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Review of Research and Challenges Concerning Rolling Stock

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Summary

Since the mid-20th century, there has been a continuous increase in societal demand for both passenger and freight transport. One of the transport modes undergoing constant development is rail transport. The advancement of rail systems, the need for their optimisation, and the requirement to ensure the highest level of safety have driven the ongoing modernisation of research methodologies. Since its inception, the Railway Research Institute has conducted extensive research on rolling stock. This article presents a review of the fundamental research methods implemented by the Rolling Stock Testing Laboratory. It discusses the procedures for conducting dynamic testing of vehicles, brake testing, derailment safety testing on twisted track, noise testing, and strength testing.

Keywords: rail vehicles, rail vehicle testing, vehicle dynamic testing, brake testing, safety testing, noise testing, endurance testing

1. Introduction

Economic changes, along with the resulting increase in trade exchange and societal mobility, have led to a growing demand for efficient, effective, and needs-oriented means of both passenger and freight transport. Since the mid-20th century, an intensive development of rail transport has been observed, reflected in its increasing share in the total volume of land transport. The overloading of road networks, leading to extended travel times on various routes, the high cost of both passenger and freight road transport, as well as environmental considerations, have all indicated the potential for rail transport to compete with road transport. The prerequisite for successful competition was the adaptation of rail transport capabilities to the increasing demands of users. This became the primary factor driving organisational and technological progress in the railway sector. This progress encompasses all technical areas that constitute the railway system as a whole, and is particularly significant in the field of rolling stock technology. The development of rolling stock technology has progressed – and continues to progress – in alignment with the following key objectives:

- increasing transport speeds and thereby reducing journey times in both passenger and freight traffic;
- increasing the number of passengers and the volume and diversity of goods transported;

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- optimising vehicle–track interaction and the dynamic behaviour of rolling stock in terms of running safety, generalised wear of both the track and the vehicle's running gear, as well as passenger comfort;
- minimising the environmental impact of rolling stock, particularly in terms of noise and vibrations affecting residents;
- utilising green energy sources in rail transport;
- ensuring protection of passengers and train staff (particularly drivers) in the event of a collision, i.e. providing the highest possible level of passive safety;
- reducing operational costs throughout the entire life cycle of rolling stock;
- ensuring the ability of all types of rolling stock (traction and hauled vehicles) to operate throughout the European railway network, i.e. interoperability, in accordance with the relevant European Union legal regulations.

The achievement of these objectives requires the continuous improvement of existing solutions as well as the introduction of new design concepts in rolling stock. The development of computer technologies has significantly facilitated and accelerated the design process; however, the fundamental role in assessing the validity of the adopted solutions is still played by testing conducted on real objects.

The development of rolling stock technology in the aforementioned directions necessitates the advancement and refinement of testing methodologies – both in terms of development-oriented research and in verification testing aimed at assessing the correctness of implemented solutions and their compliance with normative documents in force in Poland and the European Union. The latter require the application of strictly defined testing procedures carried out by accredited laboratories. This article presents selected types of tests based on the activities and achievements of the Rolling Stock Testing Laboratory of the Railway Research Institute.

2. Rolling stock dynamics and travel comfort tests

One of the fundamental issues inherently associated with the movement of rail vehicles is their dynamic behaviour. These matters have been extensively addressed in the literature, for example in publications [3, 8, 23]. The first method for assessing the dynamic behaviour of rolling stock was the ride quality index W_z, also known as the Sperling index. This method was based on measuring the amplitude and frequency of accelerations on the floor of the rail vehicle and calculating the index using the following formula:

$$W_{Z_i} = 0{,}896 \cdot c(f) \sqrt[10]{a^3 \cdot f^{-1}} \tag{1}$$

where:
- a – displacement amplitude [cm],
- f – vibration frequency [Hz],
- $c(f)$ – frequency weighting factor reflecting the impact of vibration frequency on passenger comfort.

The resulting W_z values were then evaluated as follows:
- up to 1 – vibrations barely noticeable,
- up to 2 – vibrations clearly perceptible,
- up to 2.5 – strong vibrations, but still within a comfort threshold.
- up to 3.25 – strong vibrations, unpleasant but still tolerable,
- up to 3.5 – exceptionally unpleasant and disturbing vibrations, intolerable over prolonged exposure,
- up to 4 – highly disturbing vibrations, potentially harmful if sustained over longer periods.

With the advancement of rolling stock and the increasing performance requirements – particularly those related to higher travel speeds – testing methods and measurement technologies also evolved. Testing based solely on the W_z index became insufficient. In addition to measurements reflecting passenger perception, it became necessary to assess the dynamic behaviour of rolling stock in terms of operational safety and its interaction with the track. Over time, the concept of ride quality assessment diverged into two distinct areas of testing:
- Passenger ride comfort testing, initially carried out in accordance with UIC Leaflet 513 [5], and later based on the EN 12299 standard [10],
- Safety, dynamic behaviour, and track interaction testing, initially conducted in accordance with UIC Leaflet 518 [6], and subsequently under the EN 14363 standard [12].

Ride comfort testing in accordance with UIC Leaflet 513 [5] could be carried out using two methods:
- simplified method (N_{MV} index) – involving the measurement of accelerations in three directions (X, Y and Z) on the vehicle floor;
- full method, which distinguished between: seated passenger comfort (N_{VA} index) – measuring vertical acceleration (Z-direction) on the vehicle floor, longitudinal acceleration (X-direction) on the seat backrest, and lateral and vertical accelerations (Y and Z directions) on the seat cushion; standing passenger comfort (N_{VD} index) – measuring ac-

celerations in three directions (X, Y and Z) on the vehicle floor. In this case, the difference from the simplified method lies in the subsequent processing of the recorded data.

UIC Leaflet 513 [5] proposes the following evaluation scale:

- $N < 1$ – very good comfort,
- $1 < N < 2$ – good comfort,
- $2 < N < 4$ – moderate comfort,
- $4 < N < 5$ – poor comfort,
- $N > 5$ – very poor comfort.

In the EN 12299 standard [10], the following evaluation scale is adopted for average comfort (N_{MV}):

- $N_{MV} < 1.5$ – very comfortable,
- $1.5 \leq N_{MV} < 2.5$ – comfortable,
- $2.5 \leq N_{MV} < 3.5$ – average,
- $3.5 \leq N_{MV} < 4.5$ – uncomfortable,
- $N_{MV} \geq 4.5$ – very uncomfortable.

The latter test, developed on the basis of the running behaviour coefficient, is used to assess the dynamic performance of rolling stock in terms of running safety, dynamic characteristics, and track loading. Initially performed in accordance with UIC Leaflet 518 [6], it is now carried out pursuant to the PN-EN 14363 standard [12]. To this end, various research centres have developed methods for the continuous measurement of contact forces between the wheel and rail during motion – namely, the vertical force Q and the lateral force Y, also referred to as the guiding force (Fig. 1).

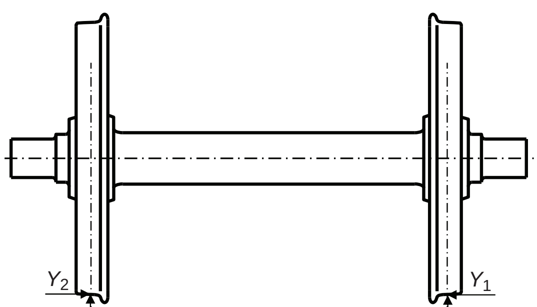

Fig. 1. *QY* interaction forces between wheelset and rail [photo: A. Zbieć]

The then Science and Technology Railway Centre (CNTK), in cooperation with the German railway centre DB Minden, developed and implemented a method based on the measurement of bending moments on the axle of the wheelset. For this purpose, depending on whether a non-powered or powered axle is being tested, three or four cross-sections of strain gauges are applied near the wheel (Fig. 2 and 3).

By measuring strain and applying dedicated calculation formulas, it is possible to determine the *QY* forces acting between the wheel and rail at any angular position (i.e. at any moment in the wheelset's rotation).

Fig. 3. Wheelset during installation preparation for *QY* force measurement [photo: A. Zbieć]

The Rolling Stock Testing Laboratory developed dedicated electronic equipment for the automatic real-time determination and reading of these forces. At the same time, signals are transmitted to a data acquisition system that records all signals from the sensors, including acceleration, velocity, and gyroscopic sensors. The next stage involves post-processing of the recorded data, which includes statistical analysis in accordance with the assumptions defined in the PN-EN 14363 standard [12]. Depending on the filters applied, the same data set can be divided into three categories: running safety (with index s), running behaviour (with index q), and track loading (with index qst or max). The example data presented combine results

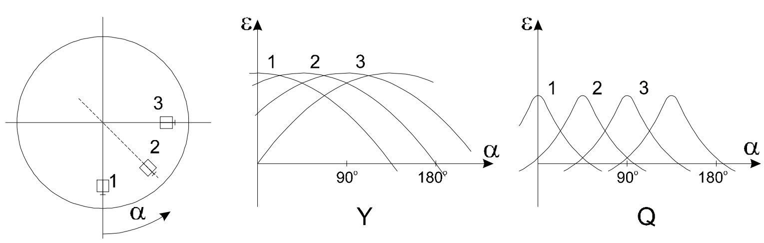

Fig. 2. Principle of *QY* force measurement using strain gauges placed on the wheel disc [9]

from runs on straight sections and curves. In addition to parameters describing the dynamic behaviour of the tested vehicle, test reports also include key track and running data, such as train speed, cant deficiency in curves, curve radii, track gauge, and vertical and lateral irregularities.

The method implemented by the Laboratory, in addition to being used in standard type approval testing, has also been applied in the following projects:

- testing of the ED250 high-speed train (Pendolino);
- turnout testing on Line 9 (Warsaw–Gdańsk) and on Line 4 (CMK);
- testing of a new family of EMUs.

The measurement technique applied during the testing of the ED250 train enabled safe operation at the required speed of V_{max} + 10%, i.e. 275 km/h. It is worth noting that at that time, the maximum permitted speed on the PKP network was 160 km/h. Therefore, in order to test the vehicle in accordance with the requirements of standard PN-EN 14363 [12], it was necessary to exceed the maximum line speed by 115 km/h. For this purpose, a dedicated "Test run procedure for reaching a speed of 275 km/h" was developed. Compliance with the requirements defined therein allowed the train speed to be increased by 5, 10 or 20 km/h in the subsequent run, depending on the results obtained in real time. It should also be mentioned that the process involved additional and significant engagement from institutions responsible for the preparation of the track and overhead line infrastructure. On this occasion, a new Polish railway speed record of 293 km/h was set on the Central Rail Line (CMK) [1, 2]. The entire testing process generated significant media and public interest. Railway enthusiasts with cameras gathered along the route, and the stations were filled with people eager to see the high-speed train up close (Fig. 4).

Fig. 4. People gathered at a station during an ED250 (Pendolino) test run [photo: A. Zbieć]

The same measurement technique (wheelsets fitted with sensors and special processing and recording electronics) was also successfully applied in a non-standard way during approval tests of newly designed railway turnouts constructed for 200 km/h on the Gdańsk line and for 200 and 250 km/h on the Central Rail Line.

A vehicle with well-known dynamic characteristics was used, fitted with instrumented wheelsets. A series of test runs was then carried out, gradually increasing speed up to 10% above the maximum design speed, as is done in rolling stock testing. Using dedicated software, the dynamic behaviour of the vehicle was evaluated on a narrow, isolated section of track including the turnout itself. In this way, a test method normally used for rolling stock was successfully applied for the assessment and eventual approval of railway turnouts.

In parallel with the ongoing improvement of the standard measurement method (i.e. using instrumented wheelsets and accelerometers), a simplified measurement method was also being developed, based solely on vibration acceleration measurements of selected structural components of the vehicle. This simplified method is particularly suitable for testing multiple units. In recent years, Railway Research Institute has tested many multiple units, mainly electric, with maximum speeds not exceeding 160 km/h. These vehicles are used on all types of routes – from urban agglomerations (rapid transit systems) to long-distance connections.

3. Brake tests

3.1. History of Traction Vehicle Brake Testing at the Brake Section of the Railway Research Institute Laboratory in Kraków

The current Brake Section of the Laboratory of the Railway Research Institute, operating within the Rolling Stock Testing Laboratory, originated as a section of Central Research and Development Centre of Railway Technology (COBIRTK) at the Institute of Rail Vehicles of the Cracow University of Technology. Initially, it was located on Św. Filipa street in Kraków.

In the late 1980s, it became the Brake Section of the Laboratory of Science and Technology Railway Centre (CNTK) and moved to its present location at 1 Półłanki in Kraków.

In addition to brake testing of individual vehicles, the laboratory conducted tests related to increasing train speeds on the PKP network – for example, up to 140 km/h (in 1984), then 160 km/h (in 1988) on the Central Rail Line, and finally 200 km/h (in 2014).

An example of rolling stock modernisation was the ED73 electric multiple unit manufactured in 1997 by the former PaFaWag plant in Wrocław. Another example of the introduction of modern vehicles was the E412 electric locomotive (Fig. 5), produced by ADtranz. This was a fully modern locomotive, designed and built for the Italian state railways (FS). Due to its compatibility with 3 kV DC supply, the E412 was intended as the basis for the EU43 and EU11 locomotives offered to Polish railways. These locomotives were tested between 1997 and 2001. Unfortunately, due to the collapse of PKP's financial situation, they were never purchased. Nonetheless, the testing of these locomotives marked a breakthrough, as it was the first time a completely new and modern design was tested. In 1998, the brake tests on the E412 locomotive were also the first brake tests carried out by the Brake Section of the Laboratory at the Test Track Centre near Żmigród.

Fig. 5. E412 electric locomotive for the Italian railways Ferrovie dello Stato Italiane (FS) during brake testing conducted by the Brake Section from Kraków – Test Track Centre near Żmigródk, 1998 [photo: P. Urbańczyk]

As part of the development of rail transport in regional markets, lightweight diesel passenger rail vehicles (also referred to as railbuses) were designed and manufactured by Polish companies. These included vehicles of types 214M and 218M (manufactured by PESA), and 213M and 215M (manufactured by ZNTK Poznań).

The next milestone in this new phase of development was the design of the first entirely new Polish electric multiple unit, the ED74 (Fig. 6), manufactured by PESA Bydgoszcz.

Since Poland's accession to the European Union, there has been intensive development of companies manufacturing and modernising rail vehicles. The number of rail carriers purchasing both new and used traction vehicles, often from abroad and therefore requiring adaptation to the Polish railway infrastructure, has increased. All these vehicles had to undergo testing, including brake testing, before being approved for operation. The first group of new vehicles included, among others, the Impuls electric multiple unit manufactured by Newag and the ELF electric multiple unit manufactured by PESA. The second group included, among others, many modernised locomotives of the SM42, SM48 (TEM2) and ST44 (M62) series, as well as EN57, EN71 and ED72 multiple units.

Fig. 6. ED74 electric multiple unit during preparations for dynamic brake testing – Włoszczowa Północ station on the Central Rail Line, 2007 [photo: P. Urbańczyk]

After gaining experience, Polish manufacturers successfully began selling their vehicles to demanding European customers. Naturally, these vehicles also had to undergo testing. The Brake Section of Laboratory of Railway Research Institute also conducted such tests outside Poland, e.g. the ATR 220 diesel traction unit purchased by an Italian carrier from PESA was tested in Italy in the Lombardy and Emilia-Romagna regions.

The next breakthrough period was 2013–2015, when new electric multiple units designed for long-distance traffic were put into service for the first time – DART manufactured by PESA and FLIRT 3 manufactured by Stadler, as well as the first high-speed train in Poland – ED 250 Pendolino. The testing of the latter was a particular challenge due to the vehicle's maximum speed of 250 km/h.

3.2. Brake testing methodology for traction vehicles

The primary objectives of brake testing for any railway vehicle are:

- to verify the correct functioning of brake-related components and systems,
- to determine the braking performance.

Additionally, for traction vehicles, the objectives also include:

- verifying correct train brake control,
- verifying proper cooperation with other vehicles in multiple-unit operation.

The scope of brake testing can be divided into:

- stationary tests, carried out with the vehicle at a standstill, the successful completion of which permits the next phase, namely:
- dynamic tests, carried out while driving.

For a proper assessment of the brake system performance in a railway vehicle, the following parameters must be measured:

- compressed air pressure (e.g. in brake cylinders, main pipe, auxiliary reservoirs, main reservoirs),
- times (e.g. brake cylinder filling and emptying times, reservoir filling times in the pneumatic system),
- forces in friction pairs (forces between brake blocks and wheels, or between brake pads and discs),
- vehicle speed,
- distance travelled, particularly the braking distance,
- vehicle deceleration during braking,
- temperature of brake friction elements.

During on-site testing, the tightness of the pneumatic system, its correct operation, the correctness of brake control and the braking and release process, as well as the method of informing the driver and on-board personnel about the brake status are assessed.

A positive assessment of the stationary test results is a prerequisite for starting the next stage – dynamic testing. The purpose of dynamic testing is to check the correct operation of the braking system and all related systems during driving, both during normal operation and in emergency situations, in which failures that may occur during vehicle operation are simulated. The operation of safety systems (passenger and driver emergency brakes, active vigilance device, automatic train protection, Radio-STOP, ETCS) and the anti-skid system are checked.

One of the main objectives of dynamic brake tests is to determine the braking performance, which for European railway vehicles is defined by the following parameters:

- braked mass,
- braked mass percentage,
- braking deceleration,
- braking distance.

Test locations

Stationary brake tests are most commonly performed at the Brake Section of Laboratory in Kraków, although this is not a strict rule. In the early years of the Laboratory's operation, dynamic brake tests for traction vehicles were carried out on segments of normally active railway lines that were temporarily closed for testing, including:

- Kraków – Medyka railway line (e.g. Podłęże – Kłaj section),
- Warsaw – Kunowice railway line (e.g. Kutno – Łowicz section),
- Central Rail Line.

Since 1998, dynamic testing has increasingly been carried out at the Science and Technology Railway Centre (now Railway Research Institute) Test Track. Brake tests involving speeds above 160 km/h are typically conducted on the Central Rail Line.

3.3. Selected traction vehicles tested in the Brake Section of the Laboratory of the Railway Research Institute in Kraków

Brake testing has been carried out on all types of railway vehicles: multiple units, locomotives, rail-buses, metro trains, special-purpose vehicles (e.g. rail grinding machines, track measurement trolleys), and dual-mode (rail-road) vehicles.

Table 1 lists selected vehicles that, from today's perspective, can be considered groundbreaking and introducing a new standard. Each of the brake tests conducted on the vehicles listed in this table can be considered a milestone in the history of brake testing. Some of them earned this status due to the vehicle itself being a breakthrough for Polish railways (e.g. EU43, Pendolino), while others were noted for innovative braking system solutions (e.g. ED73, 36WEa-DCC).

ED250 Pendolino high-speed electric multiple unit for PKP Intercity

Preparations for the tests began well before the vehicle was delivered to Poland and included numerous technical meetings with representatives of the vehicle manufacturer – Alstom Ferroviaria S.p.A. – as well as a visit to the manufacturer's facility in Savigliano, Italy, during the assembly of the unit.

The testing process involved several technical challenges. The first was the length of the train (7 cars, total EMU length of 187 metres) and the number of measuring transducers used, resulting in a total cable length of approximately 3.5 kilometres. The second challenge stemmed from the maximum speed of 250 km/h, which required special care to ensure the safety of test runs and the secure installation of measuring equipment and cables mounted on the exterior of the vehicle.

Table 1

Selected traction vehicles tested in the Brake Section of the Laboratory of the Railway Research Institute in Kraków

Year of test	Type of vehicle	Notes
1997	ezt ED73	first Polish multiple unit equipped with disc brakes and pneumatic spring-applied brake as the secondary braking level
1998	E412 locomotive	first locomotive tested in Poland with disc and electrodynamic brakes, multisystem, V_{max} = 200 km/h, designed for Italian operator FS; first vehicle tested by the Brake Section of the Laboratory on the Żmigród Test Track
1999–2001	EU43 and EU11 locomotives	first modern locomotives for PKP, based on the E412 design
2001–2002	214M	first modern Polish-built vehicle, developed after the fall of communism, the so-called railbus with disc brakes
2007	ezt ED74	first Polish modern multiple unit mass-produced after the fall of communism; equipped with disc and electrodynamic brakes, V_{max} = 160 km/h
2011	ATR220	diesel multiple unit - first traction vehicle tested by the Brake Section of the Laboratory outside Poland – in Italy
2013	ezt ED250 Pendolino	first high-speed train intended for operation in Poland, V_{max} = 250 km/h
2014	ezt ED160	first long-distance electric multiple unit produced in Poland, V_{max} = 160 km/h
2015	Sundeck	first push-pull train designed and built in Poland, featuring double-deck coaches, V_{max} = 160 km/h
2018	ezt 36WEa-DCC	world's first electric multiple unit equipped with an automatic constant deceleration brake control system, V_{max} = 160 km/h
2020	ezt ER160	first Polish-built multiple unit tested in triple traction configuration, V_{max} = 160 km/h

Own study.

Fig. 7. The Laboratory test team from Kraków during testing of the ED250 Pendolino EMU – Railway Research Institute Test Track, 2013 [photo: P. Urbańczyk]

The first phase consisted of stationary tests carried out at the Railway Research Institute Test Track in Żmigród in September 2013. After their completion, dynamic brake tests were conducted on the same test track, covering speeds up to 140 km/h.

The third and final phase comprised dynamic brake tests at speeds of 160–250 km/h (see Fig. 7), conducted on the Central Rail Line on a closed section of track in accordance with a specially developed testing procedure and methodology. These tests were performed in November and December 2013.

36WEa-type electric multiple unit with DCC system

During the braking process, the most critical components determining not only the effectiveness of the brake but also the stability and repeatability of its performance are the friction pair elements – in the case of a disc brake, the friction linings and brake discs.

Ideally, the coefficient of friction of the friction pair materials would remain constant regardless of speed, temperature, clamping force, or wear. Under such conditions, constant pressure in the brake cylinders would ensure a constant braking force, and thus constant deceleration.

However, in reality, this is not the case. Due to noticeable – and for some materials (e.g. cast iron) very strong – variability in the friction coefficient depending on these factors, the braking force significantly fluctuates even with constant pressure in the brake cylinders.

The objective of the research into railway braking systems was to develop a brake system that would actively modify the operating parameters during braking in such a way as to keep the deceleration as close to constant as possible. This has now become feasible thanks to the use of high-speed processors in the electronic modules that control vehicle braking.

Knorr-Bremse developed the innovative DCC brake system to meet this objective. The 36WEa-type electric multiple unit (Fig. 8), designed and manufactured by Newag in Nowy Sącz, was selected as the test vehicle. The testing was divided into the following stages:

- stationary tests to verify compliance with the design requirements;
- dynamic tests with the DCC system deactivated, to verify whether the brake parameters met the performance requirements in the vehicle's original configuration (i.e. without the DCC system);
- dynamic tests with the DCC system active, to verify whether the system maintained approximately constant braking deceleration while continuing to meet the regulatory requirements for braking performance;
- verification of the vehicle's response under emergency conditions – various potential system failure scenarios were tested.

Fig. 8. Kraków specialists during testing of the 36WEa equipped with an innovative active brake delay control (DCC) system – Railway Research Institute Test Track, 2018 [photo: P. Urbańczyk]

The significant amount of work and wide range of tests, covering all possible braking modes and conditions, is evidenced by the fact that over 1,000 tests were performed during the motion tests alone!

3.4. Testing of brake system equipment

At the beginning of the second millennium, the International Union of Railways (UIC) initiated a verification process for older types of distributor valves that had been approved according to previously applicable standards. In the meantime, those standards had been partly expanded and tightened. The essence of the verification, referred to as an identity check, was to verify whether the valves also met the current (at that time) UIC requirements. If compliance was confirmed during testing, the UIC would extend the valve's approval for use in newly manufactured and modernised rolling stock. As part of this work, the UIC compiled a list of tests that each distributor valve was required to undergo for the identity verification. In agreement with the manufacturer (Bumar-Fablok), PKP submitted the ESt3f distributor valve to the UIC for testing – a valve widely used in Poland at the time and produced under licence from Oerlikon. This valve could only meet the necessary requirements when used together with an external pressure transducer. Tests of this configuration were conducted at the Railway Research Institute (then CNTK) between 2000 and 2001. Based on positive test results, the UIC approved the continued use of the ESt3f valve in new and modernised rolling stock.

The Rolling Stock Testing Laboratory received two commissions from brake equipment manufacturers to carry out tests required for obtaining UIC approval:

1. Tests of brake modules (distributor valve combined with a pressure transducer) MBF-01A, MBF-01B and MBF-02. These brake modules, developed by Bumar-Fablok, were an evolution and improvement of Oerlikon's licensed brake equipment, incorporating the ESt3f distributor valve and pressure transducers of the same origin. Between 2006 and 2008, the Railway Research Institute (then CNTK) conducted tests of these modules on a single-valve test stand and on a freight wagon, in accordance with the UIC Leaflets 540, 547 and 541-04 as applicable at the time, supplemented with exhaustiveness tests based on the first edition (then in preparation) of EN 15355.
2. Between 2010 and 2011, the Institute carried out tests of the EDS 300 electronic distributor valve, developed by KES (Germany). The EDS 300 is the first distributor valve to use electronic control to convert the pneumatic braking and releasing signal (pressure in the main pipe) into a pneumatic output signal – i.e. the appropriate compressed air pressure in the brake cylinders. The valve also enables pressure adjustment based on the vehicle's

load status. The standard UIC test programme for distributor valves was extended to include tests of the device's behaviour in the event of voltage fluctuations or loss (including complete power failure) of the electronic system. Tests were performed in Kraków both on a single EDS 300 valve and on six valves connected to a full-train brake test stand. Based on the results obtained at the Railway Research Institute, the new brake equipment – both from Bumar-Fablok and KES – was awarded the UIC mark of conformity.

3.5. Testing of friction components of brake systems on a test stand

The history of the brake friction pair testing rig at the Railway Research Institute dates back to the 1990s. At that time, such facilities were available only at a few institutions, including the German railways (DB), French railways (SNCF), and manufacturers of friction components such as Becorit, BSI (Bergische Stahl Industrie), and Textar.

In the mid-1990s, a decision was made at the CNTK to build a state-of-the-art brake test stand. The German company ZFP (Zahnradfabrik Passau GmbH) was commissioned to construct the rig for CNTK. The dynamometer test rig was completed in 1997 and, after several years of verification and evaluation testing, it received its first UIC approval in 2001 (category D for V_{max} = 420 km/h). In 2023, as part of Project RPMA.01.01.00-14 E210/20 implemented in the Rolling Stock Testing Laboratory of the Railway Institute, a comprehensive modernisation of the test rig was carried out by the German company RENK. The scope of the upgrade included the replacement of obsolete and heavily worn electronic and control systems, which were no longer suitable for modern test stand control and monitoring solutions, as well as upgrades to the data acquisition and processing systems, and to the monitoring and diagnostics systems for the dynamometer's components. A new spray system was also introduced for the brake friction pairs, allowing simulation of wet braking conditions.

The design of the test stand enables full-scale testing of friction pairs used in pneumatic brake systems for high-speed trains, multiple units, locomotives, and railbuses, under conditions corresponding to actual operation (see Figures 9–11). The measurement equipment and technical specifications of the rig allow for homologation and certification testing of friction materials in accordance with, among others:

- Test programmes for friction materials as specified in the applicable UIC Leaflets 541-3, 541-4 and standards PN-EN 16452:2015-08, PN-EN 15328;
- Test programmes for railway wheels according to UIC 510-5 and PN-EN 13979-1+A2:2011, including thermal load resistance testing;

a) b) c)

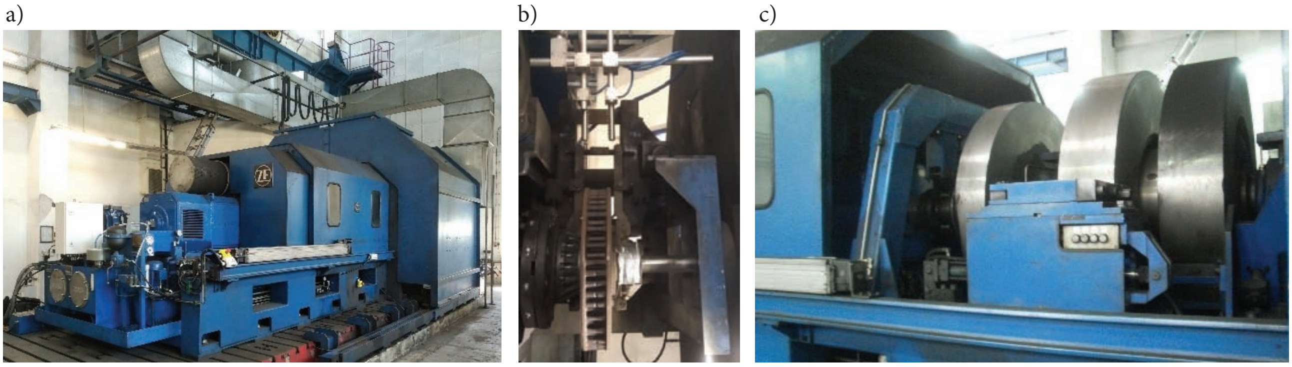

Fig. 9. Stationary test stand: (a) general view, (b) test cab, (c) mechanical masses [Railway Research Institute archive collection]

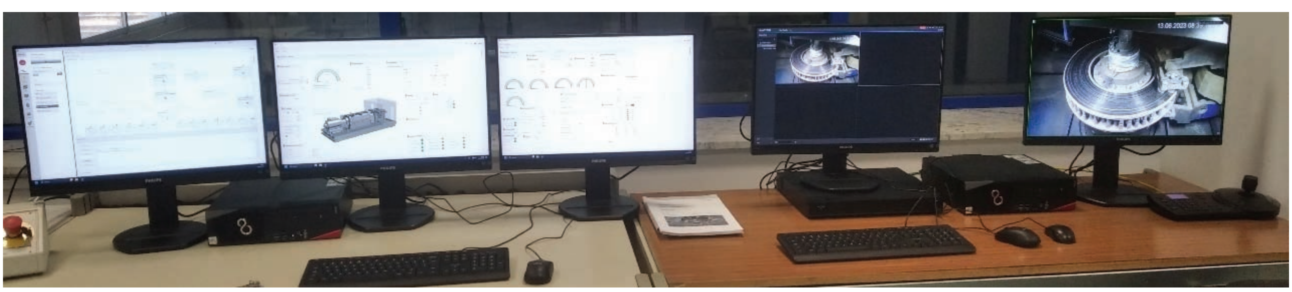

Fig. 10. Control panel of the test stand [Railway Research Institute archive collection]

a) b)

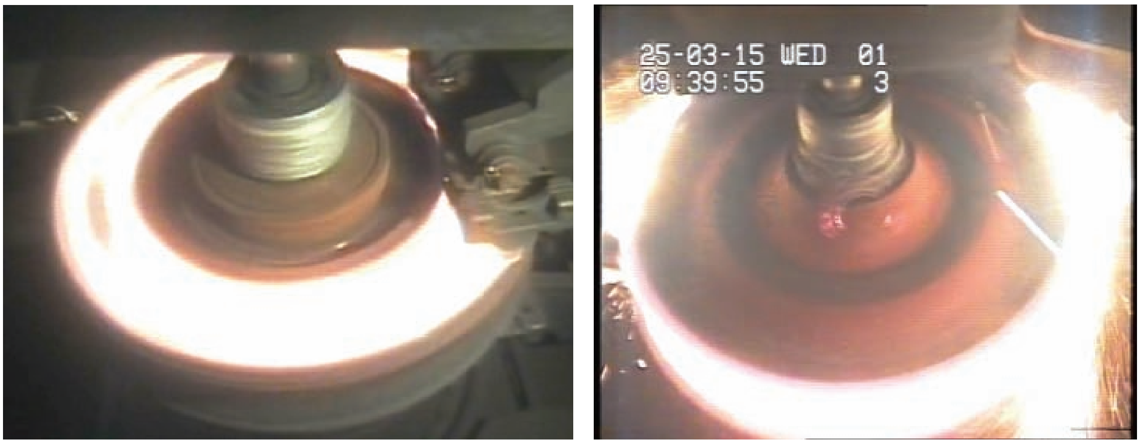

Fig. 11. View of thermal rings during verification testing of resistance to thermal loads: (a) disc mounted on an axle; (b) monoblock wheel [Railway Research Institute archive collection]

- Test programmes defined in the Technical Specifications for Interoperability (Loc & Pas and TSI WAG);
- Test programmes for brake discs according to PN-EN 14535-3:2016-02;
- Test programmes according to ERA/TD/2013-02/INT ver. 3.0 (European Union Agency for Railways);
- Custom test specifications defined by the client, simulating actual operating conditions for friction pairs.

4. Safety testing against derailment

4.1. Vehicle running safety tests on twisted track

One of the fundamental vehicle tests is the verification of running safety on twisted track. The assessment method is specified both in the TSI WAG [19] and TSI LOC&PAS [18], with reference to standard EN 14363:2016 (in Poland: PN-EN 14363 [12]). PN-EN 14363 [12] defines three test methods for rail vehicles negotiating twisted track. Two methods apply to all types of rail vehicles, while the third is applicable only to vehicles with car bodies supported by two bogies, each with two axles.

Method No. 1

In Method No. 1, tests are carried out on a track with a radius of $R = 150$ m. The test track is long enough to ensure that the entire vehicle (or vehicle section) remains within the curve during the test run. Additionally, the track is equipped with a 3‰ twist segment. If greater track twist is required during testing, the standard [12] recommends introducing twist into the vehicle itself, for example by placing steel shims of appropriate thickness under the primary suspension. During the tests, the following are measured: guiding forces Y on the outer wheel (Y_a) and inner wheel (Y_i), vertical wheel loads Q_a and Q_i, wheel lift (Δz) of the leading axle's outer wheel. A high wheel-rail friction coefficient must be ensured during the test. To this end, the wheel-rail striking angle is also measured. The assessed parameter is the $(Y/Q)_a$ coefficient. For vehicles fitted with wheels with a flange angle of 70° and a dry friction coefficient of $\mu = 0.36$, the $(Y/Q)_{\text{lim}}$ limit value should be 1.2. If the critical value $(Y/Q)_{\text{lim}}$ is exceeded, the wheel climbing effect is evaluated. During each run, the lift of the outer wheel (Δz) of the guide assembly over the entire measuring curve must not exceed 5 mm. This criterion is treated as conclusive proof of vehicle running safety on twisted track. Fig. 12 shows the measuring curve at the Railway Research Institute.

Fig. 12. Measuring curve built in accordance with EN 14363 [12] method no. 1 [photo: A. Chojnacki]

Method No. 2

To assess the running safety of rail vehicles on twisted track according to Method No. 2, parameters measured at two test stands must be used.

The guiding force Y_a is determined on a measuring curve with a radius of $R = 150$ m. In this method, the curve has no superelevation – the rails are at the same level along the entire curve. As in Method No. 1, the following are measured: guiding forces Y on the outer wheel (Y_a) and inner wheel (Y_i), as well as vertical wheel load Q_i. The wheel-rail striking angle is also measured. The ratio $(Y/Q)_i$ and the wheel-rail striking angle are used to determine the coefficient of friction of the wheel against the rail.

To measure vertical wheel forces on the rails, the Railway Institute uses the TENSAN PLW test stand (Fig. 13), owned by PKP Intercity. Measurements are performed while the rail vehicle is moved up and down from track level, in accordance with PN-EN 14363 [12]. The obtained data are used to prepare so-called twist diagrams, from which minimum wheel loads $Q_{a\ min}$ are determined during simulation of vehicle movement through twisted track. The forces $Y_{a\ max}$ and $Q_{a\ min}$ are then used to calculate the $Y_{a\ max} / Q_{a\ min}$ coefficient, which – as in Method No. 1 – must not exceed the critical value.

$$(Y/Q)_{\lim} = 1.2. \tag{2}$$

Fig. 13. PKP IC stand used by the Railway Research Institute [photo: A. Chojnacki]

Method No. 3

According to method No. 3, a rail vehicle equipped with two two-axle bogies can cross twisted tracks safely if the following conditions are met:

- stress relief

$$\Delta Q/Q_0 \tag{3}$$

- and the rotation resistance of the bogie

$$X = \frac{M_{z,R\min}}{2a^{+}P_0} \tag{4}$$

where:

- Q_0 – average vertical wheel force of the test set on a horizontal track (twist $g^0 = 0$),
- ΔQ – deviation from Q_0 under conditions of maximum twist,
- $M_{z,R\min}$ – torque required to rotate the bogie relative to the vehicle body during its passage through a curve of minimum radius,
- $2a^+$ – wheelset spacing in the bogie (bogie base),
- P_0 – average load of the wheelset in the bogie.

The criterion values of the individual coefficients are as follows:

$$\Delta Q/Q_0 \le 0.6 \tag{5}$$

$$X \le 0.1 \tag{6}$$

for passenger vehicles and locomotives (Fig. 14),

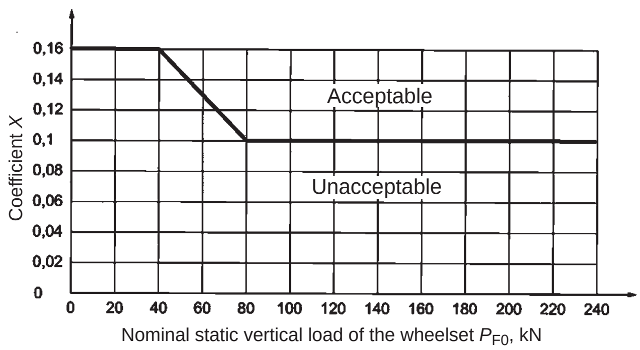

Fig. 14. Maximum permissible value of coefficient X for freight cars according to PN-EN 14363 [12] method No. 3

The Railway Research Institute uses the TENSAN PLW test stand to determine the load reduction coefficient. The obtained data are used to prepare so-called The data obtained is used to prepare so-called twist diagrams, from which the load of the tested wheel on the horizontal track Q_0 and the deviation ΔQ of the load caused by the wheel load reduction as a result of its passage through the track with maximum twist are determined. The coefficient determined for each wheel must meet the criterion value specified in standard [12]. Based on the results of measurements during the twist test, the average wheelset load in the bogie P_0 is also determined.

In order to determine the rolling resistance coefficient of the bogie, it is necessary to carry out measurements on a test bench for measuring the moment of resistance of bogies relative to the body. Such a test stand is located at the Railway Research Institute in Warsaw, as shown in Fig. 15.

Fig. 15. The Railway Research Institute's test stand for measuring the moment of resistance of bogies relative to the body [photo: A. Chojnacki]

The moment required for the bogie to rotate relative to the vehicle body and the angle of rotation of the test stand are measured. Using an angle indicator, it is possible to determine the angle of rotation of the test bench at which the collision between the bogie and the vehicle body occurred. The angle of rotation of the test stand is ±10°. The speed of rotation of the test stand is continuous in the range of 0–1°/s.

After completing the measurements, graphs of the bogie's resistance moment as a function of the bogie (stand) rotation angle and for different stand rotation speeds are prepared. The graphs show the moment values corresponding to the minimum curve radius through which the vehicle can safely pass. In Poland, under operating conditions, this is a radius of R = 150 m. The assessment should be based on the moment of resistance determined during the rotation of the bogie relative to the body at a speed of 1°/s.

The bogie rotation resistance coefficient X is determined on the basis of the bogie resistance moment relative to the body $M_{z,R\min}$, the average wheelset load in the bogie P_0 and the bogie design parameter, which is the wheelset spacing in the bogie $2a^+$.

According to method no. 3 of the PN-EN 14363 standard, a rail vehicle equipped with two two-axle wagons can safely run on twisted tracks, if it meets the criteria values given for the load reduction coefficient – $\Delta Q/Q_0$ and the bogie rotation resistance factor X.

5. Environmental impact of rolling stock

5.1. Noise tests

Rolling stock affects the external environment in various ways, e.g. in terms of noise emissions, exhaust fumes emissions and electromagnetic emissions. The issue of noise emissions is significant because rolling stock, both passenger and freight, constitutes a significant part of the entire transport sector in Europe. Rail lines run through built-up areas, they very often enter urban centres, certain types of rolling stock, e.g. trams, underground trains or various forms of surface urban railways, are specifically associated with cities. With the current degree of urbanisation, this means that a large number of the population is exposed to noise emissions from rolling stock.

Rail noise is a factor that has an adverse effect on the residents near railway areas. In Europe, a particularly noticeable impact of rail noise is observed in the countries with the highest population density, i.e. the Netherlands, Belgium and Germany. Based on research, the World Health Organisation (WHO) has identified the most common problems of people exposed to rail noise: cardiovascular disease, sleep disturbance, hearing impairment, tinnitus or constant irritability.

Consequently, there is a lot of attention paid to noise emission reduction at both European and national levels, and this is reflected in the regulations relating to the approvals of new types of rolling stock, which translates into the scope of testing of new rolling stock.

Over the last 20 years, there has been a trend towards extending the scope of noise testing, with new EU directives, national regulations, standards, and within them, new ways of testing and test methods. It is a dynamic process as part of which the research and measurement level is correlated and results directly from the legal level, which forces the continuous development of research potential. Such a process has taken place and is still implemented at the Rolling Stock Testing Laboratory of the Railway Research Institute.

In the early 2000s, the Laboratory conducted noise tests, but within the scope limited by the applicable standards, i.e. primarily related to passenger rolling stock (with emphasis on measurements of noise inside the cars) and locomotives (primarily in driver's cabs and measurements of the noise of the sirens). Noise measurements in the external environment were carried out to a rather limited extent. Freight wagons were not tested either, as there were no relevant national regulations. At that time, there were no accredited measurement procedures; the equipment used was based on magnetic recorders, and the auxiliary equipment was primitive from today's perspective.

The main reason for the change was the European Union's work on the interoperability of the trans-European conventional rail system. As part of the works, Transport Safety Investigation Regulations emerged. The regulations introduced obligatory tests in accordance with prEN ISO 3095:2001, and listed criteria for the results evaluation. The end of that stage from the legal side was the introduction of the Noise TSI in 2006. This meant that noise tests, depending on the rolling stock class, became mandatory. The research capabilities of the Rolling Stock Testing Laboratory include the following noise measurements:

- Stationary noise emission (at standstill) measurements for the whole vehicle;
- Stationary noise emission (at standstill) measurements for vehicle compressors;
- Pass-by noise measurements – running tests, driving at set speeds;
- Start-up noise measurements – running tests, vehicle start-up;
- Noise measurements in driver's cabs under stationary conditions (standstill) without audible warning signals (vehicle sirens);
- Noise measurements in driver's cabs in stationary conditions (standstill) with audible warning signals (vehicle sirens);
- Noise measurements in driver's cabs while driving – running tests, driving at steady speeds;
- Internal noise measurements, i.e. in the passenger and service areas of the vehicle – stationary conditions (standstill) and while running (running at steady speeds);
- Audible warning signals noise measurements (vehicle sirens) – sound level and basic tone frequency;
- Sound level of the acoustic information signal measurement, generated by the on-board equipment in the driver's cab;
- Determination of sound level and frequency of passenger door warning signals;
- Determination of the STIPA value for the tested vehicle's sound system – in stationary conditions (standstill) and while running (running at steady speeds).

5.2. Ways to reduce traffic noise in Europe

In the context of the impact of noise emissions on the external environment and such non-standard measurements carried out for research purposes, a good example is the study of the noise of passing coal wagons performed at the time when there was a pan-European discussion on the advantages and disadvantages of cast iron and composite brake inserts. The studies described below can be treated as the Laboratory's contribution to that discussion, as these were not homologation studies and the obtained results could not be used to obtain approval of the wagon type. The main objective of the tests was to determine the noise levels emitted to the external environment during the passage of coal wagons under simulated normal operating conditions and to compare the noise levels to those emitted by identical wagons equipped with composite and cast iron brake inserts.

In accordance with the Noise TSI provisions for a speed of 120 km/h, the obtained $L_{pAeq,Tp}$ results should be normalised to a speed of 80 km/h in accordance with the conversion formula given below:

$$L_{pAeq,Tp}\,(80\ \text{km/h}) = L_{pAeq,Tp}\,(\text{V}) - 30\log(\text{v}/80\ \text{km/h}) \tag{7}$$

The obtained $L_{pAeq,Tp}$ results (average values from 3 or 5 measurements according to the description of the measuring run, values for 120 km/h are given in Table 2 (M1, M2 – microphone markings), 120norm, mean the value for 120 km/h after normalisation, directions A and B according to the description of the measuring run. The train used for the tests is shown in Figure 16.

Table 2

Test results for final measurements

Travel direction	Speed [km/h]	$L_{pAeq,Tp}$ value in dB_A			
		Cast iron		Composite	
		M1	M2	M1	M2
A	80	88.9	88.8	86.7	87.0
	120	93.7	93.4	90.2	91.7
	120norm	88.4	88.1	84.9	86.4
B	80	89.1	88.8	87.6	87.9
	120	94.4	94.4	89.6	90.1
	120norm	89.1	89.1	84.3	84.8

Own study by the Institute.

Fig. 16. Composition of a train for the noise study conducted at the Institute's experimental track in Żmigród [photo: P. Tokaj]

In conclusion, it can be stated that this was one of many different studies conducted both in our country and in other countries of the European Union, which showed that wagons equipped with composite brake inserts are characterised by significantly lower noise emissions than wagons with cast iron inserts. Following the study results, specific decisions were taken at the political and legal level with the purpose of moving away from cast iron as a material for brake inserts. The use of composite brake inserts is expected to reduce the roughness of the wheel rolling surface. The condition of the wheels after the operation with composite and cast iron inserts is shown in Figure 17.

To reduce the roughness, the railway rails are subjected to cyclic grinding processes, which allow a noise reduction of up to 5 dB. To reduce the noise, it is sufficient to use noise barriers up to a height of 1 m (Fig. 18).

Fig. 18. Low noise barrier to protect against the rolling noise [source: UIC]

6. Strength tests

6.1. Impact (buffing) tests

As part of the strength tests performed by the Rolling Stock Testing Laboratory of the Railway Research Institute, it is worth mentioning the possibilities of the run-up hill used for tests related to the behaviour of a rail vehicle at the moment of collision, known as pile-up [6]. The idea to build the test bed was born in the 1990s. Initially, the test stand was intended to enable the implementation of two basic research programmes:

- couplings,
- track brakes.

With the construction of the main building and the subsequent new facilities, the track system was created. On the current hill, an earth overpass was built and reinforced with a concrete and iron structure. Over time, it was supplemented with equipment used in mines, which, after suitable adaptation, is used to pull wagons up the ramp. The drive system was purchased from the Mortimer-Porąbka coal mine in Zagórze. The current building with the control system was put into operation at the turn of 1974–1975. That mechanical system, after numerous upgrades, is still in operation today.

In the Laboratory, strength tests are carried out of freight and passenger wagons and their components during collisions at specified speeds, in accordance with the recommendations of the EN 12663 standard [4]. The results of such tests provide valuable information about the resistance of the vehicle body to overloads during the operation of a particular vehicle. The tests also make it possible to detect a variety of per-

a) b)

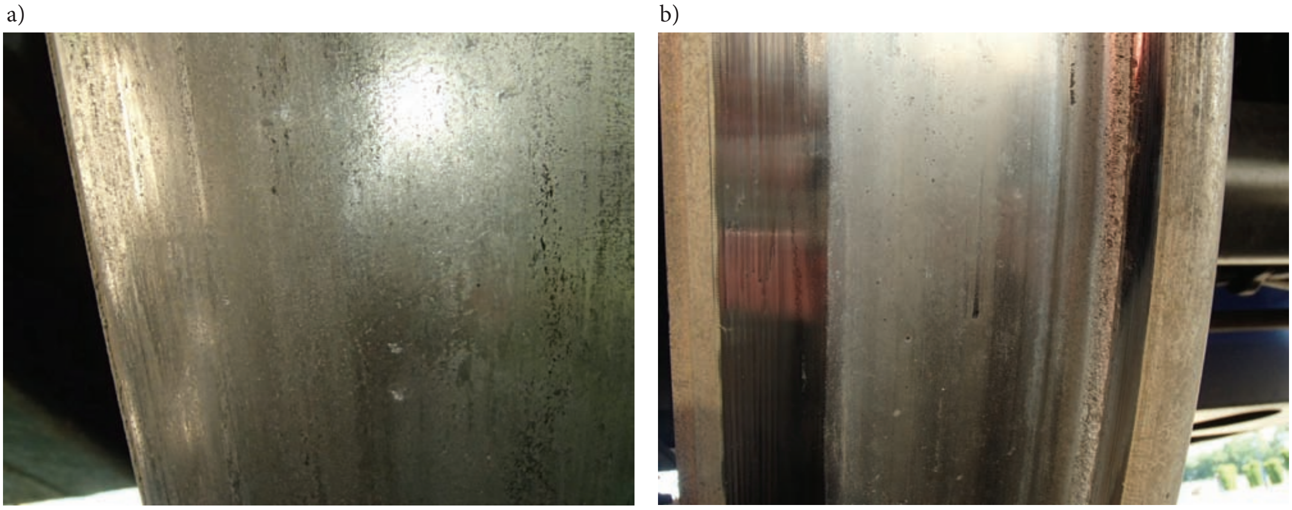

Fig. 17. (a) Rolling surface of a wheel with a cast iron insert (R_a = 2,11µm), (b) surface of a wheel with a K-type composite insert (R_a = 0,47 µm) [photo: P. Tokaj]

a)  b) 

Fig. 19. (a, b) Test run-up hill general view [archival collection of the Institute]

formance faults, including, for example, asymmetry in the vehicle body. On the test bed, wagons can be accelerated up to a speed of 40 km/h. Figure 19 shows a general view of the test run-up hill.

The test run-up hill is equipped with a ramp (flyover) and control devices that allow one of the wagons to be accelerated to the pre-determined, well-defined and controlled speeds. To facilitate the preparation and conduct of the collisions, the stand is equipped with devices enabling the positioning and braking of the colliding wagons. Tests and measurements are carried out on both prototype and modernised wagons, as well as on prototype shock-absorbing devices. Thanks to the use of the measuring equipment owned by the Laboratory, comprehensive strength tests are performed on the freight and passenger wagons and their components during collisions, which include:

- strain and deformation of the rolling stock components;
- measurements of displacements, forces, accelerations and dynamic characteristics of buffers and automatic couplers;
- durability tests of guide bars;
- tests of track brakes.

Among the tests included in the accreditation scope (No. AB 742), the are wagon impact (buffing) tests simulating the behaviour of wagons (after 16 years of its operation) during train formation in marshalling yards. The impact tests very often reveal weak points of the structure, mainly in the front part of the wagon, which is very helpful in developing its final design version. The tests are carried out in accordance with EN 12663-2 [4] and other normative documents [7, 14, 15, 19].

An unbraked wagon standing on a horizontal, straight track, both empty and loaded, is subjected to a collision with a ram wagon loaded to a gross weight of 80 t and equipped with buffers with an energy absorption capacity of ≥ 30 kJ. After the collision, the wagon undergoes a strength assessment. From the point of view of ensuring the safe operation of a wagon, the following criteria are taken into account:

- there must be no visible permanent deformations of a wagon body;
- accumulated residual deformations from preliminary tests and 40 basic impact tests must be below 2‰ and must stabilise before the 30th impact;
- changes to the basic dimensions of the wagon must not reduce its functionality.

Collision tests are usually accompanied by static experimental tests on vehicles or their components. These take place before and after the wagon is loaded with ballast to replace the actual load. Prior to that, strain gauges are placed at pre-determined points of the wagon body to show the deformation status, based on which the strain is calculated. The results are used to assess whether the permissible strain related to fatigue strength was not exceeded at the measurement points, in accordance with the guidelines of the standard [4]. The method recommended according to the standard assumes that the strain changes over time from the σ_{min} value to the σ_{max} value, with $\sigma_{min} = \sigma_m(1 - K)$ a $\sigma_{max} = \sigma_m(1 + K)$, where for freight wagons $K = 0.3$. It follows that for fatigue strength assessment, it is sufficient to measure the mean strain value, i.e. the value of the strain induced by the nominal load from the cargo and from own weight. Thus, after the measurements, the following condition is checked:

$$\sigma_m = \sigma_{m1} + \sigma_{m3} \leq \sigma_{m\lim} \tag{8}$$

where:

σ_{m1} – is the strain value resulting from the weight of the wagon,

σ_{m3} – is the strain value resulting from the load, measured using the strain gauge,

$\sigma_{m\lim}$ – is the limit (permissible) average value of the measured strain, according to [4], depending on the notch category (A, B, C, D or E).

The above-mentioned tests are sometimes accompanied by readings of the deflection angle of the vehicle body. The maximum value of the deflection (the so-called deflection arrow) f should meet the following condition: $f \leq 0{,}003L_b$, where L_b – is the so-called wagon base, i.e. the distance between the axes of the bogie pivots.

6.2. Testing while running on a railway track

In the case of prototype wagons, the results obtained from experimental running tests on railway routes are very valuable. The trains run on measuring sections with good and average maintenance conditions. The lines consist of straight sections, curves and turnouts. In the measuring section, some parts of the rail track's condition must enable driving at the maximum speed specified in the design documentation of the tested vehicle. The length of the measuring route should be approximately 1,000 km. During the measurement journeys, the strain, travel speed and route configuration data must be recorded. The most important guidelines for such tests can be found in [7, 15].

The requirements of the ERRI Report [15] are adopted as the criterion for evaluating the results of the tests. After completion of the tests, the dynamic strains recorded during driving are statistically processed to determine the so-called equivalent surpluses. At the tested structural points, the sum of the strains recorded during static vertical loading and the equivalent dynamic excess strains must not exceed the permissible values specified in [15]. The values of equivalent dynamic strains obtained after statistical processing are mapped on Goodman-Smith diagrams in the form of a parallelogram inscribed in these diagrams separately for each tensometric point. The diagrams include limit lines appropriate to the steel used and specific to the position of a given strain gauge. The fatigue strength of a given node is considered sufficient as long as the parallelogram of equivalent strain lies within the corresponding limit lines of the Goodman-Smith diagram [21].

7. Conclusions

Rolling stock is a very complex technical solution. The tests described in this article are a verification of classical characteristics, which are absolutely necessary, although far from sufficient. These tests are fundamental, and many additional checks are carried out as part of the approval processes. For example, requirements regarding heating, ventilation, air conditioning, lighting, sound system, passenger information and the visibility and audibility of trains are determined and verified. There are special tests to check, e.g., dual-mode vehicles or working machinery. Rolling stock is also considered in terms of traction characteristics, electromagnetic interference, on-board communication systems and safe driving control systems.

References

1. 293 kilometry na godzinę Pendolino w Polsce [293 kilometers per hour Pendolino in Poland], https://www.intercity.pl/pl/site/o-nas/dzial-prasowy/aktualnosci/293-kilometry-na-godzine-pendolino-w-polsce.html [available: 20.02.2025].
2. Badania Pendolino, Większe drgania mogą wpływać na budynki przy torach [Pendolino research, Greater vibrations may affect buildings near the tracks], https://www.money.pl/gospodarka/wiadomosci/artykul/badania;pendolino;wieksze;drgania;moga;wplywac;na;budynki;przy;torach,193,0,1617089.html [available: 20.02.2025].
3. Cichocki Z. et.al.: *Rozwój metod badawczych własności mechanicznych taboru w sześćdziesięcioletniej historii Instytutu Kolejnictwa* [Development of research methods for mechanical properties of rolling stock in the sixty-year history of the Railway Institute], Problemy Kolejnictwa 2011, zeszyt 153, s. 93–116.
4. EN 12663-2:2010 (PN-EN 12663-2:2010): Kolejnictwo – Wymagania konstrukcyjno-wytrzymałościowe dotyczące pudeł kolejowych pojazdów szynowych – Część 2: Wagony towarowe [Railway applications – Structural requirements of railway vehicle bodies – Part 2: Freight wagons].
5. Karta UIC 513: Guidelines for evaluating passenger comfort in relation to vibration in railway vehicles [UIC Leaflet 513: Guidelines for evaluating passenger comfort in relation to vibration in railway vehicles, Edition I, 1.07.1994], Wydanie I, 1.07.1994.
6. Karta UIC 518: Testing and approval of railway vehicles from the point of view of their dynamic behaviour – Safety – Track fatigue – Running behavior [UIC Leaflet 518: Testing and approval of railway vehicles from the point of view of their dynamic behaviour – Safety – Track fatigue – Running behavior], Wydanie IV, September 2009.
7. Karta UIC 577: Wagony towarowe – Obciążenia [UIC Leaflet 577: Rolling Stock – Wagon stresses], Wydanie V z 01.2012 r.

8. Massel A. et.al.: *Rola Okręgu Doświadczalnego Instytutu Kolejnictwa w badaniach taboru i infrastruktury kolejowej* [The role of the Railway Institute Experimental District in research on rolling stock and railway infrastructure[, Wydawnictwo Naukowe Instytutu Kolejnictwa, Warszawa, Żmigród, 2021.
9. Opis metod pomiaru sił na styku koło szyna stosowanych w CNTK [Description of the methods of measuring forces at the wheel-rail contact used in CNTK], Laboratorium Badań Taboru CNTK, Warszawa, marzec 2003.
10. PN-EN 12299:2009: Kolejnictwo – Komfort jazdy pasażerów – Pomiary i ocena [Railway applications – Ride comfort for passengers – Measurement and evaluation].
11. PN-EN 14363:2007 [EN 14363:2005 – IDT]: Kolejnictwo. Badania właściwości dynamicznych pojazdów szynowych przed dopuszczeniem do ruchu. Badania właściwości biegowych i próby stacjonarne [Railway applications – Testing for the acceptance of running characteristics of railway vehicles – Testing of running behaviour and stationary tests].
12. PN-EN 14363+A1:2019-02: Kolejnictwo – Badania i symulacje modelowe właściwości dynamicznych pojazdów szynowych przed dopuszczeniem do ruchu – Badania właściwości biegowych i próby stacjonarne [Railway applications – Testing and Simulation for the acceptance of running characteristics of railway vehicles – Running behaviour and stationary tests].
13. PN-EN ISO 3095:2013-12: Akustyka – Kolejnictwo – Pomiar hałasu emitowanego przez pojazdy szynowe [Acoustics – Railway applications – Measurement of noise emitted by railbound vehicles]..
14. Procedura badawcza PB-LW-S01: Pomiar poziomu naprężeń i odkształceń konstrukcji wagonu towarowego podczas zderzeń na Badawczej Górce Rozbiegowej [PB-LW-S01 test procedure: Measurement of strain and deformation levels of freight wagon body during collisions on the test run-up hill].
15. Raport ERRI B 12/RP 17: Wagony towarowe. Program badań wagonów towarowych z pudłem ze stali oraz program badań stalowych ram wózków [ERRI B 12/RP 17 report: Freight wagons. Test programme for freight wagons with a steel body and test programme for steel bogie frames]. Wyd. 8 z 01.04.1997.
16. Raport ORE B 55 Rp. 8 (Final Report): Prevention of derailment of goods wagons on distorted tracks. Conditions for negotiating track twists – Recommended values for track twist and cant; – Calculation and measurement of the relevant vehicle parameters, Vehicle testing, Utrecht, April, 1983.
17. Raport ORE B 55/RP 1/E: Prevention of derailment of goods wagons on distorted tracks. Wheel load measurements as a means for testing 2-axled goods wagons. Utrecht, October 1964.
18. Rozporządzenie Komisji (UE) nr 1302/2014 z dnia 18 listopada 2014 r. z póź. zmianami w sprawie technicznej interoperacyjności odnoszącej się do podsystemu „Tabor – lokomotywy i tabor pasażerski" systemu kolei w Unii Europejskiej [Commission Regulation (EU) no. 1302/2014 of 18 November 2014 on the technical specification for interoperability relating to the "rolling stock – locomotives and passenger rolling stock" subsystem of the rail system in the European Union, as amended].
19. Rozporządzenie Komisji (UE) nr 321/2013 z dnia 13 marca 2013 r. z późn. zmianami dotyczące technicznej specyfikacji interoperacyjności odnoszącej się do podsystemu „Tabor – wagony towarowe" systemu kolei w Unii Europejskiej i uchylające decyzję 2006/861/WE [Commission Regulation (EU) no. 321/2013 of 13 March 2013, as amended, concerning the technical specification for interoperability relating to the subsystem "rolling stock – freight wagons" of the rail system in the European Union and repealing Decision 2006/861/EC].
20. Rozporządzenie Ministra Infrastruktury i Rozwoju z dnia 13 maja 2014 r. w sprawie dopuszczania do eksploatacji określonych rodzajów budowli, urządzeń i pojazdów kolejowych [Regulation of the Minister of Infrastructure and Development of 13 May 2014 on admission to the operation of certain types of structures, devices and railway vehicles] (Dz.U. z dnia 30 maja 2014 r. poz. 720).
21. Sanecki H.: *Badania wytrzymałości zmęczeniowej w pojazdach szynowych* [Fatigue strength tests in rail vehicles], Seminarium Instytutu Kolejnictwa, Warszawa, 09.02.2016, http://www.ikolej.pl/seminaria-instytutu-kolejnictwa/ [available: 20.02.2025].
22. Skóra R., Kukulski J.: *Możliwości badawcze górki rozbiegowej Instytutu Kolejnictwa* [Test possibilites of the Railway Research Institute buffing stand], Prace Instytutu Kolejnictwa, 2018, z. 158.
23. Wysocki G., Zbieć A.: *Badania dynamiczne taboru kolejowego* [Dynamic testing of rolling stock], Przegląd komunikacyjny, 2017, nr 9, s. 2–6.