Chapter

Automation of the Freight Wagon Subsystem

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Abstract

The wagon as part of the rail freight system is lagging behind other vehicle classes in terms of automation and monitoring. This stems partly not only from a fierce competition with regard to the vehicle cost but also from a long vehicle lifecycle and long innovation cycles. The drawback of the low amount of automation and monitoring of the vehicle is the additional manual labour required for operation and inspection, as well as the many use cases that cannot be served in an optimal fashion. The Wagon 4.0 concept sets out to mitigate these drawbacks by implementing monitoring and automation technologies into the wagon subsystem in an economically feasible manner. Minor extensions to the rail freight systems already lead to major reductions in labour intensity and use cases that can be served in a novel fashion. This chapter introduces the Wagon 4.0 concept and illustrates the benefits based on use cases.

Keywords: rail freight, automation, industry 4.0. smart vehicle, brake tests, smart logistics

1. Introduction

For decades, freight rail has been vital to growth in countries around the world. This development took place despite the fact that freight takes significant manual labour for handling and checking the wagon subsystem. The manual labour is spent mostly during train formation as well as on the first and last mile.

While in the original applications of rail freight, mostly the efficient transport of mass goods such as coal and ore, these inefficiencies were outweighed by the energy efficiency of rail freight, such goods are set to decrease due to decarbonisation and the circular economy. Instead, shipments are getting increasingly individualized and require more timely and efficient handling. **Figure 1** shows the development of lifted goods in the UK, with the decline in fossil fuels and raw materials clearly visible.

The wagon subsystem differs from most vehicle types in the railway system in that it is in many cases optimised to provide low investments, with wagon prices ranging from 50.000 € to 140.000 € [2]. For this reason, little to no advanced technology is supplied with the wagon, such as monitoring or actuation. Telematics systems are considered feasible and economic, despite providing only limited assistance in the handling of the rail freight system [3].

While low investment in the wagon subsystem leads to very economic freight rail operation for the original mass goods, it leads to higher costs when handling high-value, comparatively light goods to individual sites.

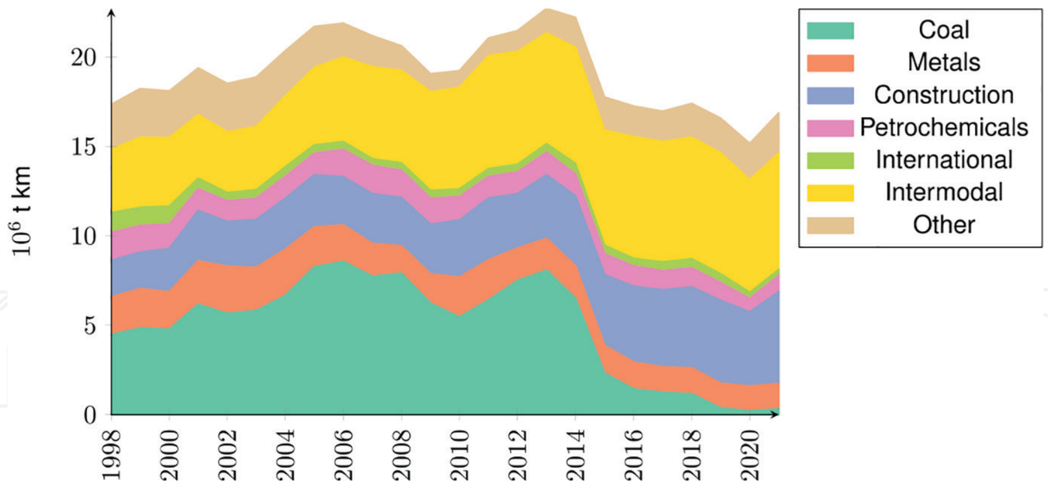


Figure 1.
Freight moved in the UK (financial year) [1].

The costs occur mainly due to

- Manual preparation of the wagons for the current train setup, including coupling and brake settings;
- Manual inspections before train departure, most notably routine inspections and brake tests;
- Unplanned maintenance due to lack of condition monitoring.

Further, this leads to a high requirement of track capacity for serving sidings, mostly due to the fact that the little advanced wagon subsystem cannot be operated safely together with passenger services within their schedule due to these time-consuming activities.

The Wagon 4.0 concept [4, 5] was conceived aiming to provide solutions to these challenges while at the same time yielding a sufficiently high return to justify the inevitable cost increase. This is mainly achieved by adding automation and assistance systems to replace manual activities.

2. Current handling of freight wagons and trains

2.1 Introduction

Wagon handling is required multiple times per journey due to the multi-stage nature of the railway network (**Figure 2**), in particular for single wagon loads. These need to be collected from the shipment points and regrouped to form trains, potentially multiple times, in order to maximise capacity utilization.

A loss in single wagon load cargo moved, as observed in most economies in the past decades, leads to a reduced point-to-point connection between regional distributions and thus further reduces the advantages of the rail freight system due to longer train running times. For this reason, it is vital to increase the overall portion of rail freight in order to keep it vital.

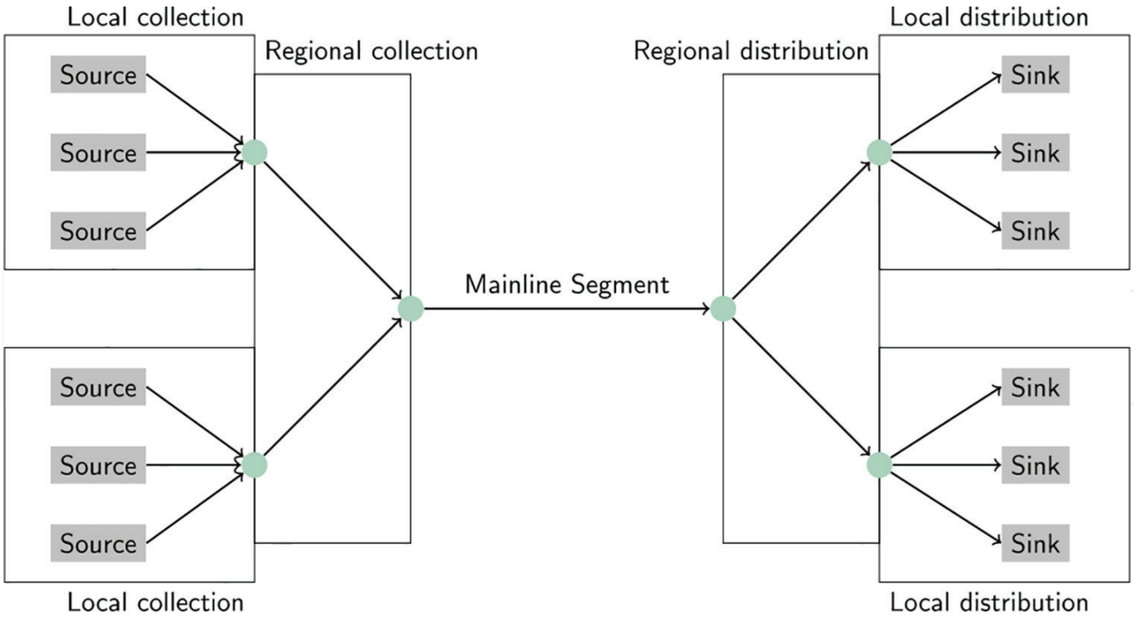


Figure 2.
Multi-stage rail network example.

The local regulations in place typically require a full train inspection at each of the collection or distribution site, which includes a brake test and a routine inspection besides the manual effort of coupling and preparation.

The current routines and practices for train preparation and inspection stem partly from the quasi-universal usage of the pneumatic air brake system, for example, as laid out in Ref. [6]. This system relies on the de-energise-to-activate principle, requiring a distributed system with local energy storage as well as a continuous brake pipe. It is depicted in **Figure 3**.

The distributed nature of the system, together with the lack of sensors and communication equipment, requires manual preparation action as well as pre-departure checks in order to ensure safe operation.

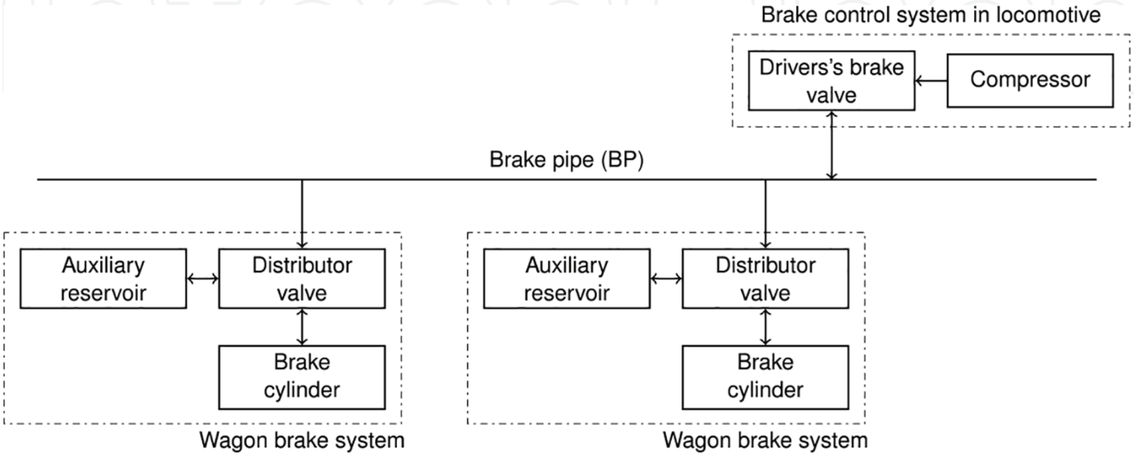


Figure 3.
Pneumatic brake system.

2.2 Preparation

During preparation, the train needs to be automatically or manually coupled, and the brake mode is set manually. This requires knowledge of the train currently handled as well as of the particular wagon since the brake mode is selected according to train mass and length, while for many wagons, the empty-loaded selection is also handled manually.

These steps are executed manually, which requires an operator (typically especially skilled yard personnel or the train driver) to walk along the train. This wasteful motion of the operator consumes time, depending on the length of the train and the number of required actions to be taken.

Further preparation steps include filling of the brake pipe and the associated reservoirs, which may be time-consuming depending on the train's state.

2.3 Inspections

The preparation of the overall consist is followed by inspections of the individual wagons within the consist. The most notable step is the brake test, which aims to avoid critical malfunctions in the brake system.

Hazards of a malfunctioning brake system include:

- Non-continuity of BP: In this case, the portion of the train after the non-continuity (in running order) does not apply the brakes as requested, leading to reduced retardation and potentially the inability to maintain a safe velocity on a downhill gradient.

- Failure to apply brakes upon request: An individual wagon or coach does not apply the brakes when requested by the leading vehicle, resulting in a minor increase in the braking distance of the train consist depending on the total number of wagons.

- Untimely application of the brakes: An individual wagon or coach applies the brake without being requested. Such behaviour may lead to wheel flats or even catastrophic failures such as derailments due to an overheated wheel tread.

- Reduced braking effort due to low pressure in the BP: The reduced BP pressure, often resulting from leakages, leads to reduced pneumatic energy stored in the local auxiliary reservoirs and consequently reduced brake cylinder pressures.

In freight trains, the application to and release from the wheel of the individual brake blocks is required to be checked by visual inspection, requiring additional walking times for the pre-departure checks.

The procedure following German regulations as laid out in Ref. [7] (similar regulations are in place, e.g., in the US [8]) consists of the following steps:

1. Visual inspection of all brakes in train consist, including setting of brake mode and empty-loaded selection.

2. Filling of BP to release pressure.

3. Check the released state by inspection of all wagons for release of brake blocks from wheel tread or released state of visual indicators.

4. Tightness check of BP with the help of a pressure drop of less than 50 kPa per minute.

5. Brake application by a pressure drop of approximately 80 kPa in BP.

6. Inspection of all wagons for application of brake blocks to wheel tread or applied state of visual indicators.

7. Release brakes by filling of BP to release pressure.

8. Check the released state of all wagons by block position or visual indicator.

9. Continuity check of BP by opening of end cock on the last wagon.

10. Check the removal of scotches.

11. Report brake test.

The first step was described under preparation. Stages of the brake test set in bold font require a full walk of the train length; in the case of a single operator executing the test, a double walk of the train length is required due to the necessity to return to the leading vehicle. For the maximum European train length of $l = 750\,\text{m}.$ including locomotives, this results in $d = 2 \cdot 4 \cdot l = 6000\,\text{m}$. At a realistic walking velocity in the track area of $v_{\text{walking}} = 1\,\text{m/s}$, this relates to a time consumed just for walking of $t_{\text{walking}} = 100\,\text{min}$

Following German regulations, a brake test has to be executed on each newly assembled train, after adding wagons or changing the direction of the train, and is repeated at least every 24 hours. In certain cases, for example, during a direction change, a so-called simplified brake test is acceptable, which does not check each wagon individually but rather focuses on the continuity of the BP and the braking of the last wagon.

In addition to the brake test, the wagon subsystem is visually inspected for its technical state, for example, the state of the suspension system, as well as for the integrity of the wagon and its load. Since the operator passes by each wagon, this is currently included in the inspection.

2.4 Siding operation

The operation in sidings, as part of the more general shunting operation, is typically executed in order to serve the individual loading points. Wagons arrive in a closed consist to the siding, typically in shunting mode from the last station passed on the way. Shunting operation is executed on-sight, and thus the velocity on the mainline is limited, in the German case, to a maximum of 40 km/h with further restrictions based on infrastructure or a particular operation.

The mainline track between the last station and the siding switch remains blocked during the whole time that the shunter operates on this section of track, as it can only be safely considered free once the shunter returns to the station (**Figure 4**).

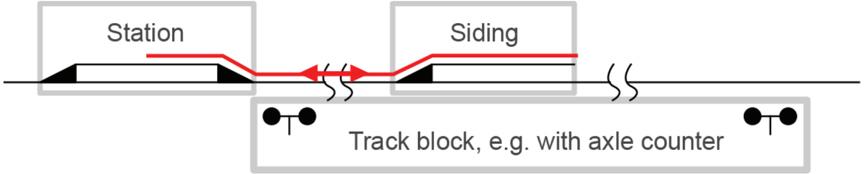


Figure 4.
Line segment with siding and train motions required to serve it.

This mode of operation uses a lot of capacity as the line is blocked for two trains, with a typically long stop and pushing operation into the siding, both operated at low velocities.

In the siding, the consist frequently needs to be split up into wagon groups or single wagons, which are then transported with the help of a shunting locomotive to the loading point for processing. After processing at the loading point, the wagons need to return to a collection point to be picked up in the same fashion as they were brought to the siding.

Different designs of sidings exist, listed either as passing siding or station siding, which yield improvements over the basic design. In the former, the line is only blocked for service to and from the siding point; in the latter, a full train movement is possible up to the siding. Both, however, come with significant investments in command, control and signalling infrastructure. This makes such designs only viable for sidings handling large quantities of wagons.

3. Wagon 4.0 concept

The development and the concept of Wagon 4.0 (W40) are largely driven by the interest to maintain an attractive freight rail system despite adverse 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 [9].

The W40 is based on conventional freight wagons, with conventional bogies and couplings according to local standards. It generates much of its added value, thanks to its local control hardware and software, supplied by a wheelset generator with a 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 and without a locomotive. Due to the operating system and other interfaces to the power supply, it can be optimised 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 [10–12].

The W40 is based on five key structural elements, which are as follows:

1. Power supply: Electrical power plays a vital role in automation as well as in condition monitoring. Freight wagons are typically unpowered assets. In order to have sufficient power for a variety of actuators, a 24 V power network supplied by electricity produced by local generators and stored in local batteries is implemented for W40 with a standardised architecture defined in Ref. [13].

2. Data network: The data network uses standard technologies to establish a connection with wagons as well as within the train consist.

3. Sensors: The sensors of the W40 will mainly consist of position and pressure sensors, aiming to reduce manual inspection and use the sensor feedback to increase safety and efficiency. Also, monitoring of vital components of the wagon is provided in order to replace inspections and enable predictive and condition-based maintenance.

4. Actuators: While sensors and networks provide useful data, the actuators enable operators to operate certain aspects of the wagon subsystem remotely, for example, the brake mode setting.

5. Operating system: The so-called WagonOS, an open-source operating system, unifies the above-mentioned base elements to allow for extending the capabilities of the W40 and to standardise communication protocols, data formats and related standards. A central operating system will furthermore enable currently disjointed efforts to unite under the umbrella of a single industry standard.

The W40 concept follows a class structure aiming to modularise the system, ease introduction into fleets and allow the selection of the most appropriate and economical class for a certain wagon or fleet. **Figure 5** shows a schematic of a W40, indicating the class of the respective functionality.

The classification starts with a W40 of class 1, allowing communication with and over this wagon. A class 2-W40 adds an interface to the brake system, including measurements of brake cylinder and brake pipe pressures as well as the remote activation of brake mode or empty-loaded selection. A further sensible addition to the system is the so-called ep-light brake, an indirect electro-pneumatic brake. This is the only additional functionality of class 3 over the other classes. A class 4 wagon aims to fully automate the wagon subsystem with an additional end-of-train signal, whereas a class 5 wagon adds a drive system to enable automated movements in the siding.

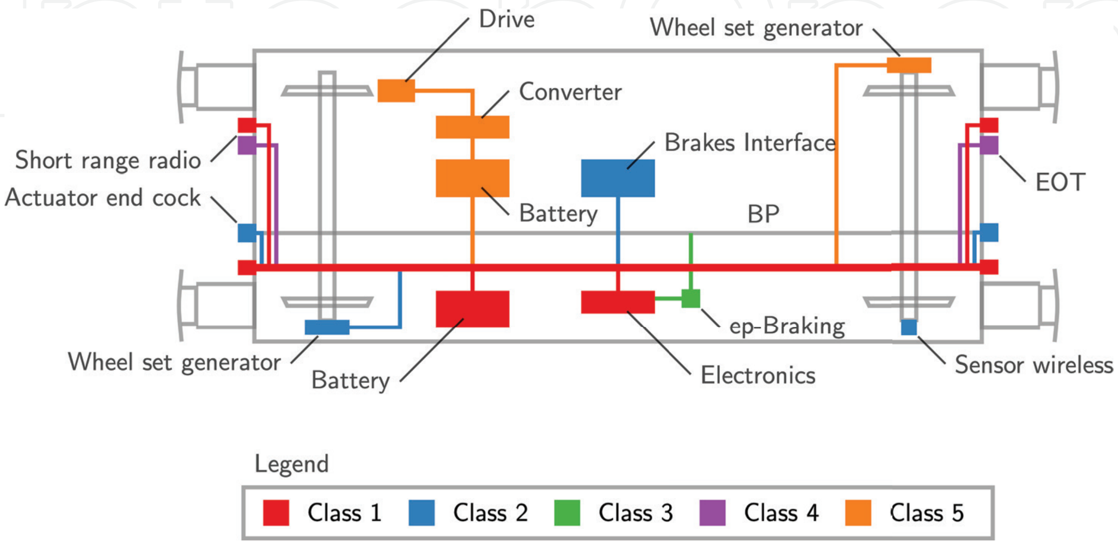


Figure 5.
Wagon 4.0 structure and functional classes.

4. Wagon 4.0 contributions

4.1 Train formation and setup

Assisted brake tests as well as automation in train data handling rely on information on train set-up, especially the order and orientation of wagons is important. Although human operators intuitively capture the order and completeness of the wagon group and convey information, a technical system needs to gather and transfer information explicitly.

In automatic brake test systems currently implemented, the completeness of the wagon group is assured by comparison of the rake to a wagon list transmitted beforehand [14]. This information regarding wagons in the rake and their order may be potentially supplemented by GNSS localisation. The intra-train communication relies on point-to-point radio or mobile communication.

The authors expect that both point-to-point and mobile communication may lead to problems limiting the availability of the systems, for example, in areas with poor cell coverage. Further, the usage of wagon lists for train topology generation may yield disadvantages over the detection of the actual state of the rake, since such lists may contain errors and need to be generated first.

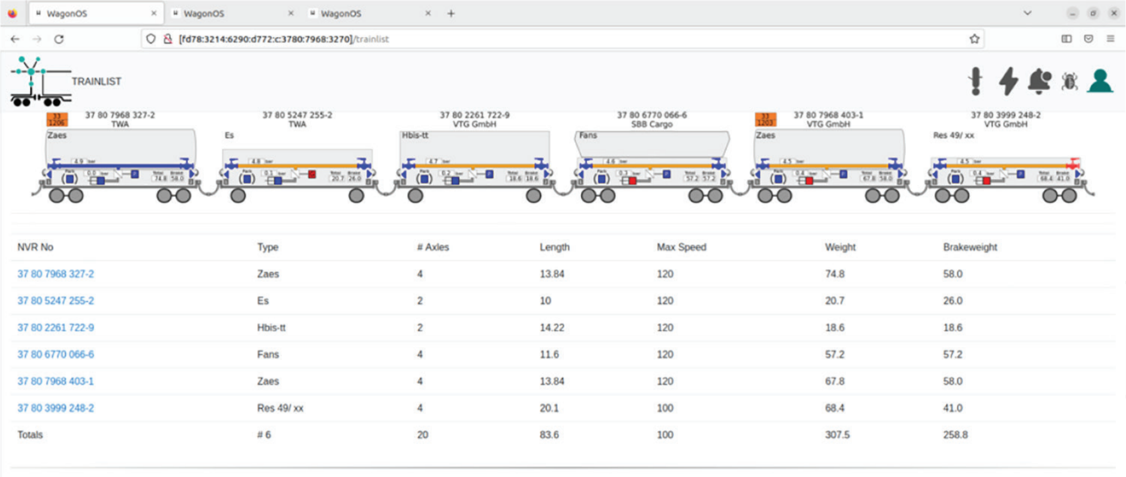
For this reason, the W40 follows a different approach. Each wagon is equipped with controllers at both ends of the wagon. A local area network connects both controllers as well as sensors and actuators installed in the wagons. Adjacent wagon ends are connected by a V2V communication system. This creates a linear network closely replicating the rake structure. Each wagon is able to identify its neighbouring wagons and may share this information on the network. This makes it possible to maintain a digital representation of the wagons in the rake as well as their state on each wagon.

This yields the advantage that communication throughout the train can be implemented comparatively easily and reliably. The physical layer of the wagon-to-wagon interface can be formed by the recently proposed digital automatic coupler [15] or with the help of short-range radio communication. It is reasonable to assume that such a radio connection is at least as reliable as a galvanic connection since a line-of-sight connection is always available. The radio connection between wagon ends is realised with the help of a WifiDirect (trademark of Wifi Alliance) connection. Additionally, a Bluetooth Low Energy connection may be used to measure distances in order to safely connect to the next wagon [16].

Since the W40 concept implements remote-controlled end cocks and BP pressure sensors, as indicated in **Figure 5**, this distance measurement is not strictly necessary since adding wagons to the train consists that are not pneumatically coupled will not lead to a successful brake test, and thus any wrong connections will be contained and will not endanger the mainline operation.

Operating personnel connect to the wagon with the help of Wifi formed *ad hoc* using a smart device such as a tablet. **Figure 6** shows the corresponding user interface.

In the target market of freight wagons, it is reasonable to expect non-equipped wagons. The W40 concept is not intended to pass by any non-equipped wagons. Instead, the basic equipment of the wagon to allow communication and detection of neighbouring wagons (termed W40 class 1) comprises only low-cost, low-maintenance components. The class 1 equipment enables the wagon to identify its neighbouring wagons and to participate in the V2V communication. This equipment uses semiconductors from the consumer range and can be operated for years on battery power; thus no wheel set generator is required.



NVR No	Type	# Axles	Length	Max Speed	Weight	Brakeweight
37 80 7968 327-2	Zaes	4	13.84	120	74.8	58.0
37 80 5247 255-2	Es	2	10	120	20.7	26.0
37 80 2261 722-9	Hbis-tt	2	14.22	120	18.6	18.6
37 80 6770 066-6	Fans	4	11.6	120	57.2	57.2
37 80 7968 403-1	Zaes	4	13.84	120	67.8	58.0
37 80 3999 248-2	Res 49/ xx	4	20.1	100	68.4	41.0
Totals	# 6	20	83.6	100	307.5	258.8

Figure 6.
Web interface of a device connected with WagonOS showing the train list.

4.2 Brake test

An analysis of accidents [17] highlights discontinuities in the brake pipe (BP), untimely brake applications and the inappropriate use of hand brakes and scotches as causes for catastrophic outcomes. Irregularities or damages to the brake rigging or brake calipers reduce the brake effort only for single bogies or wagons, with no significant effect on the train.

The observed failures and errors causing the accidents are

- discontinuity or limited continuity of the BP,
- leakage of the BP,
- failure of the distributor valve (static and dynamic) and
- untimely application of the service or parking brake.

In the investigated cases, all of the above went undetected using the existing brake test procedures conducted prior to the accidents. Most of these are difficult to detect using only visual inspection and the common static brake test procedure. Further, in some cases, the failure developed during the train mission, such as in the Llangennech rail disaster [18].

The W40 approach introduces a novel definition of system borders for brake tests based on the brake-related accidents analysed in Ref. [18]. Based on this analysis, a different split of test steps between brake tests and inspections is proposed.

The effectiveness of visual checks for brake application and release or cylinder stroke needs to be questioned. Such visual checks are costly and do not sufficiently mitigate errors such as discontinuities in the BP.

On the other hand, irregularities in and damages to the brake rigging appear at a very low frequency in accident reports. In contrast to the failures in handling and operation of brake systems reported above, these typically result in the unavailability of brake functionality on single wheelsets, bogies, or wagons. Such singular failures are not likely to endanger the safety of the train as a whole. From a perspective of the overall safety of the railway system, an automated test based on brake cylinder pressures rather than visual checks of brake block travel may be an appropriate alternative.

The required sensors are robust and cost-efficient pressure sensors for brake cylinder and BP pressure, whereas for the detection of an untimely application of the brake, a position sensor on the brake cylinder is required.

A pneumatic scheme with added pressure sensors is depicted in **Figure 7**.

This set-up is able to detect the following states:

1. Brake released (by position sensor attached to the brake cylinder),

2. Brake cylinder pressurised (by cylinder pressure sensor) and

3. Brake command state (by BP pressure sensor).

Thanks to continuous measurements of brake pipe and brake cylinder pressures, it is also possible to observe both the propagation of the brake command in the BP and the filling and release time of the brake cylinder. This enables the development of further diagnostic systems, for example, to detect deterioration of the distributor valve or an incorrect brake mode. The propagation also serves as a second channel beside WIFI for the verification of the consist order.

The information on the ongoing brake test is displayed on the user interface screen, effectively assisting the operator in the brake test by providing information formerly obtained by walking to the brake system in question. The user interface is shown in **Figure 8**.

Further, the sensor equipment can continue to observe these values during mainline operation, which improves safety over the singular observation in classical brake tests. The continuous observation is capable of detecting untimely service brake applications as well as inappropriately applied hand brakes.

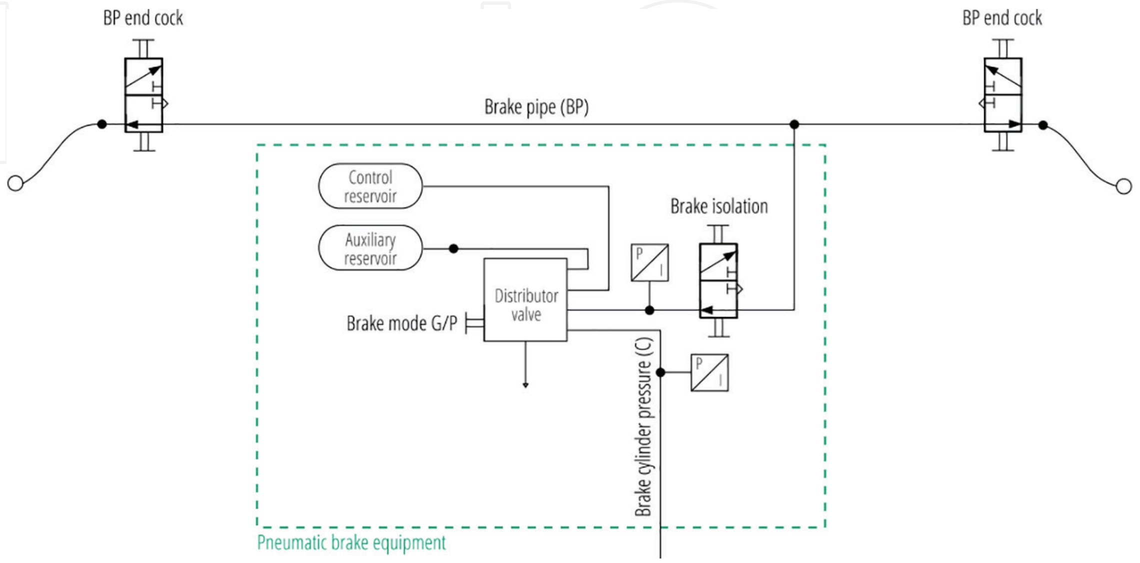
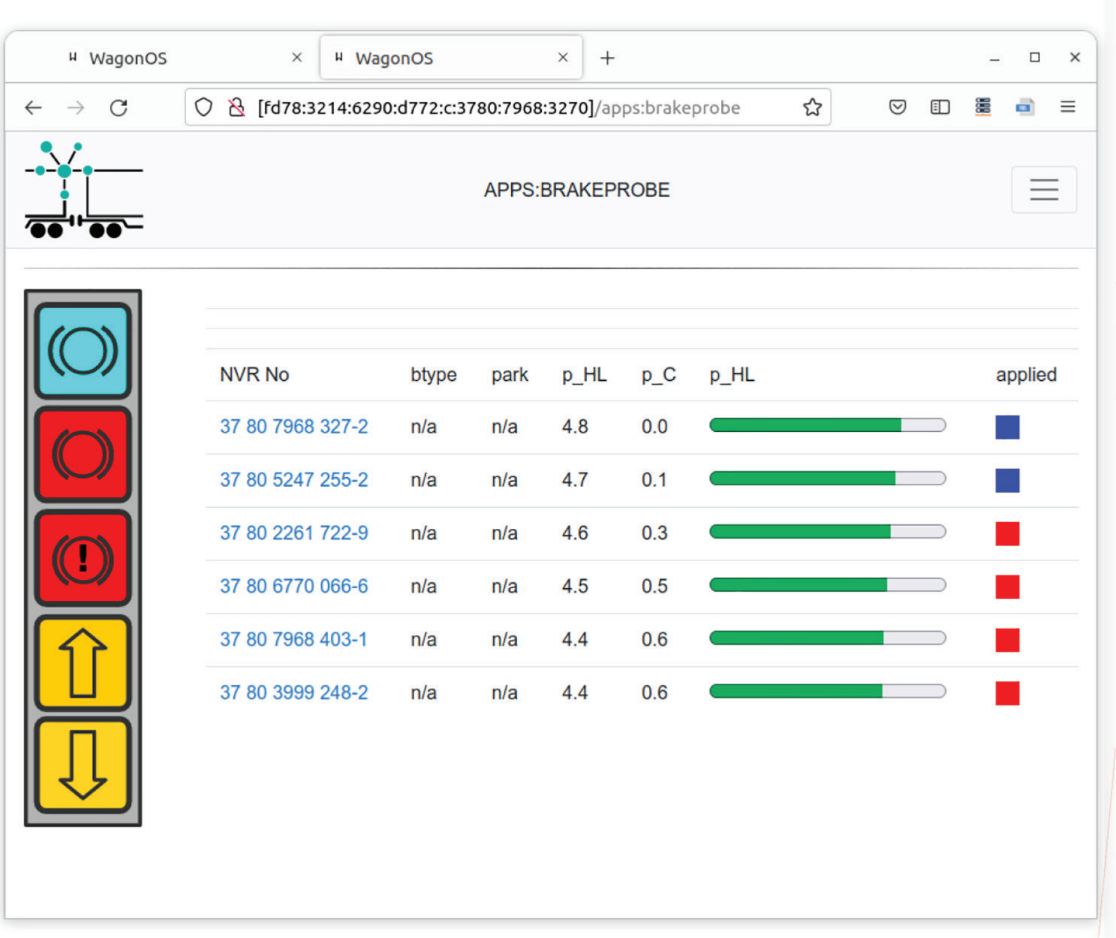


Figure 7.
Pneumatic scheme of a wagon brake system with sensors for BP and brake cylinder pressure, from [13] (CC-BY 4.0).



NVR No	btype	park	p_HL	p_C	p_HL	applied
37 80 7968 327-2	n/a	n/a	4.8	0.0		🟦
37 80 5247 255-2	n/a	n/a	4.7	0.1		🟦
37 80 2261 722-9	n/a	n/a	4.6	0.3		🟥
37 80 6770 066-6	n/a	n/a	4.5	0.5		🟥
37 80 7968 403-1	n/a	n/a	4.4	0.6		🟥
37 80 3999 248-2	n/a	n/a	4.4	0.6		🟥

Figure 8.
User interface displayed during the assisted brake test.

4.3 Technical inspection

Under German as well as most other regulations, it is common to execute a visual inspection together with the brake test. When automating the wagon subsystem and assisting in brake tests, it is important for economic viability to automate or reduce these inspection steps as well.

The approach of W40 is not able to detect

- immobility of brake cylinders when pressure is applied,
- uneven distribution of braking force,
- the full release of brake blocks after venting of brake cylinder and,
- wear on the slack adjuster.

Such failure modes typically evolve slowly since they are related to the wear of the equipment. These failure modes, as well as other slowly developing deteriorations, such as the inappropriate state of the brake blocks, should be addressed by additional technical inspection as opposed to a brake test. In this way, ensuring the brake functionality for the next mission is separated from determining the technical condition of the wagons. Wagon condition monitoring may be automated without large investments into the individual wagons by providing a wayside train monitoring system (WTMS).

In the current state of development, WTMS uses visible light imaging to estimate brake block thickness, and this may easily be extended to detect further visible failures, enabling WTMS to replace most visual checks by human operators [19]. The remaining inspection items such as the closing of hatches, which need to be checked prior to departure, can be automated using cheap and reliable sensors on the rolling stock. The overall system combining an extended network of wayside monitoring with sensible and economical equipment on the wagons is capable of yielding improved safety of the freight rail system at a reduced cost.

5. Use cases

5.1 Letterbox style operation (handover tracks)

Rail freight operations in an open access multi-stage wagon load network (shown in **Figure 2**) generate, as for all similar networks (e.g., road traffic and electric grids), the highest specific costs in the last collection and distribution stages. The reason is that the costs of a valuable locomotive and corresponding staff can only be allocated to one or two wagons on the last metres of the journey. These last metres consume many loco/staff hours but produce almost no traffic volume given in tons or kilometres. The problem is well known for more than a century. So historically, railway companies avoided using expensive mainline steam locos for this kind of operation. A typical solution is a group of handover/holding tracks. The first of these tracks holds the wagons delivered by the mainline loco. A second track contains the wagons, which need to be picked up. Further (empty) tracks may be needed for locomotive movements (**Figure 9**).

The customer can then move the wagons based on his internal timing needs to the loading docks using horses (historic solution) or nowadays road-rail vehicles. But we must note the disadvantages: the railway operator streamlines his operations, but the customer now needs an expensive device.

The W40 class 5 features a shunting drive system, which can overcome these disadvantages. Without needing an additional rail-road vehicle, the customer may now move the wagons himself on his premises by using the shunting drive. The user interface as well as the training of the staff will be aligned with current practice used for forklifts, which makes it also a viable solution for customers who only receive a single-digit number of wagons a week.

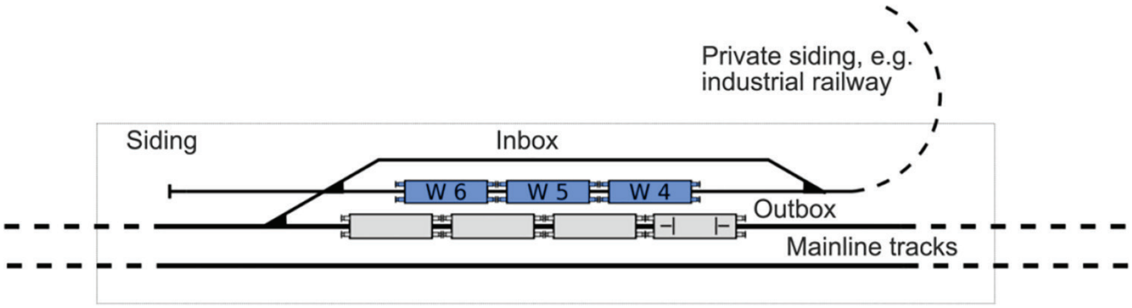


Figure 9.
Letterbox—handover tracks.

5.2 Port interaction

Cooperation with cranes and other facilities in the port area provides plenty of potential for operational optimisation. Since the infrastructure is costly and frequently the landside rail operation forms a bottleneck, this optimisation can vastly improve the overall performance of the port.

In many cases, port rail operation comprises reversing of the freight train, for example, onto a dock track. 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. This enables a single person to safely perform reversing operations.

In many ports, a train consist is broken down into small groups of wagons, with distances introduced between these groups to allow for the 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 industry 4.0-style self-organisation, container cranes and wagons can communicate on the sequence of containers to be loaded and adjust the trunnions according to the wagons' trunnions.

After loading, the train can be formed again quickly using the assisted brake test, while communicating with the container carriers and other automated vehicles in the harbour. The train can leave almost immediately, thanks to the assisted brake test and train formation. The cycle of operations is illustrated in **Figure 10**.

5.3 Intra-site logistics

Similar to port operations, there may also be other loading sites that require intensive cooperation with the customer and the moving of wagons during loading operations. Typically, this may be the filling and unloading of tank wagons, where the loading site has a limited length and offers only unloading single or small groups of wagons simultaneously, or hopper wagons that need to be filled or emptied at a loading site. If these sites are highly frequented, they are often equipped with electric tractors or steel cables/winches to move wagons during (un-)loading operations. But for smaller sites, this kind of infrastructure is too expensive. So, for small customers, the railway operator keeps his locomotive and staff busy supporting the loading operations, which is not very cost-efficient. The same applies for loading sites inside a plant, for example, a household appliances factory doing metal forming. Normally, these factories receive single wagons with coils of steel sheets, which must be positioned under a crane for unloading. Currently, at such sites, the only option is to ask the railway operator to move the wagons or have their own shunting tractor. This is especially costly for small factories that do not receive high volumes of wagons. The Wagon 4.0 class 5 overcomes these challenges as it features a shunting drive system. Without needing additional assets, the customer may now move the wagons himself on his premises by using the shunting drive.

5.4 Power boost by distributed power

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 cooperative control, that is, the wagons apply tractive power if their neighbouring wagons apply it, the train may be able to help the locomotives in certain situations, for example, when starting or on steep uphill grades.

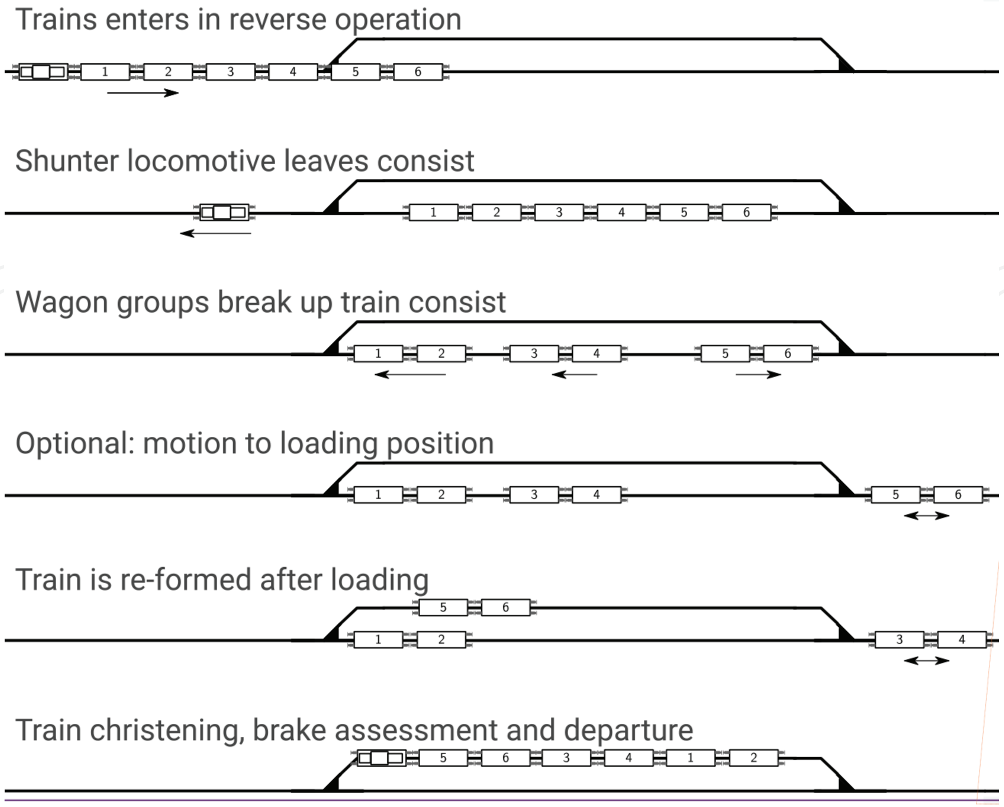


Figure 10.
Port operation stages.

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

Figure 11 shows a simulation of a train set up with 30 container cars type Sgjs, each of them loaded with three 20'-containers. The total train mass is in the range of 1100 t. As a loco, a DB class 145 (mass 82 t) is assumed, delivering 250 kN of tractive effort and a power of 4.2 MW.

W40 class 5 is equipped with a traction system. In this way, the wagons may operate like multiple-unit vehicles and support the locomotive during acceleration.

When using the tractive capabilities of the W40 for a short term during the acceleration of the train, the tractive effort of the whole composition will be 880 kN, signifying an increase by a factor of 3.5.

The short-term power of the system will only increase slightly by 10%. That means, as shown in **Figure 11**, that use of the tractive capabilities of the W40 makes only sense for speeds below 20 km/h.

This velocity range, however, is the range that is important for freight traffic. Normally, turnouts in freight yards are designed for branch speeds of 40 km/h due to cost reasons. Consequently, the most important task is accelerating up to 40 km/h as fast as possible to reduce the occupation and locking times of train path elements in the interlocking system. As an initial estimate, the acceleration will take approximately 1 minute less with W40 traction applied.

On heavily used mainlines, headways are normally in the order of four minutes, so saving one minute during the acceleration of a freight train may significantly increase capacity in congested nodes.

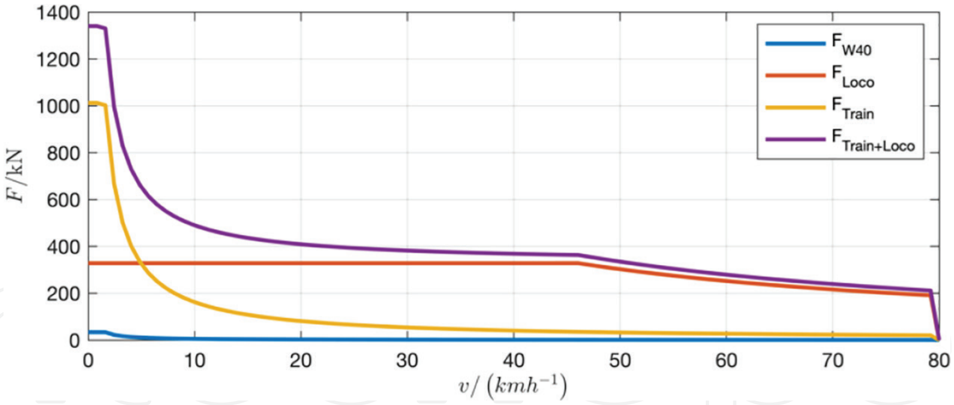


Figure 11.
Traction curves of individual W40 (F_{W40}), a locomotive (F_{Loco}), a train of 30 W40 (F_{Train}) as well as the total tractive effort of the train setup.

5.5 ep-light brake

Thanks to the continuous power supply of the W40 and the intra-train network capability, it is possible to extend the brake system of the wagon by a valve to command an indirect electro-pneumatic brake application locally.

This is achieved by locally venting the brake pipe to the atmosphere. The benefit of locally commanded brake application (ep-apply) is a faster propagation of the brake request through the brake pipe, which leads to three effects:

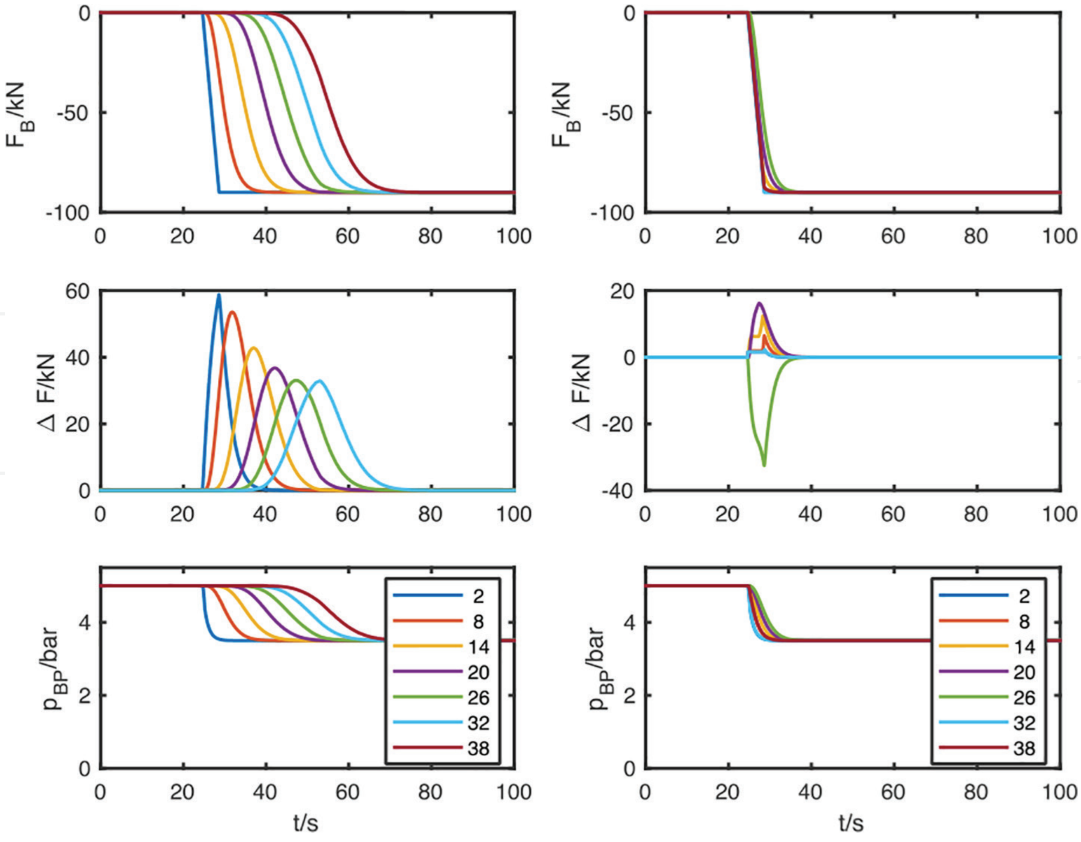


Figure 12.
Traction power boost by distributed power.

- On the operations level, the braking distances and, therefore, the headway are reduced.

- On the train level, the longitudinal buffer forces within the consist are lower than for a brake request from the front of the train (Refer to **Figure 12** left column conventional braking, a right column with ep-assist).

- On the wagon level, a more equalised brake application leads to less wear on certain wagons, such as the first P-braked wagon in an LL-braked train consist.

The reduction of buff forces may lead to increased train masses being braked in the P-regime, which in turn also increases maximum velocities. In terms of industry 4.0, the ep-assisted brake can be considered a collaborative function, as no master is required for this functionality. Instead, the wagons support each other in braking the train, with the most sensible way to react to the neighbouring wagon's braking being to support the process.

Depending on the treatment of the improved functionality with respect to operations (i.e., braked weight, train length and masses), such a function does not require particularly high equipment safety levels, since failures in individual wagons do not impede the overall safety of braking at the whole train level due to the continuous brake pipe.

6. Economic advantages and return-on-invest

The freight Wagon 4.0 as well as the concept of industry 4.0 has economic advantages in many situations but not in all. Often, digitalised concepts are only paying off if, for instance, the cost of internet access is priced based on marginal costs, which is reasonable because a mobile phone base station is nearby anyway for other purposes. In the case of Wagon 4.0, the user base is limited, and economic feasibility must be checked for the individual use case. Normally, wagons that do not move very often are used as storage rooms rather than vehicles and will never give a positive return on investment. In all other cases, the operational setup and the chosen class determine the results. Class 1 wagons allow communication and certainly can also be position tracked via the mobile network. Thus, they may already allow some operational benefits (e.g., knowledge of miles travelled and adapted maintenance schedule), but savings are limited.

Bigger savings of operational costs will be found for class 2–4 wagons. This especially applies in cases when handling times for train inspection and brake checks can be significantly reduced. It is mostly not the costs of staff that count, since in many railway industry applications, staff are relatively cheap compared to the capital costs of assets used. More significant are the savings in turnaround times of trains and track occupancy, for example, in a port setup or a bimodal terminal. When applied together with loading site automation in a seaport environment, the benefits may even increase further. So intelligent freight wagons may be handled like autonomous container movers by the port automation system, removing inefficient manual interfaces and risky or heavy manual labour:

- Control of all vehicles can be centralized in the port operations centre with seamless integration of container handling and train movements.

		Time/minutes		Savings/minutes			
Step	**Description**	**Current**	**Novel**	**Labour**	**Loco**	**Train**	**Track**
1	Arrival and split-up	30	5	60	30	25	25
2	Unloading (4 stackers, manual vs. automatic)	45	30	180	0	15	15
3	Train inspection	30	0	45	0	30	30
4	Trunnion setting and loading (as above)	45	30	225	0	15	15
5	Assembly and brake test	90	10	120	80	80	80
	Total	240	75				

Table 1.
Time savings in port for container trains.

- Increase in worker safety as there is no need for heavy manual labour on tracks anymore.
- Faster train setup and brake check.
- Less tracks needed or higher capacity with existing tracks, higher throughput and efficiency of tracks and vehicles compared to legacy operations.

The most important point is the higher throughput and efficiency. This especially applies to train turnaround times as well as track occupancy. Comparing the time needed for current (legacy) operations compared to a setup with wagons 4.0, significant time savings can be achieved, as given in **Table 1**.

The handling time of a 30-wagon trainset at the terminal facility falls from 4:00 to 1:15 hours. As can be seen, more than 66% of turnaround time may be saved, and therefore, rolling stock and track assets show significantly better utilisation. This especially becomes true if a complete trainset can be saved in the timetable.

Also, the port obtains benefits; without changing track infrastructure, the capacity of the facility increases by 200%. On an average port, this may generate an additional 20% savings on the cost of the track infrastructure.

Taking higher classes of Wagon 4.0 (e.g., class 5) into account, savings may not be as big for a standard use case from the railway operators' side, but they may enable rail services in cases where customers do not have their own shunting devices or in cases where crowded mainlines with lots of commuter passenger traffic will not allow freight services with conventional methods.

7. Conclusions

The W40 concept is able to yield significant operational and logistical advances, yet it relies on proven technologies. The concept can be scaled depending on the intended application, ranging from communication to full automation of wagon movements.

While the concept yields operational and economic benefits, it is at the same time a means of reducing the manual labour required, a further contribution to the future of the rail freight system by providing meaningful and safe jobs to future railway workers.

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Conflict of interest

The authors declare no conflict of interest.

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