Wagon4.0 – the smart wagon for improved integration into Industry 4.0 plants

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ABSTRACT: In many instances, freight vehicles exchange load or information with plants that are or will soon be Industry4.0 plants. The Wagon4.0 concept, as developed in close cooperation with e.g. port or mine operations, offers a maximum in railway operational efficiency while providing strong business cases already in the respective plant interaction. The Wagon4.0 consists of main components, a power supply, data network, sensors, actuators and an operating system, the so called WagonOS. The Wagon OS is implemented in a granular, self-sufficient manner, to allow basic features such as WiFi-Mesh and train christening in remote areas without network connection. Furthermore, the granularity of the operating system allows to extend the familiar app concept to freight rail rolling stock, making it possible to use specialised actuators for certain applications, e.g. an electrical parking brake or an auxiliary drive. In order to facilitate migration to the Wagon4.0 for existing fleets, a migration concept featuring five levels of technical adaptation was developed. The present paper investigates the benefits of Wagon4.0-implementations for the particular challenges of heavy haul operations by focusing on train christening, ep-assisted braking, autonomous last mile and traction boost operation as well as improved maintenance schedules.

1 INTRODUCTION

1.1 *Motivation*

The development and the concept of the Wagon 4.0 (W40) is largely driven by the interest to maintain an attractive freight rail system despite adversary trends such as autonomous lorries or reduced amounts of mass goods to be transported. The main aim of the work is to improve the competitiveness of single wagon loads as this is to be considered a major driver of future logistics demands (Lammgard, 2012).

However, the idea of a smart, connected and powered wagon will also yield significant advantages in heavy haul operations, as this paper will outline.

1.2 *Industry 4.0 Concepts*

By exchanging information between cargo, wagons and equipment, it is possible to optimise the process of distributing, manufacturing and shipping goods. Key concepts known from and applied in industry 4.0 (I40) are

- Self-organisation of assets,
- Mass customisation of manufactured items and
- Updated value generation and value proposition.

While all of the above are of great interest and value to rail freight and logistics, the high initial investments for technology upgrades in numerous assets with a long lifespan inhibits an easy acceptance of the such technological advantages.

The W40 approach starts with a strong business case for all required investments, enabling an economically feasible start with subfleets that yield a return on investment from the beginning of operation of the upgraded assets.

The concepts and architectures from I40 are used in many ways to generate added value in many levels of the rail freight system, from vehicle owners to shippers. It differs from standard telemantics approaches (Berends, 2016, Galonske, 2016) mainly in the provision of actuation and continuous power.

1.3 *Wagon 4.0 Architecture*

The W40 is based on conventional freight wagons, with conventional bogies and couplings according to local standard. It generates much of its added value thanks to its local control hardware and software, supplied by wheelset generator with buffer battery as well as sensors, actuators, communication units and a shunting drive.

The W40 is self-sufficient, self-aware and recognizes other W40 in its vicinity. Thanks to a battery that is charged during mainline operation, it is also smart when stationary. Due to the operating system

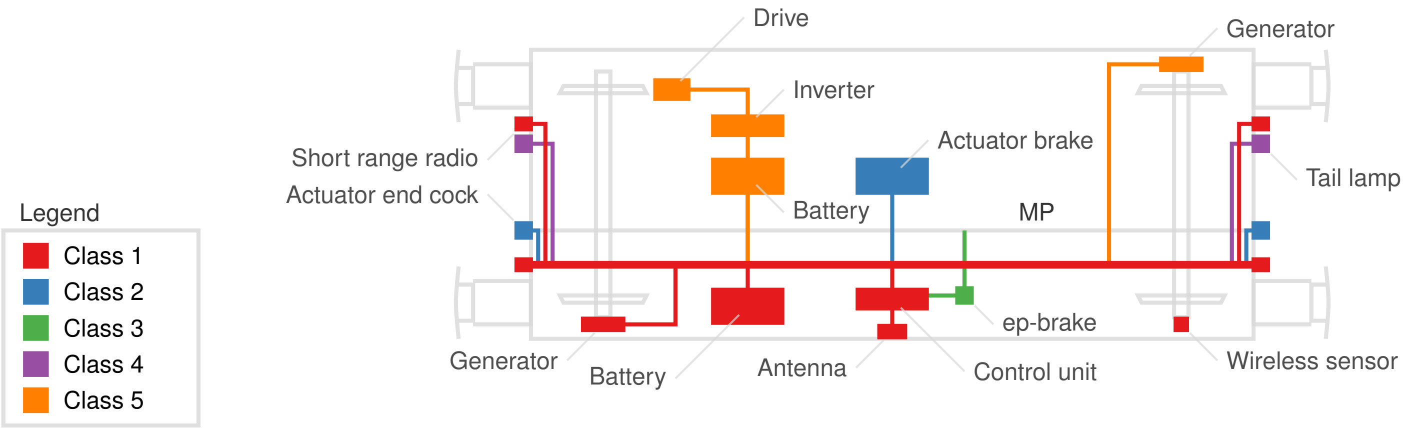

Figure 1. Wagon 4.0 architectural elements and classes

and other interfaces to the power supply, it can be optimized for various applications.

Details about the staged introduction scenario, using the idea of classes as well as more information on potential advantages in mainline operation can be found in the tripartite paper (Enning & Pfaff, 2017; Pfaff & Enning, 2017, Schmidt, Enning & Pfaff, 2018).

1.3.1 *Key Components*

The W40 is based on six key structural elements, these are:

1. Power Supply: Power plays a crucial role in 4.0-style operation as well as condition based maintenance (CBM), since freight railcars are typically unpowered assets. In order to have sufficient power for a variety of actuators as well as the autonomous shunting operation while at the same time reducing maintenance workshop requirements, a 24 V power network supplied by electricity generated by generators stored in local batteries is proposed.
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 intra-train network uses a Wi-Fi mesh protocol that is capable of real time transfer of e.g. video streams along the train, while using redundant paths make data transfer highly available.
3. Sensors: The sensors of the W40 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. For this purpose, the W40 applies mostly electrically powered actuators since the storage of electrical energy is far more advanced than storage of compressed air. The most powerful actuator of the W40 is the shunting drive, a 15 kW electrical motor to enable local autonomous shunting.
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 or bandwidth 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 time (i.e. near real-time).
6. Operating System: The so called WagonOS, an open source operating system, will unify the above mentioned five base elements to allow for extending the capabilities of the W40 and to standardize communication protocolls, 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.

1.3.2 *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 W40 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 W40 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

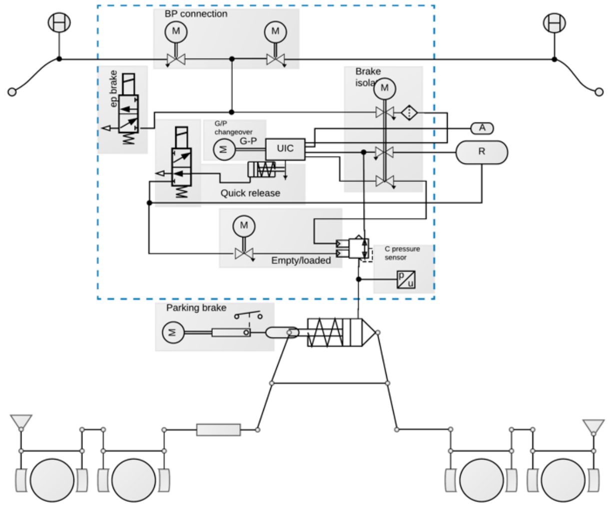

Figure 2. Wagon 4.0 brake system

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 2.

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 a 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	Current / min	W40 / min
Train preparation	39.5	1.0
Fill Brake Pipe	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 W40 brake system consumes less than 5 Wh per wagon for a typical shunting cycle, including three applications of the immobilisation brake.

2 USE CASES

2.1 *Harbour interaction*

Cooperation with cranes and other facilities in the port area makes it possible to optimise port operation. This is of high value since the infrastructure is costly and frequently the landside rail operation forms a bottleneck.

Frequently, harbour rail operation requires reversing of the freight train. In this case, the intra-train Wi-Fi mesh network can transfer real-time video and sensor data from a mobile device temporarily attached to the unmanned end of the train, enabling a single person reverse operation. Due to the train length, these mobile devices will need to include additional information, e.g. the train end position on a map of the network.

In many harbours, a train consist is broken down into small groups of wagons, with distances introduced between these groups to allow for passing of container carriers. Using the local control and shunting drive, the related uncoupling and motion can be achieved by the wagons autonomously, speeding up preparation for loading.

Using the I40 feature self-organisation, it is possible that container crane and the wagon communicate on the sequence of containers to be loaded, allowing for an automatic adjustment of the wagons' trunnions.

After loading, the train can be formed again autonomously, while communicating with the container carriers and other automated vehicles in the harbour. The train can leave almost immediately thanks to the automated brake assessment and train christening.

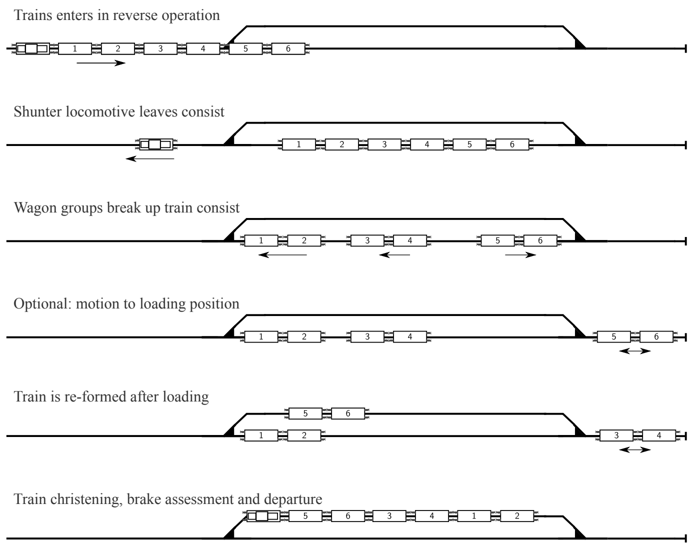

Figure 3. Harbour operation example steps

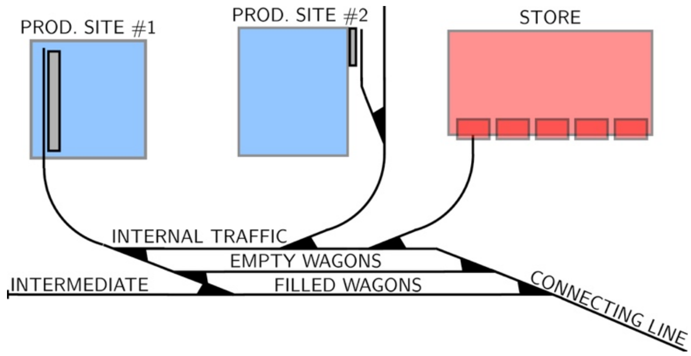

Figure 4. Example I40 plant

The sequence is shown in Figure 3.

2.2 *Industry 4.0 Plant*

As an example to an I40 plant integration, consider a local network consisting two production sites and a store, with some railway network connected to the siding as depicted in Figure 4.

The wagons can be used as an unmanned transportation system within the plant, yielding benefits over the traditional lorry logistics. The wagons can interface the smart machinery as well the smart storage in a self-organising fashion, paving the way towards logistics 4.0.

2.3 *Shunting*

The freight W40 can be helpful when shunting and, in addition to the possible shunting drive, can also assist in train composition. Information from previous journeys simplifies technical wagon handling, load changes, brake settings and brake calculations. This saves time and staff.

The automatic immobilisation brake eliminates the need for shoes or other rugs. This reduces sources of failure, but above all ensures smoother operation because they no longer have to be collected.

The power supply also makes it possible to equip the last car with a camera and other sensors. This makes it possible to drive with the train end monitored, even without shunting assistants, and at the

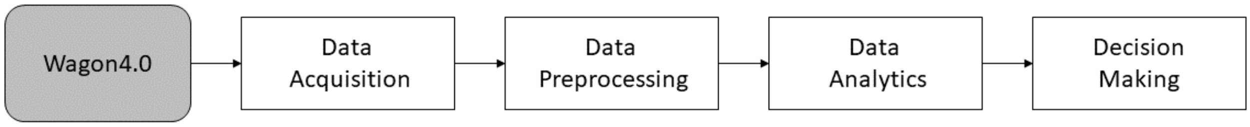

Figure 5. Wagon 4.0 Condition Based Maintenance Pipeline

same time provides a more ergonomic and pleasant workplace for the locomotive driver.

The preparation of coupling and separation points enables faster train dispatch with coupling field operations.

3 POTENTIAL BENEFITS FOR HEAVY HAUL

3.1 *Condition Monitoring and Maintenance*

In order to increase the attractiveness of rail freight transport, it is necessary to reduce the life cycle costs of rail vehicles. An instrument to achieve lower life cycle costs is the use of intelligent forms of maintenance. Figure 1 shows an example of a simplified process for intelligent forms of maintenance from a formal point of view (Atamuradov, 2017). As the following section shows, the as described above freight wagon4.0 provides the appropriate equipment to handle the aspects of the process.

The equipment of the vehicle with sensor solutions for monitoring the components is the basis for the acquisition of data. The generated data must be transformed into a form suitable for further analysis, e.g. by averaging or standardization. In predictive maintenance, data analysis usually consists of the short-term detection of anomalies or the detection of a wear trend in the operating data of the monitored component in order to predict the time of failure. Especially for the pre-processing and the analysis of the data an intelligence and computing power is necessary, which the freight W40 provides as a distributed resource.

The decision for an appropriate action completes the process of intelligent maintenance. The decision is often made on the basis of the current state of technology and expert knowledge, i.e. the human being in the process. In this case, the W4.0 does not have the task of autonomous derivation of maintenance activities, but rather to support the maintenance decision making for the present situation. From the point of view of data analysis techniques, the procedure described above corresponds to predictive analysis and pursues the question of what will happen if a detected wear trend continues. The next evolutionary form of data analytics called prescriptive analytics, attempts to answer the question of what is best that can happen. It quickly becomes clear that the integration of this form of analytics into operators' maintenance strategies means an even greater complexity, since not only one action but many possible actions are considered and the best maintenance alternative must be selected from these possibilities within the framework of a highly complex optimization problem (Franzen, 2018). Nevertheless, the distributed intelligence of the freight wagon4.0 as well as the data continuity related to the overall system of systems and not to the individual vehicle itself, form a basis for the research of prescriptive maintenance approaches.

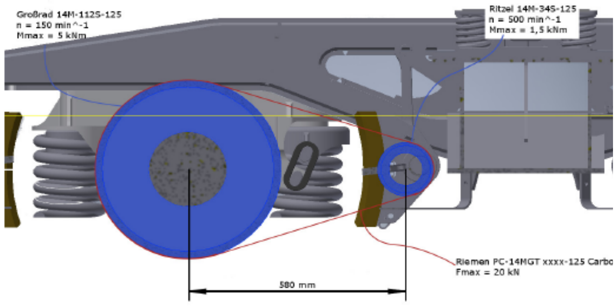

Figure 6. Mechanical integration in Y 25 bogie

3.2 *Remote Train Christening and Brake Calculation*

Each W40 carries information about itself as well as about its freight and neighbouring wagons, the task of train christening, i.e. generation of an ordered list of the vehicles, can be easily solved. The process is initiated by an arbitrary wagon in the train, which is the master throughout the process. Next it uses the short-range radio to detect the next wagons to either side of the master and then the Wi-Fi mesh and an IP V6 encrypted connection to obtain the data of the vehicles.

3.3 *Autonomous Last Mile Operation*

Operations in the loading area and in sidings are strongly linked but currently often operated by different people. The railroad company moves the wagons and the loading agents operate the cranes, loading machines, wagon sliding walls and wagon doors. Often this means that waiting times of either team are unavoidable.

Existing solutions on the shippers' side have been horses in the past, which now have been substituted by tractors (e. g. 2-way-unimogs). Obviously, this equipment (although cheaper than a shunting locomotive) generates significant costs and needs skilled users. Clearly, this will not be cost efficient if such a machine is only used 30 minutes per day. This means, regarding the current competitive environment with road shipment, new solutions will be needed to equip an intelligent freight wagon with limited means to move itself.

This implies an operational setup, in which the railroad company moves the wagons to a handover track in the siding like a postbox and the shippers' loading staff move these wagons by using their own traction module. The user interface may range from a device similar to a crane remote control in order to make training easier to elaborate solutions encompassing wearable devices or drones for guidance.

Due to the regulatory as well as training requirements, power and speed are limited on a level similar to forklifts or excavators on private property. By this setup loading operations may get optimized e.g. as longitudinal movements can be done by using the wagon itself and the loading cranes only need to be used for transversal movements. Furthermore, operation by the same staff minimizes risk of accidents and speeds up operations.

Within budgetary constraints, a lean technical concept is required. When moving a wagon on the public railway network, the traction module must be inactivated and must not have any influences. This allows these wagons to be operated and meet the safety requirements of traditional wagons. Taking into account typical setups of private sidings in Europe, tractive forces of approximately 21 kN and a traction power of approximately 15 kW is needed to allow operation in standard cases. The energy needed will be approximately 1 kWh which allows an inexpensive electrical setup using a 10 kW induction machine and a standard inverter-battery pack setup used in regenerative energy applications. Control will be part of the W40 on-board computer system and will be integrated into the WagonOS. The mechanical dimensions are adapted to the standard Y25 bogie and require only minor modifications of the braking system which are already available of the shelf. The torque will be transmitted either by teeth belts or friction wheels.

3.4 *Traction Boost Operation*

Depending on the velocity range of operation and the local legislation, the shunting drive may remain activated in certain velocity ranges during mainline operation. Using a cooperative control, i.e. the wagons apply tractive power if their neighbouring wagons apply it, the train may be able to help the locomotives in certain situations, e.g. when starting or on steep uphill grades.

This reduces longitudinal forces in the train consist and makes higher commercial speeds possible.

3.5 *ep-Assisted Braking*

In a similar cooperative fashion, the wagons may be enabled to vent the brake pipe locally. Since this implements an indirect acting ep-brake, the safety requirements are comparably low, since single wagons not venting the brake pipe do not influence the brake propagation significantly.

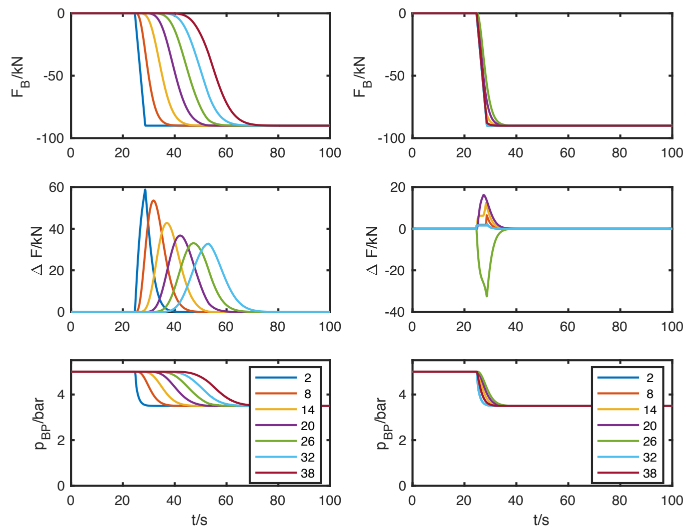

Figure 7. Comparison of standard brake pipe operation (left) to cooperative ep-Assist (right)

As an example for the increased performance of such a system, the brake propagation and development in a 40-car-trainset is compared for a full service brake commanded only from the locomotive to an application in which one out of five wagons vents the brake pipe locally in addition to the locomotive. It is obvious from Figure 7 that the cooperative ep-assist reduces longitudinal buff forces by more than a factor of three while not relying on additional wagon connectors.

4 CONCLUSIONS

While the W40 concept was developed in order to revive the so-called single wagon load market in rail freight, it offers advantages also for shippers, railway undertakings and infrastructure owners of heavy haul operations. Among these are the improved potential of condition based maintenance, the expandability of an open source operating system and performance improvements due autonomous and cooperative functions.

While in open freight rail systems the allocation of the return on invest between shipper, vehicle owner, vehicle operator and infrastructure manager are difficult, the frequently closed structure of heavy haul operations may provide more incentive to invest into connected and smart rolling stock.

5 ACKNOWLEDGMENTS

The authors from Aachen University of applied Sciences gratefully acknowledge support from German Ministry of Education and Science, under the grant title "Güterwagen4.0".

The first author thanks Dr. Parham Shahidi for a fruitful cooperation on the condition based maintenance aspect of W40.

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