Research Article

A risk-based approach to automatic brake tests for rail freight service: incident analysis and realisation concept

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Abstract
This study reviews the practice of brake tests in freight railways, which is time consuming and not suitable to detect certain failure types. Public incident reports are analysed to derive a reasonable brake test hardware and communication architecture, which aims to provide automatic brake tests at lower cost than current solutions. The proposed solutions relies exclusively on brake pipe and brake cylinder pressure sensors, a brake release position switch as well as radio communication via standard protocols. The approach is embedded in the Wagon 4.0 concept, which is a holistic approach to a smart freight wagon. The reduction of manual processes yields a strong incentive due to high savings in manual labour and increased productivity.

Article Highlights

- Brake tests are time-consuming and hinder the adoption of freight rail.
- Recent incidents indicate that the mechanical brake rigging does not play a significant role in accidents.
- A simpler set-up for brake testing, separated from inspections, and the brake test procedure are presented based on the risks observed.

Keywords Freight rail · Brake test · Incident analysis · Train composition · Brake set-up

1 Introduction

Rail freight is by far the most energy efficient means of goods transfer thanks to the low friction in the wheel rail contact. However, current real-time logistics requirements and increasingly smaller shipments are not easy to handle by a system optimised for the efficient transport of mass goods such as fossil fuels and minerals. The intended decarbonisation of the global economy will reduce the amounts of such freight while highly individual, high value shipments will not make up the loss in traffic unless the rail freight system drastically increases its performance. Figure 1 shows the recent development in the United Kingdom, which decarbonised its energy sector in the past years. The performance increase in competition to road transfer needs to be measured in the point-to-point speed, reliability and cost of single wagon loads which is not favoured by the common metrics such as freight moved and freight lifted.

Rail freight, particularly single wagon load (SWL) transport, suffers from drawbacks opposed to road freight:

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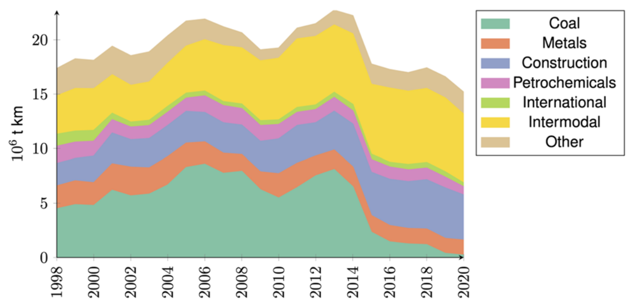


Fig. 1 Freight moved in the UK (Financial year), [1]

- Multi-stage networks for SWL are time consuming and reduce overall reliability.
- Manual processes such as wagon inspections and brake tests are costly and time consuming.
- Asset lifecycles of more than 30 years limit the speed of introduction for novel technologies.

A partial reason for this shortcoming of rail freight lies in the amount of time consumed by train set-up and preparation, partly due to the brake tests required in most, if not all, regulations. Together with the routine inspection of freight and rolling stock, the required air brake tests are among the most time-consuming steps in preparation of trains. One inspection on both sides of the wagons [2] at least on newly built trains or even up to three inspection passes on newly built trains or every 24 h [3] is considered necessary depending on the regulation in place. With variations due to train length, local situation and personnel employed, brake tests may consume up to three hours of time in a European setting.

A potential time reduction for this is the automation of brake tests, which appears rather obvious given the state of transport technology. In fact, passenger rail applies automatic brake tests for decades mostly for multiple units. Rail freight operators however are reluctant to introduce automatic brake tests for a variety of reasons, most notably the high cost for existing solutions that replicate the manual processes. Further, the systems available on the market provide singular solutions to e.g. the brake test problem, while they do not integrate further automation requirements such as those arising during train composition or brake set-up.

This article addresses the automation of air brake tests from a risk perspective and develops an architecture for a simplified, yet safe air brake test system. This includes technical solutions for vehicle-to-vehicle-communication (V2V-communication) as well as the embedding of the system in the rolling stock addressing further automation requirements.

Section 2 of this article provides the state of the art of the wagon subsystem and air brake test procedures as well as existing approaches. In Sect. 3, the methodological approach to the incident analysis, the brake test architecture and the embedding in the wagon subsystem is presented. Section 4 covers the results, which develops a brake test concept and its embedding into the wagon subsystem based on an initial accident analysis. Section 5 discusses the results and provides an outlook.

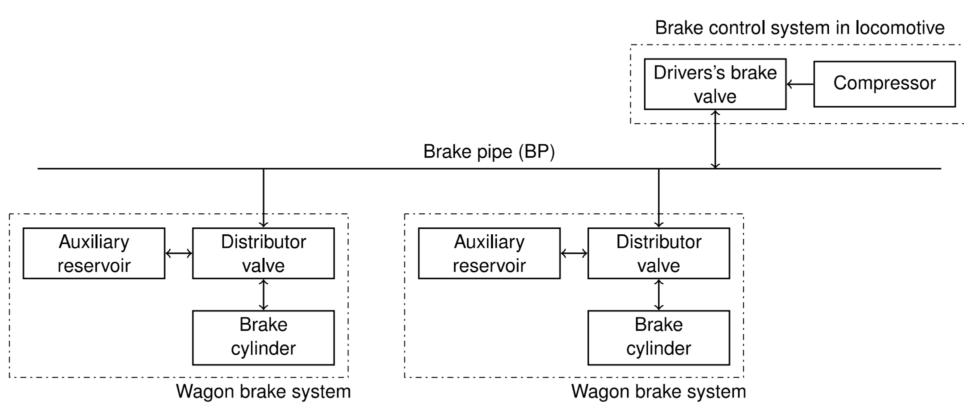
2 State of the art

2.1 Technical equipment of train and wagon

The air brake of a railway vehicle or a train consist is a highly safety relevant system, as it delivers the emergency brake force. Different from road vehicles, the brake system of a train is composed of numerous individual wagon brake subsystems, which are centrally commanded from a leading vehicle**.** This set-up is depicted in Fig. 2 following [4].

The brake command is mostly transferred by help of a pneumatic brake pipe (BP) and the brake action itself follows the *de-energise-to-activate*-principle, i.e. the BP is vented for brake application, in order to be failsafe.

Fig. 2 Train-wide brake system schematic (only two wagon brakes shown)



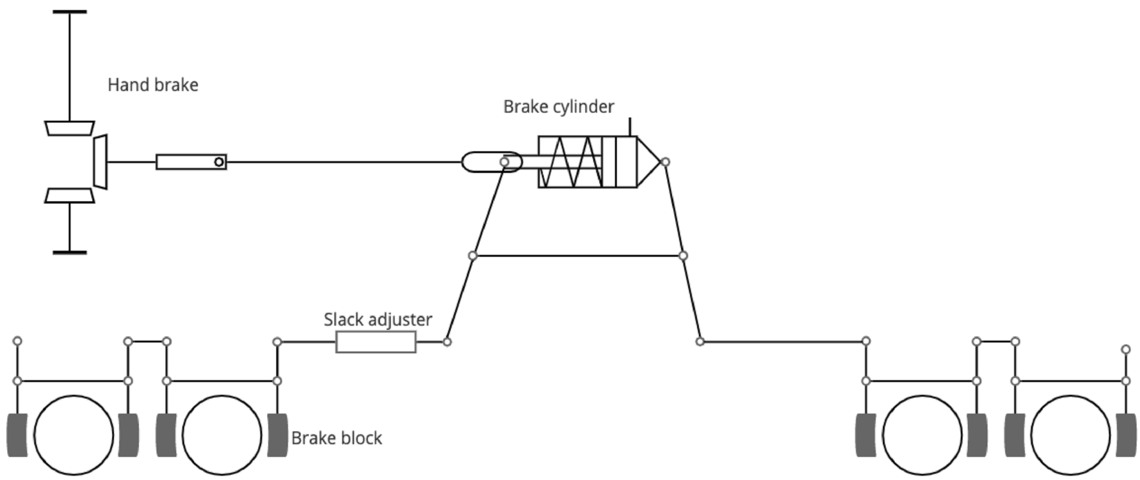


Fig. 3 Braking force generation

The wagon brake system employs a local reservoir as an energy storage device to apply the wagon brake, which is controlled according to the BP pressure by the distributor valve (in a US context called triple valve). The braking force is generated by help of one or more single acting pneumatic cylinders pressing the brake blocks to the wheel tread via a mechanical rigging. The wear of the blocks is compensated by a mechanical slack adjuster. This, together with the optional hand brake, is shown in Fig. 3 in an arrangement following [5].

Railway braking is limited by the longitudinal dynamics of the train consists as well as force transfer via the wheel-rail-interface, limiting instantaneous retardation values to approximately 0.8 $\frac{\mathrm{m}}{\mathrm{s}^2}$ to 1.5 $\frac{\mathrm{m}}{\mathrm{s}^2}$. This means that especially for gradients (almost) all wheelsets need to be braked to achieve an acceptable stopping distance.

2.2 Air brake tests

Since the air brake system is a distributed system that needs to rely on the correct operation of almost all wagon brake systems, these need to be tested periodically to ensure their proper operation. 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 a reduced retardation and potentially the inability to maintain velocity on a downhill gradient.
- *Failure to apply brake upon request* An individual wagon or coach does not apply the brakes when requested by the leading vehicle, resulting in a minor increase in 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 catastrophic failures such as derailments due 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.

The brake test of passenger vehicles is automated in such a way that the brake cylinder pressure is used as indicator for a successful brake application and release, while in freight trains the application to and release from the wheel of the individual brake blocks is required to be checked by visual inspection.

The precise procedure (following German regulations as laid out in [3]) contains 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 released state:
    - Inspection of all wagons for release of brake blocks from wheel tread or released state of visual indicators
    - Inspection of parking brakes for released state and securing of actuation elements
4. Tightness check of BP:
    - Pressure drop less than $50\,\mathrm{kPa}$ per minute for freight trains with BP isolated from driver's brake valve
5. Brake application by pressure drop of approximately $80\,\mathrm{kPa}$ in BP

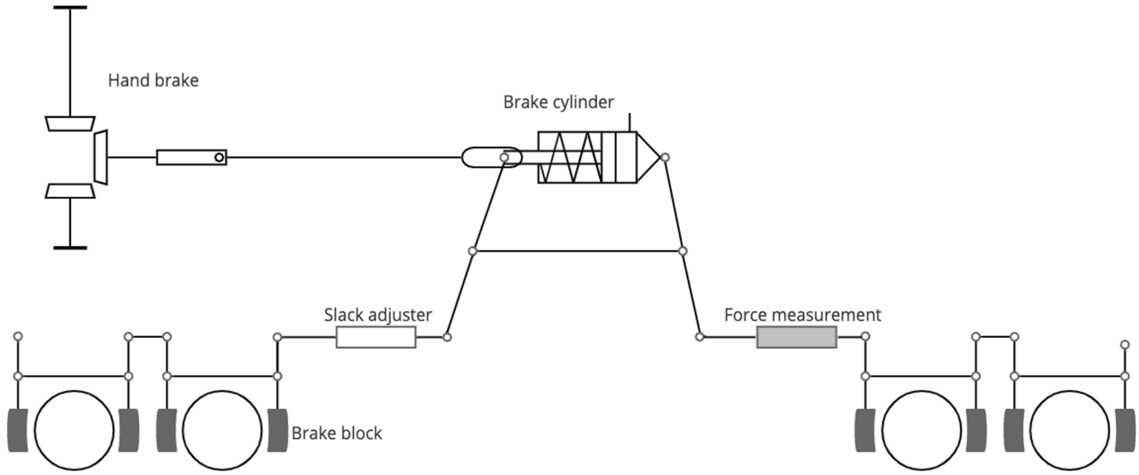


Fig. 4 Instrumented brake rigging

- Inspection of all wagons for application of brake blocks to wheel tread or applied state of visual indicators
6. Release brakes by filling of BP to release pressure
   - Check released state of all wagons by block position or visual indicator
7. Continuity check of BP by opening of end cock on last wagon
8. Check removal of scotches
9. Report brake test

The first step implicitly assigns wagons to the consist forming the train after a successful brake test.

The air brake test needs to be executed on each newly assembled train, after adding wagons or changing direction of the train and is repeated at least every 24 h. In certain cases, e.g. a direction change, a so-called simplified brake test is acceptable, which does not check each wagon individually but rather focusses on continuity of the BP and braking of the last wagon.

Following US regulations, similar stages are executed for the so-called class I inspection (terminal inspection), which needs to be repeated after 3000 miles or for exchanges in traction and wagons. Several brake tests with reduced scope are required between two class I inspections [6]. A class IA brake test, including full inspection of the train, is required at designated sites every 1000 miles. A class II brake test is necessary after adding wagon groups, that do not fulfil certain requirements, to the train while a class III trainline continuity check is required e.g. after changing traction or removing wagons from the consist. The class III test resembles the simplified brake test from German regulations in that it focusses on BP continuity and braking of the last wagon. It is interesting to note that the use of telemetry devices is allowed for the purpose of continuity check.

2.3 Development of automatic brake tests

It is generally agreed throughout the railway sector as well as a foundation of all relevant guidelines that innovations need to provide at least the same level of safety as the existing system. Thus, the main functionality required to perform a brake test automatically includes:

1. Assignment of wagons to train consist
2. Detection of BP continuity
3. Detection of brake application
4. Detection of brake release

A straightforward approach for the implementation of an automatic air brake test is to replicate the manual inspection as closely as possible while using automation. The range of tested functions remains the same, however the less reliable and expensive human operator is supported or fully removed from the process. While this approach appears simple and feasible, plenty of developments did not receive homologation in recent years. As a first product, the solution by Austrian company PJ Messtechnik GmbH (PJM) is a likely candidate to receive homologation for operation in Switzerland in the near future and is undergoing extensive field trials at the time of writing [7].

Table 1 Comparison of different published solutions. Solution **A**: PJM product [7]. Solution **B**: approach described in [8]. Solution **C**: approach described in [9]

Task	Solution A	Solution B	Solution C
Assignment of wagons to train consist	GNSS + Wagon List	Manual scanning	Wagon List + GNSS
Detection of BP continuity	Based on brake application	Based on brake application	BP pressure, End of train device
Detection of brake application	Cylinder force + pressure	Cylinder pressure behaviour	Cylinder pressure level
Detection of brake release	Cylinder force + pressure	Cylinder pressure behaviour	Cylinder pressure level

The approach of PJM is to measure the reactive force to the brake block force by help of deformation of the brake rigging, as depicted in Fig. 4, among other sensory information such as brake mode selector position and brake cylinder pressure. Since the force measurement subsystem is a highly customised part of the system, this as well as similar solutions are costly and time consuming in terms of installation and homologation. The assignment of wagons to the train consist is achieved by help of the intended wagon list which is compared to Global Navigation Satellite System (GNSS)-data for consistency.

An earlier academic approach discussed in [8] proposes not to use a force measurement on the wagons and instead relies on a pressure–time curve recorded on the wagons. Further it is proposed to identify the wagons in the consist by help of manually scanning wagon numbers while walking along the consist.

The approach as in [9] relies on communication of the individual wagons to a central server structure. Pressure sensors in BP and brake cylinder indicate the application and release of the brake. The assignment of wagons to the consist under test is achieved by help of GNSS position and BP pressure.

The different approaches are outlined by their respective solutions to the main tasks in Table 1.

3 Method

3.1 Accident analysis

In order to assess the performance of the state of the art of the brake test procedure, accident reports were analysed. With respect to the availability and local languages as well as different operational approaches in freight rail, Germany, the United Kingdom as well as the United States were selected.

The analysed reports are publicly accessible and cover railway accident documents created between 2007 and 2020. All reports were obtained from the websites of national bodies governing railway safety, namely the National Transport Safety Board (NTSB) for the United States [10], the Railway Accident Investigation Branch (RAIB) for the United Kingdom [11] and the *Bundestelle für Eisenbahnunfallunterschungen (BEU) for* Germany [12].

These were analysed manually for critical incidents in relation to the brake system and in particular brake tests. The research was limited to freight trains, as in this segment the technical innovation barrier is particularly high.

This method was chosen since all three are highly experienced public bodies and their data allows for a systematic approach.

3.2 Sensor equipment concept development

The sensor equipment is selected according to the results of the risk analysis as well as the technical requirements commonly applied in the freight wagon segment. These include shock and vibrations as well as thermal requirements to satisfy the lifecycle expectation. For the current development, the system is based on the requirements of [13] and [14].

The interface to the control system shall be such that common failures, e.g. short circuit or open loop, can be detected easily. The installation positions are chosen for a system compliant with [15], however can be adapted to other systems.

3.3 Revision of technical inspection associated with brake tests

Recent years have seen the advent of powerful wayside train monitoring systems (WTMS). Such monitoring stations inspect wagons independent of their type and collect data using optical, thermal and acoustic sensors. The collected data is analysed and fused by help of artificial intelligence, providing insight into the vehicle state.

It is made possible to detect in particular the running dynamics properties of the wagons such as bearing temperatures, wheel flats or wheel profile deviations [16]. Further developments include the automated visual detection of brake block thickness and uneven wear as well as suspension springs [17]. An integration of these

Table 2 Railway accidents between 2007 and 2020

Accident investigation body	Total accidents investigated	Brake system related accidents
BEU (Germany)	208	4
RAIB (UK)	259	5
NTSB (US)	165	2

steps was addressed in [18], where also volumetric scanning was considered.

This approach is used to separate technical inspection and brake test in order to fully leverage the advantage of an automatic brake test.

3.4 Embedding in the wagon subsystem

The concept for embedding of the automatic brake test in the wagon subsystem stems from considerations concerning economic advantages to railway undertakings (RU) and shippers. These players generate a value stream in which the shipper and the RU need to obtain sufficient economic advantage in order to justify higher rental cost for updated systems to be rented from the wagon keeper.

This value stream and in particular operational practices being particularly wasteful were analysed and useful scenarios for RUs and shippers were derived. These depend largely on the type of operation, the first and last mile infrastructure as well the goods transported as presented in [19] and [20].

Further aspects that guide the concept of the system are the particularities of wagon equipment, for the European context introduced above, as well as those of wagon maintenance. The maintenance is executed in a highly decentralised system providing a cost-efficient approach which does not cater for e.g. maintenance of high voltage electrical components.

3.5 Concept development for automatic brake test system

The concept for the automatic brake test system was developed based on the assumption of a power supply generating electric energy from wagon movement backed up by a battery for sufficient supply during standstill of the wagon. The concept was further guided by discussion with wagon system practitioners, such as locomotive engineers and shunting yard personnel.

4 Results

4.1 Accident analysis

The publicly available accident reports are generated by the respective agencies according to their protocols for selecting incidents for further analysis. This yields the number shown in Table 2: a total of 632 reports issued within the time frame. Out of these accidents, 11 can be related to brake system failures.

The majority of accidents is not related to the brake system. The relatively few accidents that can be related to brake system aspects will be analysed in more detail in the following sections.

4.1.1 Accidents in the US

In the US, two reports with a link to the brake system and a catastrophic outcome was found, namely the report on the Hyndman, PA, accident [21] as well as the report on the Granite Canyon, Wyoming [22] accident. The former report begins with the observation of a decrease in BP pressure by the end-of-train device on a downhill grade to which the crew reacted by stopping the train. After a repair to the 159th wagon and a crew change, the new crew proceeded downhill using handbrakes and dynamic braking to control the train velocity due to the experienced problems with the brake system. This application of the handbrake on the unloaded wagons on the train front lead to overheating and tread build-up. Together with the inappropriate set-up of the consist with 90% of the train mass behind the lead 42 wagons this reduced the ability of the wagons to negotiate the curve in a 2% gradient and lead to a derailment.

The Granite Canyon accident was caused by a dual failure in both the radio communication to the end-of train device as well as a reduction in BP cross-section due to inappropriate wagon maintenance. The effect was the engineer's inability to stop the train due to insufficient brake force remaining in the train and consequently a collision with a stationary train and two fatalities.

4.1.2 Accidents in the UK

In the UK reports analysed accordingly, most accidents involve run-away wagons or groups of wagons. Only in one case, an insufficient service brake force due to snow and ice influence on both brake blocks and brake rigging was reported [23]. This reduction of braking force presumably occurred during the operation of the train and would not have been noted during a brake test.

The 2020 Llangennech derailment, where the untimely application of all brakes on a dangerous goods wagon due to a potentially existing, albeit slow, bypass in the relay valve interface indicates that the untimely application of brakes bears an at least identically high risk [24].

Three accidents indicate an effect of the brake rigging. On one occasion [25], the loss of brake components due to component failure caused a derailment. This was not detected by a manual brake test found to have been executed. In two cases, run-away wagons were caused by an insufficient handbrake force [26, 27].

4.1.3 Accidents in Germany

One particularly disastrous event among those investigated was the 2012 Hosena derailment, which caused one fatality as well as injuries due to a closed end cock on a wagon in the middle of the consist causing a discontinuity of the BP. This closed end cock was not detected during the improperly conducted air brake test on this train [28]. Another case of improperly conducted brake test was the case of Gladbeck West [29], where also a non-continuous BP due to an inappropriately closed end cock went undetected. In this accident report, BEU issued a recommendation to pursue automation of brake tests in an attempt to reduce the human factor in brake tests [23, p.39].

Two further accidents are caused by scotch brakes not removed before train departure, leading to derailments and severe damages are reported in [30, 31].

Another 15 serious incidents, such as signals passed at danger, were linked to not continuous brake pipes however not investigated in depth by BEU.

4.1.4 Analysis of brake system related accidents

From the analysis of the accidents, it becomes obvious that discontinuities in the BP, untimely brake applications and the inappropriate use of hand brakes and scotches play a vital role in the recorded accidents and are prone to lead to a catastrophic outcome at a high probability. Beside this, irregularities or damages to the brake rigging or brake blocks do not appear as probable causes in the accident reports for trains, although these are no rare events. As opposed to the causes for the accidents mentioned above, in most cases such failures 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 discussed above 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.

They went undetected in the classic brake test procedures and in fact 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 case [24].

4.2 Sensor equipment for cost-efficient automated brake tests

The proposed approach requires a novel definition of system borders for brake tests. For this reason, an analysis of the accident causes prevented by the respective brake test action is performed. Based on this analysis, we propose a different split of test steps between brake tests and inspections.

For reasons laid out above, the authors question the effectivity of visual checks for brake application and release or cylinder stroke, respectively. These visual checks are costly and are not mitigating errors such as discontinuities in the BP at a sufficiently high probability due to the non-zero error rate of human operators [32].

Opposed to this, 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, they 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 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, while for the detection of an untimely application of the brake a position sensor on the brake cylinder is required.

A pneumatic scheme indicating the pressure sensor positions is shown in Fig. 5.

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

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

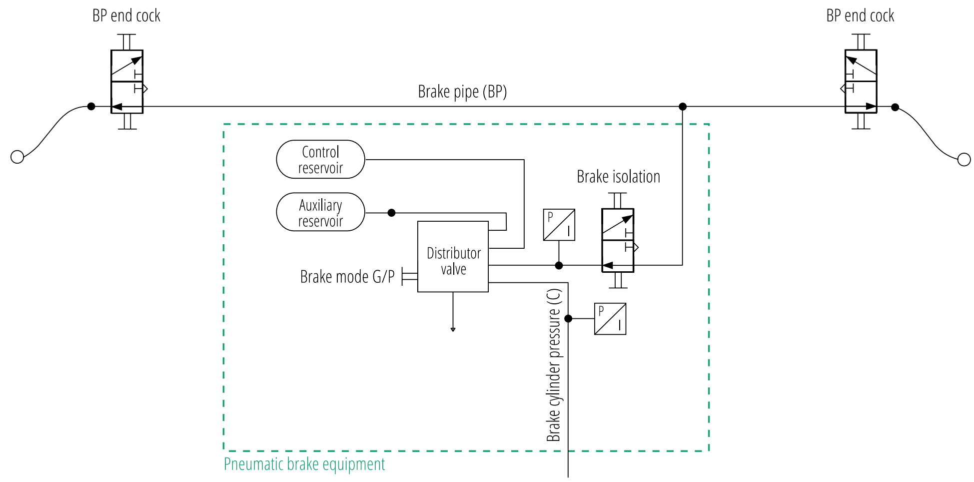


Fig. 5 Pneumatic scheme of a wagon with sensors for BP and brake cylinder pressure

2. Brake cylinder pressurised (by cylinder pressure sensor) and
3. Brake command state (by BP pressure sensor[1]).

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, e.g. to detect deterioration of the distributor valve or incorrect brake mode.

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.

4.3 Separation of technical inspection and brake test

In the current practice, it is common to execute a visual inspection together with brake test. When automating the brake test, it is important for the economic viability to include these inspection steps as well. The existing approach outlined above is not able to detect.

- Immobility of brake cylinders when pressure is applied,
- Uneven distribution of braking force and
- The full release of brake blocks after venting of brake cylinder.

These failure modes are typically slowly developing failures related to wear of the equipment. Such failure modes, as well as other slowly developing deteriorations, e.g. inappropriate state of the brake blocks, are better suited to be subject of a technical inspection as opposed to a brake test. This yields the advantage of a separation between ensuring the brake functionality for the next mission from determining the technical condition of the wagons. The wagon condition monitoring may be automated without large investments into the individual wagons by providing a WTMS.

In the commonly practiced visual inspection, such failures are not likely to be detected. As of today, the systems use visual light imaging to estimated brake block thickness and may easily be extended to detect further visible failures, enabling them to replace most visual checks by human operators. The remaining inspection items, which need to be checked prior to departure, can be automated using cheap and reliable sensors on the rolling stock. The combination of an extended network of wayside monitoring combined with a sensible equipment of the wagons is prone to yield an improved safety of the freight rail system at reduced cost.

4.4 Embedding into wagon subsystem

While the technical inspection of the wagons by use of wayside equipment is in parts well developed and also operating in a productive setting, this section discusses the required extensions of the wagon equipment. For the aim of an automated brake test, the necessary equipment consists of.

[1] The pressure sensor is connected to the BP after the isolation valve, which improves train availability due to the ability to isolate the brake system of individual wagons in the case of failures. In the Wagon 4.0, this isolation cock is set to be powered and thus the isolated position is known. For other implementations, the isolation of the brake system shall be set in the user interface.

- Communication and network equipment for train set-up,
- Sensors for brake system pressures and cylinder position and
- Independent power supply.

Once communication and power supply are established on the wagon subsystem, it is reasonable to automate basic brake functions, such as the end cocks and the brake mode selector as well as the hand brake. In this way, manual actions and resulting failures, such as scotches forgotten to be removed before departure, are further reduced.

4.4.1 Intra-train communication and topology detection

Automatic brake tests rely on information on train set-up, especially the order of wagons in the train is crucial to achieve a safe brake test. While human operators intuitively capture order and completeness of the wagon group at hand, a technical system needs to gather this information explicitly. The same holds true for the transfer of information: a human operator walks along the train, conveying information while an automated system needs to rely on electronic communication for this purpose.

For an automated brake test, it is necessary to aggregate the state information of the individual wagons to yield a state information of the wagon group. In currently implemented automatic brake test systems, the completeness of the wagon group is achieved by comparison of the rake to a wagon list transmitted beforehand [7]. This information of wagons in the rake and their order may be supplemented by GNSS localisation. The intra-train communication of existing solutions is typically achieved by point-to-point radio or mobile communication. For the control of the operation as well as the display of the result, a device installed in the drivers cab or a tablet computer is used.

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

For this reason, the *Wagon 4.0* project [33] proposes 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. These components help to create a linear network structure that replicates the rake structure closely, enabling each controller in the rake to communicate to each other. Each wagon is able to identify its neighbouring wagons and may share this information on the network. In this way, a digital representation of the wagons in the rake as well as their state can be kept redundantly on each wagon and used for an automatic brake test.

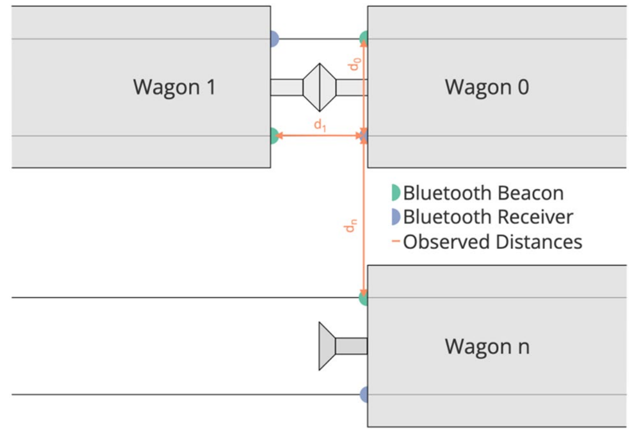


Fig. 6 Connection example: wagons 0 and 1 form a rake, wagon n would lead to a false detection

The advantage of this approach over existing ones is that a communication throughout the train can be implemented comparatively easy. The physical layer of the wagon-to-wagon interface can be formed by the recently proposed digital automatic coupler [34] or by help of a short-range radio communication, which is set to be reliable due to the fact that a line-of-sight connection is always available. The selected technology for this purpose is Bluetooth [35].

Due to its growing capabilities and increasing distribution, Bluetooth is one of the Wagon 4.0's base technologies. A particularly useful capability for train topology detection is the availability of simple connections without explicit pairing. Further the Bluetooth low energy (BLE) beacon technology offers the possibility to send the unique wagon information (EVR number in a European setting) while measuring the distance between beacon and receiver.

The continuous transmission of the wagon identity is possible thanks to the extreme low power design of the beacons. The product selected for a Wagon 4.0 demonstrator provides a lifetime of 10 years running on a 14 Wh lithium battery at a transmission interval of 1 s, which is well within typical maintenance cycles of the wagon subsystem [36]. This product is designed for harsh environment and, thanks to its power supply by battery, can be fully encapsulated, thus providing protection against dust and water jets from all directions.

In Fig. 6, the vehicle frame end of a wagon equipped with communication and identification capabilities is depicted. The beacon is attached to the right-hand side of the frame, while the receiver is mounted to the left. The receiving unit receives the transmitted signals of both the beacon of the opposite wagon, given there is an equally equipped wagon present, as well that on the wagon it is mounted on. By comparison of the signal strengths of both transmissions, it is possible to detect the neighbouring wagon. On the opposite wagon, the same process is executed, and the results are checked for consistency.

The most critical situation of train topology detection is represented by the case where a direct neighbour is not present, while on an adjacent track a wagon is located. However, thanks to the relatively precise distance measurement by help of the signal strength indicator, it is possible to detect such false couplings given the vehicle interfaces adheres to dimensions similar to those described in[37].[2] In future developments, it is planned to use the novel functionality termed *Direction Finding*, introduced in the Bluetooth 5.1 specification. This new functionality allows measurement of angle and distance, which improves the detection further.

With respect to the target market of freight wagons, it is common to ask how to handle non-equipped wagons. The concept presented here is not intended to surpass non-equipped wagons, rather the basic equipment of the wagon to allow communication and detection of neighbouring wagon**s** comprises only low cost, low maintenance components. The basic equipment enables the wagon to identify its neighbouring wagon and to participate in the V2V-communication. This equipment uses semiconductors from the consumer range and can be operated for years on battery power.

4.4.2 Sensor and actuator equipment

The aim of the current brake test procedure is to ensure three states in a safe manner:

- BP continuity,
- Release of all brakes upon filling of the BP and
- Application of braking pressure upon venting of the BP.

The *Wagon 4.0* onboard brake test system is thus equipped with two pressure transducers. One measures the brake cylinder pressure p_C immediately before the brake cylinder, i.e. after any relay valves and similar devices. The second pressure transducer observes the BP pressure p_{BP}.

In a European TSI/UIC brake system, p_C is typically in a range of $(0...380)\,\mathrm{kPa}$ while p_{BP} has a nominal range of $(0...540)\,\mathrm{kPa}$ including assimilation. In order to reduce parts diversity, the authors propose to use sensors with a maximum pressure of 600 kPa, which is in line with the specification of the TSI/UIC distributor valve. Since the control unit needs to be able to detect open loop as well as short circuit, the usage of current type sensors with an output current $(4...20)\,\mathrm{mA}$ is considered.

The task of the position sensor in the brake rigging is to indicate the release position of the brake cylinder to the control system. It is intended to place it as close as possible to the brake cylinder, since this reduces influence from slack adjuster as well as other parts of the brake rigging. Since the release position is attained by help of a return spring in the cylinder, its installation location can be determined easily without considering the wear condition of the brake system or any particularities of the brake system. Ideally, such a sensor becomes part of the mostly standardised brake cylinders.

In addition to these sensors, automatic end cocks are a sensible extension to the system. These are equipped with position switches, so any failures to open or close can be detected based on this feedback. Further, an actuated brake isolation as well as G/P-brake mode changeover, both with position switches, make it possible to perform the brake set-up fully automated. The full pneumatic scheme is shown in Fig. 7.

The values of p_C indicate whether the brake cylinder receives a significant pressure upon brake application commanded by the leading vehicle. Since a continuous transducer is applied, it is also possible to detect the brake timings (brake mode G/P in a European setting) by help of observing p_{BP} simultaneously. While this may detect any failures in brake timings, the resulting data may also be useful in monitoring of the health of the distributor valve looking for slowly developing failure modes. The BP pressure transducer aims at detecting BP leakage as well as being a second source of information of train sequence during formation of the rake.

4.4.3 Power supply

The local electronics and the actuators require electrical power to operate. In order to supply this power, the authors propose to use wheelset generators. While the use of an electrical coupler is a potential source of power, the number of interfaces even for a relatively short European freight train is in the range of 20–40. This, together with the non-zero failure rate of electrical couplers leads to an availability $A_i < 1$, which in turn leads to an overall system

[2] While this standard describes the screw coupler and side buffer arrangement as applied in Europe, equivalent or better installation conditions can be realized with centre-buffer couplers as long as $\boldsymbol{d}_0 < 2\mathbf{m}$ and $\boldsymbol{d}_1 < 2\mathbf{m}$for a parallel track distance of $4\mathbf{m}$ given sufficiently low measurement uncertainty.

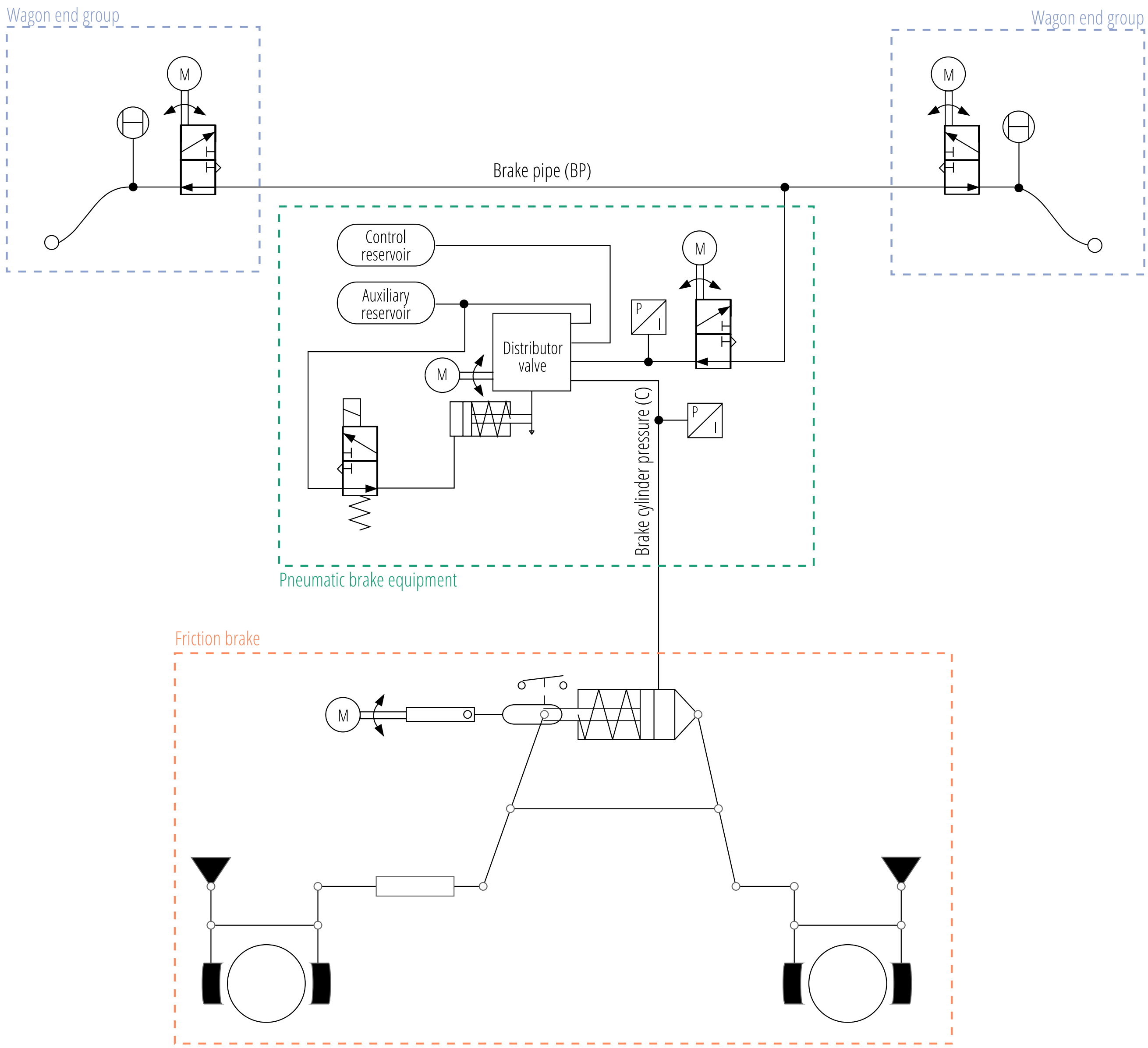


Fig. 7 Automated pneumatic brake schematic for Wagon 4.0

availability for a train of n wagons of $A = \prod_{i=1}^{n} A_i \ll 1$. This low overall availability clearly is neither desirable nor economically viable.

With regards to overall availability, a combination of wheelset generators and opportunistic charging yields the advantage of isolated failures not limiting the full train functionality. A small wheelset generator that can be attached to the axle box can supply up to 100 W of power independent of the connection quality.

Regardless of the source of power supply, the processes of brake test and train formation require energy when not connected to a locomotive and at rest. A small battery of app. 500 Wh depending on the class of *Wagon 4.0* stores the energy harvested during operation and is sufficient to run the communication equipment as well as the actuators for a sufficiently long period of time. In order to provide detectability even for wagons with exhausted actuator batteries, the localisation beacons shall be run from their local isolated batteries.

4.5 Brake test procedure

Based on the architecture consisting of communication, sensors and actuators, an adapted brake test procedure was developed. It requires a rake consisting of *Wagon 4.0* which are mechanically coupled and have their BP connected. Further, all wagons need to be in a V2V-network and kept stationary, preferably by application of the electric parking brake.

Initially, all wagons' end cocks are isolated. The person in charge of the brake tests logs in to one of the wagons and can execute all further stages of the procedure with software assistance. Since the locomotive is unknown to the system, it needs to be added manually. From this information as well as the rake information conveyed over the V2V-network, a brake calculation is performed, and appropriate lists are generated. The resulting information contains the wagon order, train mass, brake modes, braked weight and braked weight percentage. These lists can be automatically exchanged with relevant stakeholders.

Based on the wagon list and the overall train mass, the brake modes (G or P in a European setting) are selected and set on the individual wagons. The driver is then requested to set BP to release pressure. The order detected via V2V-communication is verified during filling of the BP by only filling the BP one wagon at a time, starting at the locomotive end.

After requesting the driver to isolate the driver's brake valve, the tightness is checked by observation of the pressure drop on the last wagon of the rake. Following this, all wagons need to confirm the brake cylinder pressure $p_C = 0$ and the brake rigging position switch indicating the release position. To check the BP continuity, the end cock on the last wagon is opened. The BP pressures of the individual wagons are observed for any significant deviations, indicating a reduction in BP cross section.

To verify the proper brake application, the BP is brought back to release pressure and $p_C = 0$ is checked for all wagons. The brakes are applied by reducing p_{BP} within service brake range, e.g. $p_{BP} = 420\,\mathrm{kPa}$. During this, p_{BP}, p_C are recorded for all wagons. The resulting data is evaluated for the propagation velocity c, filling time t_f and static transmission of the distributor valve. The proper brake application is ensured by verifying $p_C > p_{req}$ with p_{req} following EN 15,355 [38] with extended tolerances as well as the cylinder not being in the release position.

The final stage is the release of the brakes. For this purpose, the BP is filled to release pressure, using the low-pressure filling stroke where available. During the release process, p_{BP} and p_C are recorded for all wagons and the release time is checked for conformity with the brake mode requested. After confirming the released state of all brakes by observing the cylinder pressure $p_C = 0$ and release position switch, the brake test is successful, and the report can be generated.

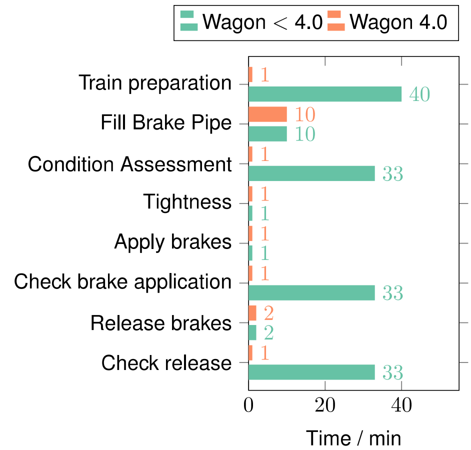


Fig. 8 Time consumed for the individual steps of brake tests, existing fleet (Wagon < 40) compared to Wagon 4.0

5 Discussion of results

The analysis of recent railway accidents with relation to the brake system shows that the brake rigging as well as individual wagon brakes do not play a vital role in railway safety. Only for cases where wagons are stabled individually, accidents with relation to the brake rigging can be observed. The failures contributing to catastrophic accidents among those investigated are discontinuities of the BP, untimely brake applications and inappropriate use of hand brakes. Thus, it is possible to perform brake tests based on BP and brake cylinder pressure combined with a position sensor indicating the release position. This result can be employed to the benefit of the freight railway system by reducing the human factor in brake tests as well as reducing manual effort of brake tests.

The introduction of the brake test system along with the required automation of the brake system in the Wagon 4.0 concept is anticipated to increase the wagon cost by approximately 5000 €. At the same time, the manual effort of the brake test will be reduced, as displayed in Fig. 8. In this figure, the duration of the individual steps of a brake test for the existing fleet as well as for a Wagon 4.0 is compared. The figures for the existing fleet are calculated based on 30 s inspection time per Wagon and 6 s per axle for a 740 m train as well as a walking speed of 0.8 m/s due to the typically challenging environment. For the existing approach, the total duration is 153 Minutes. For a Wagon 4.0, largely due to the eliminated walking as well as parallelisation of many stages, the time is reduced to 18 Minutes, which yields more than two hours of labour cost savings.

The method of this study relies on the assessment of accident reports. Depending on the legislation, these are not published in all cases, e.g. if the accident is not considered grave and no further investigation is conducted. Especially for the failures linked to the brake rigging, this prevents these from being covered in reports. However, it is reasonable to assume that in case of grave accidents these would be reported on. Another potential shortcoming of the analysis is the investigation according to current practice, i.e. employing daily visual checks. The results of these checks are not available to the authors, however could be helpful in covering minor failures.

The communication structure as well as the sensor and actuator set-up is different from solutions on the market [7] in that no forces or deformations are required. This approach is justified by help of the accident analysis. In this way, the proposed solution for freight applications is closer to currently applied approaches in transit rail for fixed train consists. Further, the proposed communication method via Bluetooth Low Energy and the utilisation of distance measurement for the identification of the train structure constitutes a further advance from already proposed solutions, e.g. described in [8, 9].

The utilisation of a point-to-point communication for brake control purposes was proposed in the FEBIS project [39]. This project used antennae attached to the vehicle side for the intra-train communication in order to control the train wide brake in longer freight trains.

For the European Digital Automatic Coupler (DAC) project [40], currently a wired bus system with data connection via an electric coupler is envisaged. For the proposed solution, a radio communication is preferred.

With regards to the implementation of the proposed system, demonstrators for both laboratory and field use are built and tested. For future projects, a pilot service is planned. Further emphasis will be put on the monitoring of the system to prevent malfunctions as well as the availability.

With regards to the methodological improvements mentioned above, a collaboration with railway undertakings or wagon keepers to record detected failures not leading to accidents will help to further improve the study and the system.

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Declarations

Conflicts of Interest The authors have no relevant financial or non-financial interests to disclose.

Code availability No code was generated.

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