spring symposium 2010, Palo Alto (Stanford), CA, March 22-24, 2010.*

Scientific papers from the service part of the project:

[14] A. Akram, M. Bergquist & M. Åkesson (2014). “Digital Visions vs. Product Practices: Understanding Tensions in Incumbent Manufacturing Firms*”, The 47th Hawaii International Conference on System Sciences, 6-9 January, 2014, Hawaii, USA.*

[15] S. Chowdhury & A. Akram (2013). “Challenges and Opportunities related to Remote Diagnostics: An IT based resource perspective”, *International Journal of ICT and Human Development*, 5(3), 80-96

[16] A. Akram (2013). “Value Creation in Digital Ecosystem–A Study of Remote Diagnostics”, *The 36th Information Systems Research seminar in Scandinavia, Oslo, Norway. 11-14 August, 2013.*

[17] S. Chowdhury & A. Akram (2012). “E-maintenance as a prospective customer value generating IT-enabled Resource: An exploration of challenges and opportunities”. *European Conference on Information Systems 2012*.

[18] A. Akram & M. Åkesson (2011). ”Value network transformation by digital service innovation in vehicle industry”, *15th Pacific Asia Conference on Information Systems, Brisbane, Australia, July 7-11.*

[19] S. Chowdhury & M. Åkesson (2011). “A proposed framework for identifying the logic of digital services”, *15th Pacific Asia Conference on Information Systems, Brisbane, Australia, July 7-11.*

[20] S. Chowdhury & A. Akram (2011). “E-maintenance: Challenges and Opportunities”, *34th Information Systems Research Seminar in Scandinavia, Turku, Finland, Aug. 16-19.*

[21] A. Akram & M. Åkesson (2011). “A research agenda to study how digital service innovation transform value network”, *34th Information Systems Research Seminar in Scandinavia, Turku, Finland*.

7. Conclusions and future research

The established way to prevent unplanned stops is throughout planned and executed use of fixed intervals and static maintenance plans, based either on general measures or on historical predictions of component wear calculated usually once for the whole vehicle model. This is a reasonable trade-off between replacing components too early and too late on the global scale, but it is possible to improve upon this scheme by using more precise, individually customised maintenance plans.

ReDi2Service is a generic and adaptive approach, not directed at specific faults but making use of the available data on-board the vehicle and developing with the life-time of the particular fleet, finding relevant faults at any point in time. It can be especially cost efficient for rare and non-critical faults, as it is not designed to replace but rather augment existing fault detection and diagnostics techniques.

In the project we have shown that self-monitoring can help avoid a number of unplanned stops e.g. due to jammed cylinder in the engine, or wheel speed sensor problems, and also result in a more efficient fleet operation, by early detection of problems such as an ECU failure affecting cooling fan or compressor wear. The data collected can also be used to increase overall knowledge about vehicles, their usage and wear patterns, for example we have applied for patent on detecting NOx sensor wear based on results from the autonomous deviation detection algorithm.

Future research directions include more autonomous matching between on-board deviations and off-board data such as service records and design specifications. It is also interesting to develop a way of predicting *remaining useful life* of various components, so that they can be replaced when needed and not too early. Finally, in this project we have been working with a single, homogenous fleet of vehicles, so it remains to be seen how this method should be adapted to a larger population, possibly requiring dynamic fleet assignments based on various conditions.

8. Participating parties and contact person

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