

The connected wagon - a concept for the integration of vehicle side sensors and actors with cyber physical representation for condition based maintenance

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Abstract: For decades, the technology of freight railcars has not changed significantly. With the advent of telematics, on-board sensing and cloud-based analytics for control and condition based maintenance, high potential for economic benefit has become possible. Furthermore, such a connected wagon offers a seamless integration into current and future logistics systems, which are driven and controlled by the industrial Internet of Things to support the fourth industrial revolution. An important concept introduced with the Wagon 4.0 is standardized hardware, together with an open-source operating system based on prognostics and health management principles for predictive analytics. Thus, the Wagon 4.0 paves the way for a new operations and maintenance concepts, user interfaces and value proposals, which originate from current developments.

The economic advantages stem from the self-organizing features of such vehicles, from the ability to achieve mass customization and from a rise in efficiency in operation and maintenance.

This paper presents an approach for such a system including the power supply, intra-train communications, sensing, cloud-based analytics and value-add proposition. Furthermore, the approach is illustrated through an example implementation for a pneumatic brake which encompasses the instrumentation, sensing, automation and cloud based analytics of the sensor data. The paper concludes with a description of how the implantation enables the railcar operator to practice predictive maintenance and increase operational efficiency.

Keywords: freight wagon; cyber physical systems; prognostics, health management, condition based maintenance; internet of things

1 Introduction

Transportation of passengers and freight is an important and growing field, for which sustainable modes need to be developed in light of greenhouse gas emission reduction requirements and pressure on operators to reduce costs and increase efficiencies. It is generally agreed that rail transport is one of the more sustainable modes of transportation, while customer choices of transportation mode with respect to sustainability are not yet identified. (Lammgard, 2012)

The freight rail vehicle sector across the world rarely exhibits technological novelty, especially not in the areas of Internet of Things (IoT) and

cloud services, which is deemed a major factor for increasing productivity (Haug, Kretschmer and Strobel, 2016). Furthermore, the integration of communication technologies into transportation systems is considered an enabler and thus highly required, despite plenty of adoption barriers (Harris, Wang and Wang, 2015).

While other modes of transportation seek to automate their operations as far as possible, refer to (Murgoitio et al., 2016), freight rail rolling stock is accepted in its current state and the system has been optimized without considering the potential of selected investments into rolling stock (Marinov and Viegas, 2009).

Another strand of development is that of freight rail telematics systems, which are installed on 85% of trucks in Europe (Behrends, Haunschild and Galonske, 2016). Such systems are added to the railcar as an isolated system, and transfer the required data directly to its destination without aggregation of data in the vehicle. Notwithstanding the capability of such systems to solve the problem that led to its integration, a deeper integration of individual systems would improve the power of the overall monitoring performance, as proposed in (Behrends, Haunschild and Galonske, 2016).

While these amendments to the freight wagon will provide effective monitoring of the vehicles, their potential for optimization and cost saving is limited with regards to last mile processes, which account for approximately half of the production cost (Galonske, Riebe, Toubol and Weismantel, 2016).

The integrated and standardized approach of the Wagon 4.0 has the potential to significantly reduce the effort of last mile processes by providing a basis for application specific functionalities (Pfaff and Enning, 2016; Enning and Pfaff, 2017). In this study, the requirements for and the concept of the Wagon 4.0 are developed and presented through sample applications for bogie and break performance monitoring.

2 Wagon 4.0 Condition Based Maintenance

Building on top of telematics systems, Condition based maintenance (CBM) is an important aspect of the Wagon 4.0 in order to decrease asset downtimes and to improve the effectiveness of maintenance schedules. Few studies with this scope have been previously completed due to the following reasons:

First, on-board condition monitoring has historically not been applied to freight rail applications and is a new technology in the realm of freight rail maintenance. Typically, condition monitoring in the freight rail industry is achieved through wayside equipment and therefore research in this area has traditionally focused on efficiency improvements. Barke and Chiu (Barke and Chiu, 2005) published a review of existing freight rail bogie condition monitoring technologies but excluded on-board methodologies and solely focused on wayside

technologies. Lagnebäck (Lagnebäck, 2007) also limited his study of potential cost and efficiency improvements through condition monitoring to wayside techniques, which resulted in recommendations to expand implementation.

Second, most condition monitoring studies have been attempted in the area of passenger rail transport (Ward et al., 2010; Ward et al. 2011). Due to regulatory safety requirements and the fact that they are a common transportation mode around the world, these systems were historically given more attention than freight rail systems. Differences in mechanical construction, in particular suspension components, and the lack of power on freight systems further complicates the transfer of passenger rail monitoring systems to freight rail systems.

Third, condition monitoring of freight rail applications is not limited to bogies and bogie suspension components. Other areas of interest, where significant work has been completed, include the wheel-rail interface (Hubbard et al., 2013), railcar speed inaccuracies due to stick-slip action (Mei and Li, 2008), end-of-car devices (Hopkins et al., 2015) and on-board weighing (Maraini et al., 2014) applications which in conjunction ultra-low power monitoring technology was proven to be able to successfully record from accelerometer or strain gauges.

It is understandable that the emergence of on-board monitoring technologies and continuous improvements in accuracy lead to a vast scope of interest which includes monitoring strategies for components which have traditionally not been able to be monitored effectively.

3 Wagon 4.0: Enablers and drivers

The development of the Wagon 4.0 was initiated by the observation that in most developing countries the freight transport of bulk goods such as coal, oil or gas is set to decrease in the light of the decarbonisation of the energy sector. The total freight volumes will not decrease at equal pace, as an increasing number of smaller items is dispatched. These items are not only smaller, but bear at the same time more value as well as more demanding requirements in terms of punctuality and speed of delivery. For such items, most of the current rail freight systems are

deemed unsuitable by the customers, who turn to road transport instead.

2.1 Industry 4.0

The key aspects of Industry 4.0 are mass customization and self configuration. The former term indicates that single, highly specialized items are being produced at the same high efficiency as mass produced articles today, while the latter term expresses the fact that in the factory of the future, machines are expected to organize themselves autonomously, e.g. in the case of failure or maintenance. Driving forces of the fourth industrial revolutions are the Internet of Things (IoT), Cyber Physical Systems and Ubiquitous Computing.

2.2 Condition Based Maintenance

With the high cost of both preventive and reactive maintenance, condition-based maintenance can be considered a key enabler of the Wagon 4.0. Typically, applications follow one of two paths: either that of model-based condition monitoring or that of data driven condition monitoring.

For model-based condition monitoring, a physics-based model, derived from first principles, is used to determine required system parameters. The system parameters are then compared against data to determine if a deviation from a healthy system state is taking place. In (Li and Goodall, 2004) this approach was used in a two degrees-of-freedom, half-vehicle bogie model to determine such parameter deviations.

For the data driven case, a signal from the system under test is used to infer what the current system health is. The signal must have a causal relationship to the system component subject to monitoring and thus be indicative of the system's performance. First, the signal is pre-processed and frequency and time domain based features are extracted. In many cases, the number of features can grow large and advanced techniques for selecting those features that are most descriptive are required. Feature selection algorithms include mutual information (Maraini and Nataraj, 2015) for estimating the similarity of two signals. The signal features constitute the inputs to machine learning algorithms which attempt to classify the health state of the system. If a target class is specified with the measurements, the problem is classified as a

supervised learning problem and if no target class exists, the problem is classified as an unsupervised learning problem. Popular machine learning algorithms include techniques such as neural networks (Haykin, 2004) and support vector machines (Cortes and Vapnik, 1995) to identify the fault modes from measurements.

In both cases, data is required to either compare against the model or to train the machine learning algorithm. Typically, this data is taken from inertial sensors such as accelerometers and gyroscopes, mounted on the system under test, but other metrics may be used as well. If prognostics is also part of the monitoring strategy, advanced filtering techniques such as particle filters (Arulampalam et al., 2002) or Kalman filters (Kalman, 1960) can be combined with the algorithm to estimate future states from the current state accelerometer measurements.

2.3 Logistics 4.0

As may be expected from the vision of mass customization and self organization, Industry 4.0 will rarely require trainloads of identical material at a given time, but rather smaller amounts of varying goods at the right time. This is well in line with the less recent trends of just-in-time and just-in-sequence logistics, but adds a layer of self-consciousness of the freight and the wagon in order to achieve the ability to be controlled by self organizing machines.

2.4 Wagon 4.0

The problems of the current freight system and especially its rolling stock to fulfill the requirements of Industry 4.0 and Logistics 4.0 call for a concept to innovate wagons on a holistic basis. An approach to this is the conception of a platform to enable extension of the wagon according to the particular needs of a service, similar to smartphone apps.

Such a basis consists of six central elements:

1. **Power Supply:** Power plays a crucial role in CBM, since freight railcars are typically unpowered assets. It was proposed above to use energy harvesting and to store the generated power in batteries for consumption by the Wagon 4.0. Power efficiency can be achieved by running the monitoring algorithm in an asynchronous, event based mode versus an always-on, continuous monitoring mode.

2. **Data Network:** The proposed data network shall be considered to consist of a node and gateway system. The nodes will be placed on components of interest and collect the data for upload to the gateway. The gateway can then either use 3G/4G/5G cellular connectivity to communicate the data to a centralized location or utilize an intra-train network to send the data to the locomotive. The locomotive can then seamlessly send the data to the processing point. The advantage of the latter idea is that the locomotive can generate unlimited amounts of power and is therefore able to transmit large volumes of data.
3. **Sensors:** The sensors of the Wagon 4.0 will be composed of accelerometers and gyroscope sensors with specific characteristics to accommodate the harsh operating environment. This includes features like analog filters to avoid aliasing during data acquisition. Furthermore, digital sensors offer the unique ability to obtain a flat frequency response down to 0 Hz (DC) which is important for collecting data about oscillatory rigid body vibration in fault modes such as *hunting*.
4. **Actuators:** While sensors and networks provide useful data, the economic effect in the daily operation of the wagon is mainly generated by automating key functions of the wagon, e.g. the brake.
5. **Algorithms:** The algorithms for condition monitoring have to address a number of machine learning requirements such as data collection, feature extraction, feature selection, classification and prediction in an efficient way. This can be realized by performing the processing on the node level and sending the classification outcome to the gateway in a power constrained situation or sending the raw data to the gateway for processing if energy harvesting is providing adequate power supply. In both cases, the algorithms have to be designed such that they can compute the desired metrics on low cost hardware in an adequate amount of (i.e. near real-time).
6. **Operating System:** The so called WagonOS, an open source operating system, will unify the above mentioned four base concepts to allow for extending the capabilities of the Wagon 4.0 and to standardize communication protocols, data formats and related standards. A central operating system

would furthermore enable currently disjointed efforts to unite under the umbrella of a single industry standard.

The provision of these elements for the Wagon 4.0 does not only lead to simplifications for freight customers, it also paves the way to new business models for wagon owners and railway undertakings.

Such business models arise e.g. from the provision of data connection to smart cargo, e.g. high value objects that require monitoring of temperatures and vibration, making the load data another payload of the railway undertaking. The respective connections are depicted in Figure 1.

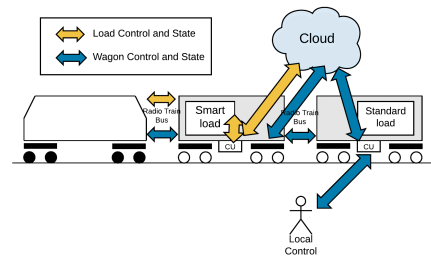


Fig. 1 Train concept of Wagon 4.0 and freight

3 Applications for particular use cases

The Wagon 4.0 is set to provide the basis for extensions according to user scenarios or use cases. Numerous discussions have been led with stakeholders in the freight rail system and solutions for different use cases were identified (Pfaff and Enning, 2016; Enning and Pfaff, 2017). Of special interest, due to the potential gain in safety as well as economic savings, are condition monitoring of running dynamic properties as well as automation of labor intensive subsystems of the freight wagon, such as the brake system.

3.1 Application Models

3.1.1 Bogie Performance Monitoring

Structured sensor data from components of interest such as brakes, wheels, bearings, and coupling systems as well as oscillation modes such as hunting, pitch, bounce, yaw and roll provide insight into the dynamic behavior of the Wagon 4.0. Previous studies have shown that such an approach can indeed provide the

foundation to practice predictive maintenance on a freight rail car. In (Shahidi et al., 2015) it was examined how such a system for bogie performance monitoring could be realized with machine learning techniques. The authors utilized sensor data from multiple locations taken on the bogie to gather vibration data in the vertical, longitudinal, and horizontal direction of the wagon. This data was then analyzed in a data processing pipeline which followed the structure explained in section 3.2 for the data driven case. The full data pipeline including an action recommendation as the outcome is shown in figure 2

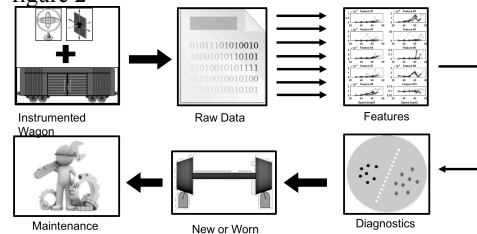


Fig. 2 CBM Pipeline

Once the classifier creates a decision in the fourth step about the wear level of the wheels, an action recommendation can be created and carried out to take the wagon out of service for maintenance at a non-critical time.

The model described above could be considered a proof of concept for the ability to successfully predict the level of wheel wear, the major factor influencing bogie performance in addition to primary and secondary suspension wear, and thus estimate the remaining useful life (RUL) of the wheelset. This information is a key driver in enhancing the planning of maintenance operations.

3.1.2 Automated freight wagon brake system

The brake subsystem of a freight wagon is, depending on the system in use, a system which requires plenty of manual labor. This labor is mostly consumed in the manual control of the modes of the brake system. The automated brake presented below is based on a UIC system. However, most of the techniques developed can be adapted to other norms, such as GOST and AAR.

A freight wagon according to UIC requires the following states of the pneumatic brake of the wagon to be set:

- Brake cylinder filling time (Brake mode G/P changeover)
- Load selector (empty/loaded)
- Pneumatic brake isolation
- Control reservoir discharge
- Brake line end cocks
- Immobilisation brake

Further, the following states are read back (during brake setup and brake assessment by an operator):

- Braked weight percentage
- Vehicle mass
- Functionality of the pneumatic brake

The manual operation of the controls as well as the brake test by an operator is time consuming, it is reasonable to assume at least 90 Minutes for a complete train preparation, depending on train length.

Considering this comparably low number of states to be controlled and read back, it appears feasible to integrate an electric/pneumatic control element into the pneumatic brake system in order to control and read these remotely.

Indeed, all functions indicated above are either obsolete on more advanced brake system, e.g. for high speed rail or are automated in other segments. In addition to the telematics and CBM capabilities described above, the Wagon 4.0 generates its incentive to invest into this new technology from automation of wagon features, due to the time consuming operation of the brake system during train set-up, automation of the brake system is particularly effective.

The brake system of the Wagon 4.0 is designed around the introduced distributor valve, in the case at hand of UIC-type. Most state changes are achieved by help of bistable magnet valves. In this way, the safety level of the system can be assured to be equivalent to that of the existing brake system by turning the automation system passive after brake assessment.

As an exception, the ep-apply functionality to vent the brake line locally to decrease brake application time and equalize braking forces in the train, is maintained active during the mainline transit. Another feature is the electric immobilisation brake, allowing the wagon to be statically secured during shunting without manual operation.

Due to the cloud based control of the brake system, no local levers and cocks are required on the wagon. This does not only reduce manual labour on the wagons, but also increases the

security of the brake system against unauthorized state changes, e.g. the intentional release of the brake system by a person external to the railways. The proposed automated brake system is depicted in figure 3.

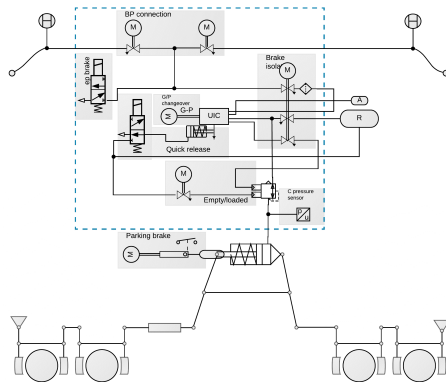


Fig. 3 Pneumatic scheme of the Wagon 4.0 brake system

On the one hand, the reduction of local control reduces the vulnerability of the brake system against misuse. On the other hand, it potentially also reduces availability, e.g. in case of absence of communication link. As a fail safe option, it is suggested to add near field communication (NFC) and smart devices or wearables to perform local, authorised control of the wagon states. Assuming that a NFC-tag is attached to the current location of the G/P-changeover cock, the wagon operator would approach the wagon with a smart device and perform the same gesture as he currently does on the lever with his smart device. NFC communication will authenticate the device and command the state change. In this way, a fail safe option offering the same security as the cloud based control can be provided.

The proposed system offers not only higher level of safety and security. In cooperation with the CBM system introduced above, it will be possible to fully automate the wagon inspection and brake assessment, currently delaying the departure of a freight train between 1 and 3 hours after consist formation.

This is achieved by three main advantages of the automated brake system:

- Higher pneumatic efficiency in controlling the local reservoirs, reducing the fill-up times of brake line and reservoirs.

- Thanks to the application of a CBM system, inspection walks on the train side will not be required in the daily schedule.
- The monitoring of the brake cylinder pressure makes an automated assessment of the brake state (apply/release) possible.

This helps to reduce train preparation times by 90% for longer trains, as is shown in table 1 for a freight train of 740 m with 250 axles.

Table 1 Comparison of operations required for train preparation

Step	Time current [min]	Time Wagon 4.0 /min
Train preparation	39.5	1.0
Fill Brake Line	40.0	10.0
Condition Assessment	33.2	1.0
Tightness	1.0	1.0
Apply brakes	1.0	1.0
Check brake apply	33.2	1.0
Release brakes	2.0	2.0
Check release	33.2	1.0
Sum	183.1	18.0

The Wagon 4.0 brake system consumes less than 5 Wh per wagon for a typical shunting cycle, including three applications of the immobilisation brake.

4 Conclusions

The idea of the Wagon 4.0 is presented in this paper. The concept of the Wagon 4.0 is unique in that it forms a holistic approach to the problem of monitoring and controlling wagons in the rail freight system.

The main elements of the Wagon 4.0 are:

- Power Supply
- Data Network
- Sensors
- Actuators
- Algorithms
- WagonOS Operating System

Thanks to this holistic approach and the provision of the elements mentioned above, the integration of application specific systems, e.g.

for condition based maintenance or an automated brake system, is more economic and also offers additional benefits due to the close integration and standardization of the subsystems.

Two application examples were presented, these are a CBM pipeline and an automated pneumatic brake system. Both show significant advantages over the use of a traditional wagon.

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