



Development trends in rail freight transport

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This paper presents issues related to the current development needs in rail cargo transport. These needs are mainly driven by market trends, and they are often enforced by competition on the freight market and the need to protect the environment and climate. Today's requirements are related to design changes in freight wagons as well as the stationary and operational research discussed in this paper. The design intentions described below can be treated as a test run prior to the launch of cross-border transport via dedicated corridors.

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1. Introduction

Modern rail cargo transport is under increasing pressure from tough market competition. In order to cope with it, it is necessary to implement new solutions that will increase the reliability and availability of such transport. The opportunities for rail freight transport increased when, in accordance with European Union directives, the rail infrastructure of European countries was made available for international traffic. In addition, the European Commission's guidelines in relation to climate targets – the European Green Deal – have been enforcing specific measures to be taken to decarbonise freight transport, which will benefit low-emission rail transport. The role of cross-border rail transport, particularly with regard to long-distance transport, has increased with the transfer of cargo from Asian destinations from sea transport. In technological terms, the so-called "corridors" of international importance through individual EU member states are being prepared, equipped with an electronic train protection system ETCS (European Train Control System) and electronic substations to further accelerate the average speed of freight transport.

2. Market trends in freight transport

2.1. Trends in freight transport in Poland

The transport of goods by rail in Poland recorded a decrease in the volume of transport related to the pandemic period, but it has been otherwise growing steadily since 2020. Both in terms of freight work and the weight of transported goods, carriers are recording increases in the share of transported goods, which is reflected in the statistics of the Railway Transport Office. Participation of freight transport on the territory of Poland is increasing its share in terms of both imports, exports, and internal transport (Fig. 1).

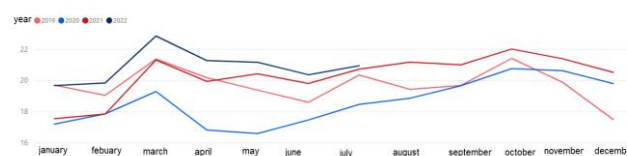


Fig. 1. The weight of goods transported by rail in 2019-2022 [1]

For many years, goods transported in bulk have accounted for the largest share of rail transport, with particular emphasis on the carriage of coal, lignite, liquefied gas and crude oil, accounting for 39% of the

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mass of cargo transported by rail [1]. The next group of goods are metal ores, mining and quarrying products, covering 24% of the mass of transported cargo with 14.63 million tonnes in Q1 2022. The third commodity group in terms of share of freight transport is non-identifiable products – transported, for example, in containers or swap trailers.

The share of intermodal transport in total freight transport in Poland is increasing year on year and in Q1 2022, it amounted to 10.55% of total transport by cargo weight. With regards to global crises – COVID-19, the climate crisis, or the aggression of the Russian Federation against Ukraine – intermodal transport is gaining in importance and the share of freight.

2.2. Challenges in transport caused by global crises

The trends evident in global supply chains can be classified in terms of three main flow disruptions that occurred between 2019 and 2022:

- the COVID-19 pandemic,
- the aggression of the Russian Federation against Ukraine,
- Climate crisis.

2.2.1. Transport problems related to the COVID-19 pandemic

The COVID-19 pandemic has significantly affected the flow of cargo from East Asia to Europe. Due to the congestion at Asian ports, lack of tonnage availability in sea freight, and the levelling off of transport rates, rail freight along the New Silk Road has gained in importance. The number of trains in 2021 increased by 20.9% from 12,406 in 2020, to a record high of around 15,000. However, the growth of intermodal train services on the China-Europe route has been accompanied by a number of problems that have increased with the demand for freight services. A significant problem corresponds to the infrastructural difficulties associated primarily with the need to tranship containers on the border of 1520 broad gauge lines and 1435 mm standard gauge lines. The need to tranship intermodal units requires suitably prepared infrastructure and transshipment facilities.

The transshipment of cargo units at the New Silk Road border also generates challenges in terms of the availability of sidings, side tracks, and securing rolling stock. Trains are travelling on the North Line of the New Silk Road through Russian territory, where the length of the trains is considerably longer than the permissible length of the trainsets on European standard gauge lines, which means that in addition to having to change the gauge of the wagons, it is necessary to tranship goods onto a larger number of trainsets than the number of trainsets passing through Russia.

Experts from the Eurasian Development Bank, already in 2018 in their report 'Silk Road transport corridors: analysis of barriers and recommendations for investment' [2] pointed out the existence of a significant constraint to the development of intercontinental transit, which is related to the length of container trains on the railways. According to EDB data, the restrictions on Eurasian transport in terms of permissible train lengths are due to the permissible lengths of trainsets on the lines:

- Russian ones – where the average train consists of 71 wagons and can reach a length of 994 m,
- Belarusian ones – where the train consists of 57 to 65 wagons and reaches a maximum of 910 m,
- Polish ones – where, according to technical regulations, the length of the train must not exceed 600 m.

Therefore, it has been calculated that trains leaving Małaszewicze station towards Poland contain a maximum of 43 wagons, carrying approximately 86 TEUs. Taking into account that a container train with the length of 65 wagons arrives in Poland, it is necessary to form one train of 43 wagons in Brest when handling wagons with containers, while containers from the remaining 22 wagons await the next train [3]. The result is the congestion at the transshipment points at the route border, due to the need to tranship and form several European trainsets from one "Asian" train. At the same time, such waiting time results in longer delivery times, an accumulation of intermodal units at the transshipment fronts and thus increased transport costs.

It is worth pointing out, however, that the transshipment of unified units such as intermodal units, despite the challenges to be faced at transshipment points, provides far fewer problems than the need to tranship conventional or specialised wagons from broad to normal track, as has been recognised in the context of the war in Ukraine.

2.2.2. Impact of the war in Ukraine

The war in Ukraine is affecting the operations of the European transport network, especially the one closest to Ukraine – the Polish transport network. The blockage of the Black Sea ports has resulted in the need to divert both the import cargo to Ukraine and the export cargo to other modes of transport, or to other ports – including Polish ports and the Polish transport network. Meanwhile, the handling of cargo diverted to Ukraine is associated with further supply problems, including mainly a shortage of means of transport and drivers. The blockade of Black Sea ports in the context of transporting bulk products such as

agricultural produce or metal ores has caused significant problems in the export capacity of Ukraine. It became necessary to transport large quantities of bulk products by road or rail.

On the border with Poland there are 6 road border crossings, and 4 rail border crossings, through which the cargo export from Ukraine can largely take place. In the case of bulk goods, to mention e.g., the Ukrainian export of 27.2 million metric tonnes of maize and 21.2 million metric tonnes of wheat in 2021, it is difficult to imagine transporting such a mass of cargo by truck overland. There is therefore a need to transport agricultural crops by rail to Polish ports, or further to the west of Europe.

The railway infrastructure at the border between Poland and Ukraine poses a significant problem in the logistics chain of bulk goods. In view of the increased transport needs, a huge congestion is being created at the railway border crossings, while, according to the Ministry of Agriculture and Rural Development, only up to 150 wagons per day were being cleared at the three railway border crossings at the peak of traffic in April 2022. Wagons waiting to enter Poland on the Ukrainian side were counted in thousands, and due to the difference in rail gauge and limited transshipment infrastructure resources, the transshipment process remains lengthy.

Before the outbreak of war, rail traffic in the Ukrainian border area had been limited and the route and terminal infrastructure had not been used as intensively as, for example, rail border crossings with Belarus. The border crossings, especially on the LHS line, were only just about to start developing intensively with the introduction of direct connections to Sławków as part of the New Silk Road. However, the LHS line has already been used in the transportation of iron ore from Ukraine and can easily benefit from the experience gained to date in both the transportation and handling of goods.

The market is looking for simple, ad hoc solutions using existing wagon and siding resources, and the answer to such a need may be the use of containerisation in the bulk supply chain. Such transport significantly improves the handling capacity of transport units and offers the possibility of using universal sub-container wagons, with any wheelbase, or truck transport. Until now, the containerisation of bulk cargo has been backed up by the limited availability of specialised wagons during the season; at the moment, an additional important argument is the ease of transshipment between modes of transport.

The global crises of recent years provide an opportunity for rail freight to continue to grow. The increase in the share of containerised freight is standardising transport, enabling different types of cargo to be

transported in unified units without the need for specialised wagons. However, it remains a challenge to standardise international transport in terms of the interoperability between the routes. Differing capacities in terms of trainset length, wheelbase or track load enforce the need for transshipment or are a barrier to the optimum use of cargo space. The freight market is looking for solutions and answers to these challenges, all the more so as zero-emission rail transport is one of the most promoted modes of transport in Europe.

3. Development trends in cargo transport

3.1. Extension of freight trainsets

In the past, many research projects have been carried out in Europe to increase the length of goods trains. The maximum length of a freight train, depending on the country on the European continent, currently varies between 700–835 m and in special cases it may reach even 1000 m [7, 10]. It should be noted that these attempts were aimed at increasing the length of goods trains on a regular basis. Incidental lengthening of freight trainsets has taken place in the global railway sector and so:

- the absolute world record holder is the BHP Run train; on June 21st, 2001, a record was set for the length of a freight trainset at 7353 km. The trainset was composed of 682 freight wagons, which were filled with a cargo of iron ore with a total weight of 99,734 tonnes and was hauled by eight General Electric AC 6000 CW locomotives with a power output of 6000 HP (4413 kW). The record was set on a 275 km-long railway line (from Port Hedland) located in Western Australia. In order to match the length of the entire trainset, as many as 612 Solaris Urbino 12 city buses would have to be lined up, and the Australians thus managed to break the previous record, which belonged to the Republic of South Africa,
- on the Sishen-Saldanha (South African) railway line, also known as the “Ore Export Line,” a trainset of 660 wagons with a total length of 7302 km was put together on 26 August 1989. As many as 16 locomotives were used to haul it: nine electric ones and seven diesel ones,
- The previous record belonged to the USSR, where a 6.5 km long train was put together in 1986. The 439 wagons carried coal with a total weight of 43,400 tonnes.

On March 7th, 2020, the longest train in the history of the Polish railway industry took to the route from

Katowice to Czarna Woda in Pomerania. The train consisted of a JT42CWRM/Class66 locomotive and 64 freight wagons. The entire trainset was 745 metres long and weighed over 4500 tonnes. The train set off on a 500-kilometre journey from Katowice Muchowiec Staszic station. The destination station was Czarna Woda in Pomerania. The 64 wagons carried coal. The freight was carried by Freightliner PL, a private rail operator in the UK, and Genesee&Wyoming Inc, the US co-owner of the rail freight company.

The increase in the length of freight trains is related to technical problems that need to be analysed, based on the results of controlled operational tests. While the regular operation of freight trains with a length of 835 metres was implemented on the Maschen line near Hamburg (DB Netz AG) and Padborg (Denmark, DSB – Danske Statsbaner SV (“Danish State Railways”), this was not extended to other DB Netz AG railway connections, on which the maximum train length of 740 metres continues to apply. Operation on the Maschen–Padborg line was limited to a maximum of 84 wagons, taking the shortest freight wagon (Ucs 908 double-axle wagon, released to service) as a basis [7]. The parameters of the Ucs 908 and Ucs 909 wagons was for the transport of cement, lime, sand, soda, and aluminium oxides, as well as foodstuffs such as sugar, flour, salt, and groats. The data for the Ucs 908 and Ucs 909 wagons with the shortest bases are given in Table 1.

Operational trials with trains of 1000 metres and 1500 metres are still underway. It must be taken into account that the implementation of longer lengths of

freight trains into commercial operation, according to §2 of the EBO regulations [15], requires proof or guarantee of safety at least to the same level as before the changes, i.e., with the existing lengths of trains in operation.

One important factor corresponds to the higher compressive and tensile forces that occur at the coupling axis. These forces (abbreviated as LZK-Längszugkräfte) can lead to fatigue cracks or temporary cracks resulting from exceeding the tensile strength limit R_m . Automatic couplings in service today have a strength of $R_m = 850$ kN, while couplings with reinforced construction have a limit strength of 1020 kN or 1350 kN.

The ad hoc tensile strength R_m of the screw coupling design and its components, is due, among other things, to the maximum tractive force developed by the locomotive.

If a four-axle locomotive e.g. 111 E is used, where the static load of the wheelset on the track $Q_0 = 200$ kN and a friction coefficient of $\mu = 0.35$, the following is obtained:

$$Z = \mu_0 \times 4Q_0 = 0.35 \times 4 \times 200 = 280 \text{ kN} \quad (1)$$

Obviously, a tractive force of 320 kN is achievable (stated in the locomotive's technical description) if a higher traction coefficient of $\mu = 0.4$ is applied, e.g. at start-up when sanding is initiated.

If a six-axle locomotive is used, e.g. ET22(201E), where the static load of the wheelset on the track $Q_0 = 200$ kN and a traction coefficient of $\mu = 0.35$, the following is obtained:

$$Z = \mu_0 \times 6Q_0 = 0.35 \times 6 \times 200 = 420 \text{ kN} \quad (2)$$

Table 1. Parameters of the Ucs 908 and Ucs 909 two-axle wagons according to the catalogue [28]

Freight wagon designation	Ucs 908			Ucs 909				
Number of tanks	2			2				
Internal diameter of the tank [mm]	3100			3100				
Load capacity [m ³]	27			27				
Number of wheelsets	2			2				
Vehicle base [mm]	5000			5000				
Length with buffers [mm]	8540			8560/9040				
Average unladen mass [kg]	11500			11600				
Load limits [t]	from 10,801 kg of unladen mass			from 11,600 kg of unladen mass				
		A	B	C		A	B	C
	S	21.1	25.1	29.1	S	20.9	24.9	28.9
	Up to 12,300 kg of unladen mass			Up to 12,300 kg of unladen mass				
		A	B	C		A	B	C
S	19.7	23.7	27.7	S	18.8	22.8	26.8	
Note to load limits	If the unladen mass of the wagon is greater by 100 kg, then the relevant load limit is reduced by 0.1 kg							
Special features of the wagon	Evacuation unit (max. operating pressure 2.5 bar, suction power 10 m ³ /min)							
	Release for international traffic only by agreement							

If an eight-axle locomotive is used, e.g. ET41(401E), where the static load of the wheelset on the track $Q_0 = 200$ kN and a traction coefficient of $\mu = 0.35$, the following is obtained:

$$Z = \mu_0 \times 8Q_0 = 0.35 \times 8 \times 200 = 560 \text{ kN} \quad (3)$$

The Q_0 values have been rounded up, they are actually derived from the unladen mass of the locomotive divided by the number of wheelsets.

As can be seen from the aforementioned calculations, the tractive effort of most Polish locomotives is less than the permissible force on the draw-hook. The traction coefficient $\mu = 0.35$ is the maximum value for the low-speed range. Its value decreases with increasing vehicle speed according to the hyperbolic relation.

If two ET22(201E) locomotives coupled together are used, the following starting force value is obtained:

$$Z = \mu_0 \times 12Q_0 = 0.35 \times 12 \times 200 = 840 \text{ kN} \quad (4)$$

Thus, as can be seen from the calculations, the total traction force is less than the maximum permissible tensile force of the draw-hook. Traction forces (including starting forces) belong to the dynamic tensile forces, increased values of which can lead to temporary cracks (cracks due to exceeding the maximum permissible static stress) and fatigue cracks (due to exceeding the tensile fatigue limit). For this reason, couplings are manufactured that can carry a higher tensile force of max. 1020 kN (1.2×850 kN) or relatively 1350 kN ($\sim 1.6 \times 850$ kN). Tensile forces are referred to in German literature as LZK (Längszugkräfte). Compressive forces in the longitudinal direction of the train are not very significant when running on a straight track, whereas their values increase significantly when running on track curves (especially in so-called S-shaped curves) and when braking the train (braking wave phenomenon), according to the European standard PN-EN 15839+A1:2015. According to theoretical and empirical analyses, the compressive force (during braking), measured at the coupling, increases linearly with the number of wagons in the train.

As it appears from theoretical and practical analyses, the following technical boundary conditions must be observed if trains of extended length are used:

- mastering dynamic longitudinal forces,
- reliable detection of overheated bearings (axle boxes),
- proving the suitability of the train protection system currently in use (PLZ-in German: PunktLinienZugbeeinflussung) or LZB (in German: LinienZugBeeinflussung),

- preventing barriers from opening at intersections of car and rail traffic,
- taking into account the increased loads acting on railway structures, e.g. railway bridges and tunnels, permanent buildings constructed along the railway line,
- maintaining the required braking distances,
- maintaining the required safety distances behind signal devices,
- the suitability of the overhead line,
- setting up operating rules to ensure safety for freight trains with greater lengths, i.e. 835 metres,
- the functional suitability of route protection when more than one short block section is occupied by a single train,
- the suitability of the current overhead line.

According to field tests carried out on the route, the resultant compressive force (referred to as LDK) at the inter-wagon coupling for a train with a non-uniform configuration (pulling wagons with different loading levels, i.e. such as e.g. empty, half-loaded, fully loaded ones) increases with the number of wagons and linearly with the length of the train. At the same time, this force is completely independent of the air brake of the train. According to simulation and empirical studies, the introduction of an electropneumatic brake may not provide the expected solution to the problem. The compression forces of the LDK increase to as much as 1000–1200 kN when there is a significant number of wagons, e.g. 100 in a freight train. Yet another problem that has arisen on the Podborg-Maschen route is that the correct operation of the LZB train protection system is limited to trains of 790 metres in length. Increasing the length of the train also means increasing the total braking force that has to be carried by the current railway surface. For a 1500-tonne freight train, the total braking force can already be around 6000 kN. This force can already pose a problem for the load-bearing capacity of long bridge structures.

3.2. Further opportunities to increase transport capacity

3.2.1. Increasing transport capacity by increasing the share of freight in the loaded condition

A further concept for increasing capacity is based, among other things, on the use of routes with loading and unloading centres in two destinations. This has the effect of eliminating the 50%:50% empty/loaded condition. The only 100% load condition is the loaded condition (also on return). Obviously, the implementation of such an objective requires investment in the railway infrastructure. According to modern assessment criteria, it is assumed that a trip in an empty

condition by a freight train to the destination station for the next cargo is not entirely efficient from the point of view of traction energy consumption. Afterwards, however, the same railway infrastructure is used more rationally. This way of transport definitely increases its efficiency and cost-effectiveness and contributes to a more rational use of energy for transport purposes. The expansion of logistics centres must be intermodal with the possibility of transshipment to other modes of transport (e.g. trucks, inland and seagoing vessels, cargo planes). It should be noted that such a powerful logistics centre on a European scale is Hamburg. It would seem that container transport (and its popularisation) is one of the proposed solutions that could increase the possibilities for reasonably efficient transshipment, although this time there should be a return to the concept of low-floor pocket wagons (the so-called "Taschenwagen"), which are designed to carry containers, swap tanks and semi-trailers.

3.2.2. Increasing the load capacity of the structure by increasing the permissible wheel-set load on the track

Yet another direction is to increase the capacity by raising the permissible static load of the wheelset in the vertical direction on the track, which is 25 tonnes. This means that the maximum gross weight of four-axle wagons would increase from 90 to 100 tonnes. This traffic is limited to 100 km/h when running fully loaded trains. Although the origins of this concept dates back to the second half of the 1990s, operation is now taking place on selected railway lines in some European countries that have been adapted to accommodate increased vehicle-track interaction forces, i.e. primarily maximum vertical and lateral forces.

The maximum vertical force Q_{MAX} , with which the wheel exerts load on the left or right rail, respectively, is according to the European standard EN 14363+A1:2019 E, P [21]:

$$Q_{MAX} = Q_0 + 90 = 125 + 90 = 215 \text{ kN} \quad (5)$$

where: Q_0 – is the maximum vertical static load of the wheel on the rail, 90 kN – is the value of the dynamic surplus that the wheel should carry.

The maximum lateral force Y_{MAX} , which loads a 2 m long track span according to the European standard EN 14363+A1:2019 E, P [21]:

$$Y_{MAX} = 0.85 (10 + 2/3 Q_0) = 0.85 \times (10 + 2/3 \times 125) = 79.33 \approx 80 \text{ kN} \quad (6)$$

The upgrading of the infrastructure to increase the permitted axle load of the wheelset to 25 tonnes (≈ 250 kN) can be seen as a logical step, especially as the speed of freight trains will be limited to 100 km/h

in the loaded condition and 120 km/h in the empty condition. By increasing the permissible vertical load, it is still possible to maintain the range of wheel rolling diameters $\phi 840\text{--}920$ mm according to UIC leaflet 510-2 [24]. Table 2 summarises the values of the maximum vertical forces Q_{MAX} and the lateral forces Y_{MAX} for the different track classes C, D and E.

Table 2. Values of vertical and lateral forces depending on track class C, D and E

Ref. no.	Track class	C	D	E
1	Force Q_0	100 kN	112.5 kN	125 kN
2	Force Q_{MAX}	190 kN	202.5 kN	215 kN
3	Force Y_{MAX}	65 kN	72 kN	80 kN

Of course, the above-mentioned criteria are to be considered as track-vehicle interaction forces. The same forces must be absorbed by the vehicle components, i.e. the wheel, wheelset, axle box, bogie frame, etc. The implementation of this issue, although regularised a long time ago, has found its way onto selected railway lines in Europe.

3.2.3. Construction of ultralight freight wagon structures

The construction of ultralight freight wagon designs can be regarded as a "signum temporis", and certainly as a major challenge, without which it is impossible to implement the fundamental objective of increasing freight efficiency. Excess unladen mass means reducing the load limits of wagons for the individual track classes A, B, C, D and E. It should be noted that the use of high-strength steel does not necessarily lead to the intended goal if one considers that the structure of, for example, bogie frames must transfer, in accordance with EN 13749:2021 [21]:

- maximum (otherwise known as extraordinary) static forces, occurring under extreme operating conditions,
- static forces occurring in normal operation,
- fatigue or dynamic forces, as a result of vehicle-track interaction during travel,
- forces of an impact nature (forces of a high magnitude, acting over a short period of time, e.g. when a vehicle travels over rail joints, junctions and track crossings),
- deflections that increase with decreasing cross-sectional areas, moments of inertia, etc.

As the weight of the wagon decreases, the natural frequencies of the vehicles decrease, which increases the risk of resonant vibrations in different directions (the critical speed of the freight wagon decreases). Particular attention should be paid to yawing vibrations and vertical vibrations [9]. It is also difficult to envisage that the structure will be executed according

to the "uniform strength beam" principle, as this leads to increased manufacturing costs. In addition, the wagon structure is a welded one (in American freight wagons, many important components, e.g. the wagon spur, are executed as a cast structure), and therefore a significant structural and technological notch, which reduces fatigue strength, comes from the technology used and the type of welded connection. This is not to question the fundamental objective of optimising unladen mass. However, it is a more complex problem, limited by boundary conditions such as manufacturing costs, the availability of specific sheet metals or profiles and objective technical issues. In recent years, the introduction of hybrid laser welding appears to be a major opportunity to increase the efficiency of welding technology and the quality of joints [8].

3.2.4. Maximum use of the permissible wagon outline

This problem has been signalled in earlier publications and has not lost its relevance [4, 5]. It seems that designing a wagon with a "safe outline", i.e. having a high safety margin in relation to the structure gauge, is certainly in a "strict sense" an inherently structurally correct action, but from the point of view of today's market requirements, it is not fully thought through and it leads to a reduction in the competitiveness of rail freight transport in relation to other modes of transport. The wagon designer should look for all the reserves resulting from the external and internal constriction formulae that limit the actual outline of the vehicle:

- reducing wheelset play by using the limits of "distance between active faces" of 1416 or 1418 mm instead of 1410 mm,
- reduction of the angle of the intrinsic asymmetry of the complete wagon below 1° , through more accurate manufacturing of the components, with reduction of the tolerance of susceptibility (stiffness) of the suspension (measured experimentally),
- very precise determination of sway poles and sway coefficients using the analytical method and their testing on manufactured wagons using the experimental method; this validation exercise leads to improved calculation and measurement methods,
- the use of shims to compensate for wheelset wear (in the kingpin-centre plate arrangement), etc.

The reduction of wheelset play requires the use of intermediate profiles, resulting from PN-EN 13715:2020 [19]. The aforementioned technical procedure guarantees the operation of rolling stock with the same equivalent conicity according to UIC leaflet 519 [26] and PN-EN 14363+A1:2019 E, P [21]. Accord-

ing to PN-EN 14363:2018 [21], the equivalent conicity value is dependent on the vehicle speed (100 km/h in loaded condition and 120 km/h in empty condition) and is 0.5 for freight wagons.

A more accurately constructed freight wagon can successfully have a larger outline and it is perfectly safe from the point of view of the applicable structure gauge. The current outline is the result of a very conservative approach to the regulations and does not take into account the current level of technology (both the manufacturing and acceptance one). Reducing the play of the wheelset in the track contributes to the preservation of dynamic properties, which are similar to the dynamic properties in the brand-new condition.

Obviously, an inspection of freight wagons (now and in the future) during operation must be foreseen. It seems that this inspection should primarily consist of measuring the vertical wheel loads on TENSAN type rail scales. Wheel loads in the vertical direction on the rail should be measured both in the empty condition and in the loaded condition of the wagon (in all loading conditions of the wagon). Asymmetries of the smallest possible value as well as the smallest possible loading asymmetry should be sought. The pressures in the vertical direction should be fairly uniform (the measurement should take place on a level part of the track, mounted on measuring scales). It seems necessary to determine the centre of mass and to control it during the design, manufacturing, and final inspection of the vehicle. Ensuring uniform vertical wheel loads on the rail is not only decisive for driving safety and the dynamic properties of the vehicle, but also for the reasonably uniform wear of the wheelsets. Since only monoblock wheels are envisaged for newly constructed wheelsets, the longer their service life, the longer the service life of the axle seat (axle seat of the wheelset).

3.2.5. Construction of maintenance-free freight wagons on the example of TBU bearings

The construction of new "smart" freight wagons is to be based on three objectives, which should be met in order to increase the competitiveness of freight carrying trains. These include the following criteria: maintenance-free operation, availability, and the reliability and driving safety of freight wagons [13, 14]. The reliability and availability of a freight wagon reach very high values, as expected by the operator, if all assemblies and their components achieve a high level of durability (service life), referred to by the term LCC (Life Cycle Costs). The introduction of maintenance-free nodes, such as the implementation of tapered roller bearing units (TBUs) $130 \times 240 \times 160$ mm, increasing the service life of wearing parts (Life Cycle Cost extension) all result in a reduction in

operating costs. The introduction of tapered roller bearing units (TBUs) appears to be necessary due to the requirement for simplified ultrasonic testing of wheelset axles on a complete wagon. TBU (Fig. 2) bearings were developed in the 1950s for American freight wagons and were made mandatory in the AAR (Association of American Railroads) regulations. This is, of course, one of many reasons for their introduction. The operation requires the removal of the front cover and the pressure ring in order to apply the test heads to the axle face to detect internal and possibly external defects in the axle of the wheelset. Then, there is the possibility of unintentional or measured loss of lubricant from the axle box and contamination of the lubricant. In addition, tapered roller bearings are more resistant to water ingress into the assembly. With TBUs, this possibility is practically eliminated.

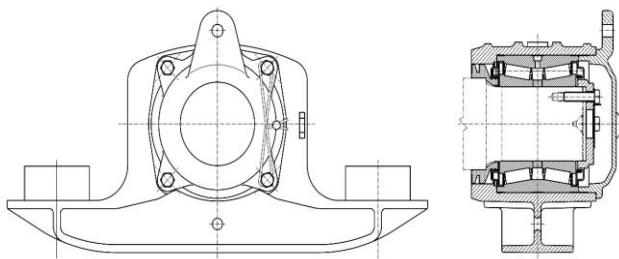


Fig. 2. TBUs arrangement (assembly) $130 \times 240 \times 160$ mm

The $130 \times 240 \times 160$ mm TBUs set is a solution that meets the requirements of maintenance-free operation, availability, and reliability. This set, together with a body made of ductile iron (demonstrating vibration damping capability, good flowing power, and diamagnetic properties) should, according to TSI regulations, meet the requirements of European standards PN-EN 12260:2021-02E [16], PN-EN 12261:2017 [17] and PN-EN 12262:2021 [18].

3.2.6. The concept of modernisation and additional equipment on a freight wagon

Another important concept is the gradual equipping of the GW 40 freight wagon [12] with new technology. The freight train has its own specifics, consisting of the possibility of forming trainsets of different freight wagons (non-homogeneous trains) or uniform trainsets (the so-called compact or homogeneous trains). The process of forming trainsets with shunting locomotives is nowadays increasingly seen by those involved in the railway industry as fulfilling its purpose, but generating traction and staff costs (the need to employ a driver to operate the shunting locomotive and the personnel who connect the wagons together by means of screw couplings). The work of persons disconnecting and coupling freight wagons is seen in Europe as hazardous to their life and health. The ar-

guments of the opposing side, representing the “status quo ante” approach applied so far about adequate training of such personnel (couplers) and an increase in overall safety in the railway sector are not very convincing and hinder the progress of research and development in this field. It was precisely the excessive number of accidents to workers in the USA during the work of forming freight trains that became the subject matter of an act making automatic couplings mandatory on North American railways (in the late 19th century). Paradoxically, the majority of freight wagons in service today have room to accommodate automatic couplings. The running gear systems of the Y25 family of standard bogies are designed so that a future automatic coupling can be fitted or removed (Fig. 3). The body frames of the freight wagons are designed to be able to transfer the longitudinal tensile and compressive forces in the central axis of the wagon, which are generated by the automatic coupling.

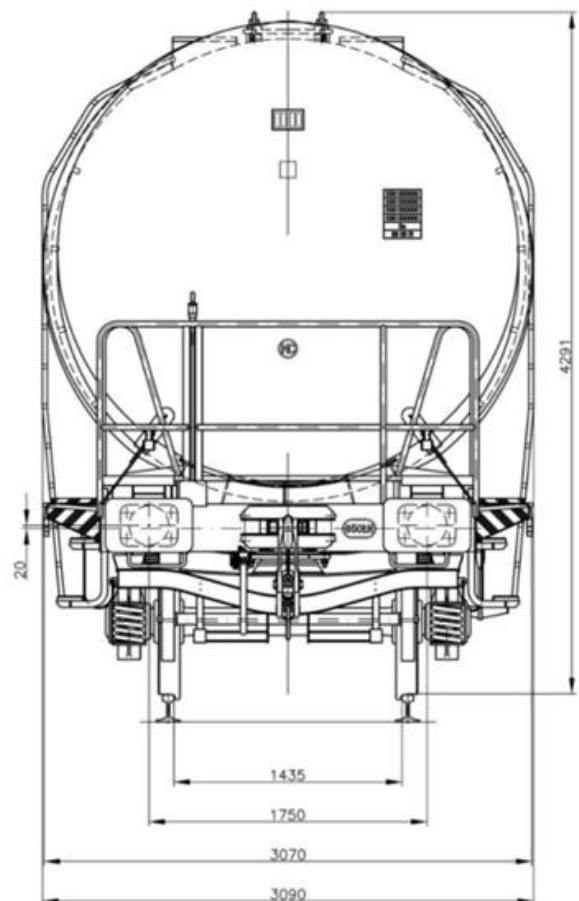


Fig. 3. View of a tank wagon with standard bogies of the Y25 family with the characteristic curve of their end face for mounting and dismounting the automatic coupling

If a standardised automatic coupling, as defined in the TSI provisions, were to be introduced, the modernisation of the entire freight wagon fleet, irrespective of type and including the wagons already in ser-

vice, would seem possible in the short term. It would be most rational to carry out such modernisation of freight wagons as part of a P4 or P5 level repair in accordance with the provisions contained in the Maintenance System Documentation (MSD).

A very important problem of today's rail cargo transport is the equipment with modern diagnostics devices:

- sensors for the continuous measurement of temperature, vibration level and rotational bearing speed in axle boxes,
- sensors for the measurement of the vibration parameters (amplitude, frequency) of the cargo,
- sensors for the measurement of the air pressure in the service line and in the brake cylinder (this allows the so-called air brake performance test to be carried out automatically before driving),
- derailment detectors in accordance with UIC leaflet 541-08 [27].

The signals from the individual sensors, installed on the wagon, must be “stored” in the on-board electronics box, which has a computer motherboard, a cell with charge controller as well as the required antennas for WLAN (the Wireless Local Area Network) and mobile connectivity.

The implementation of sensor devices may involve equipping the wagon with electrical power sources.

The source of electricity for individual wagons in a freight train can be as follows:

- electric batteries, installed on each wagon and recharged at substations, intermediate stations, and destination stations,
- fuel cells, installed on each rechargeable wagon as above,
- generators, which draw electricity from the rotary movement of the wheelset during operation and supply electricity to the energy batteries to power the sensors installed in the wagon,
- potentially the power transmitted by the locomotive as a source of current through a bundle of wires running alongside the train; coupling and uncoupling takes place automatically when an automatic coupling is introduced.

The current state of the art allows the same objective to be achieved in different implementation versions. The first allows the entire freight train to be controlled by the driver or independently of him/her, which is the case when using a derailment detector on freight wagons, especially tank wagons, intended for the transport of dangerous goods. The detectors are centrally located on both buffer beams of the wagon frame and if the acceleration value in the vertical direction of $7.5 \times g \approx 73.6 \text{ m/s}^2$ ($g = 9.81 \text{ m/s}^2$ – earth acceleration) is exceeded, an automatic train braking

is triggered, independent of the driver's actions [6]. In the first case, the train is stopped by applying the emergency brake (the derailment detector is connected to the main line). It is assumed here that the process of initiation and propagation of a vehicle derailment is accompanied by an increase in the acceleration of a freight wagon (vehicle) in the vertical direction. The second objective can be achieved using the GMS-R (Global System for Mobile Communication-Railway) Internet network. The signals from the sensors are transmitted to the on-board electronics box, which further transmits them via an antenna, e.g. to a railway control centre. Of course, the signals must be segregated (grouped), processed and evaluated in order to be useful for specific decision-making by competent persons. Currently, this information can be obtained on a smartphone, provided appropriate software has been developed to perform advanced signal processing in order to compare values to known criteria to aid the decision-making process.

When it comes to obtaining electricity from rotating wheelsets, some caution is required. In the case of passenger wagons with considerably higher mileages of up to 200,000 km per year and speeds of up to 200 km/h compared to freight wagons with a mileage range of 25,000–40,000 km per year (see UIC leaflet 510-1 [23]) and speeds of up to 100 km/h in loaded condition, this idea was implemented in the design of the running gear (the base of 2700–2800 mm according to UIC leaflet 515-0 [25]) of passenger wagons and was eventually superseded by static converters mounted on board of the passenger wagon. According to current operating experience, passenger wagons currently achieve an annual mileage of 44,000 km, tank wagons – 50,000 km and container wagons – 150,000 km [11]. One of the reasons for eliminating or abandoning the use of generators, which derive their energy from rotating wheelsets, was, among other things, their very high failure rate. The far advanced works on the development of compact batteries or fuel cells seems to be more promising here (if only to power the diagnostic sensors of the wagons). The introduction of electronic automatic couplings and the possibility of supplying freight wagons with electricity from an electric or diesel-electric locomotive can be considered to be yet another innovative solution. However, this solution has a certain drawback, as it deprives the freight wagon of its autonomous drive, allowing shunting and marshalling to be carried out in an autonomous manner (based on the autonomous drive) without the involvement of shunting locomotives. An important constraint on shunting operations is the limitation of the shunting speed of freight wagons to 12 km/h (and even 6 km/h for some types of freight wagons). The maximum shunting

speed criterion must be respected regardless of how the goods train is formed. The use of sensors and derailment detectors in this dimension is primarily preventive in nature, i.e. to prevent rail accidents and their consequences. Upon detecting, for example, overheated rolling bearings in an axle box node or vibrations with excessive values (average values, amplitudes), a decision can be taken, for example, to reduce the speed of the freight train or stop the train altogether and exclude/remove the wagon(s) with these symptoms from the train. Increasing the annual mileage of freight wagons contributes to the profitability of rolling stock and is a general trend in the railway sector. High-speed long-distance passenger transport (500,000 km–1000,000 km per year) is the most successful in this respect. Such mileages can be achieved with compact trains running only in the loaded condition between logistics centres. Hence the need to invest in extended logistics centres, allowing for the integration of two or more modes of transport.

4. Modernisation of freight wagons and freight transport – summary

The modernization of freight wagons, which includes the installation of additional equipment in terms of sensors, derailment detectors, TBU bearings, as well as automatic couplings, must comply with the principles of maintenance or compliance with:

- UIC (International Union of Railways) regulations and TSI Technical Specification for Interoperability regulations,
- the reference profile of the kinematic vehicle gauge, which must not be exceeded by the structural outline of the wagon or any part of the wagon under any actual, however standard, operating condition,
- the ability to operate without interruption in the required range of ambient temperatures and adverse weather conditions,
- compactness (density) of the development,
- interchangeability with existing solutions,
- relatively low unladen weight,
- the availability for manual assembly and disassembly in case of need for repair or overhaul at levels P1–P5,
- collision-free operation with other components installed on the wagon during different operating conditions,
- the possibility of an easy inspection (including visual one) of the technical condition by authorised persons at train clearance,
- easy integration (compatibility) with the existing systems and subsystems (see: connection of the derailment detector to the main brake line),
- interoperability with existing diagnostic equipment installed on the wagon and on the railway infrastructure,
- compatibility with railway infrastructure equipment in the railway traffic control,
- relatively low manufacturing and construction costs,
- environmental protection in a number of areas, e.g. protection of the environment against excessive noise emissions while driving (in the case of traction vehicles also while stationary), emissions of pollutants and compliance with recycling rules.

This last aspect, taking into account the economics of the issue, is particularly important. It should be taken into account that the high price of manufacturing and possible installation has inhibited the series production of very interesting solutions.

Attention is drawn to the fact that, for example, the installation of a derailment detector including manufacturing costs is estimated at around EUR 1500–1700 per freight wagon (the estimated costs specified in the year 2000). However, if rail freight transport is to meet the expectations of the future freight market, then investment in rolling stock is needed to increase its transport capacity. As the experience of many European carriers shows, the opposite is often the case, i.e. solutions are sought that are very cheap; they have nothing to do with technical innovation, are aimed at maintaining the already existing technical state of repair and do not provide any increase in driving safety at all. Repairs to freight wagons at P4 and P5 level are an opportunity to modernise the rolling stock in service. On the other hand, the installation of extensive diagnostics in the freight wagon enables future repairs to be carried out immediately after a fault has occurred, known as on-time repairs, which is a significant improvement on the term repairs, which are dependent on the mileage or years of operation. A much more modern form of freight wagon repair is the predictive repair (repair carried out on the basis of well-founded cause-and-effect knowledge, based on the assumption that a given defect or fault will occur with high probability at a given time). However, the implementation of such 'smart repairs' is not possible without the installation of diagnostic sensors beforehand, which would provide knowledge of when such repairs should be carried out.

The issue of increasing the regular operation of freight trains of a longer length than has been the case to date still needs time, although it should be borne in mind that these decisions must be supported by posi-

tive operating experience (preferably regular commercial operation) on e.g. the selected railway line(s), risk analyses, computer simulations, drawn up by expert working groups, etc., as well as by a number of other factors. Sporadic (often one-off) undertakings in this area, successfully completed, can be regarded as an auxiliary argument, but cannot be considered as

a basis for amending e.g. national or foreign regulations, such as e.g. TSI. A separate technical issue is the problem of the positioning of the train along the route (freight wagon in the trainset, cargo) by the GPS, Galileo or GLONASS navigation system.

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