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New technologies in railway transport

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The development trends of technical solutions in rolling stock and railway infrastructure have traditionally been shaped by various regulations, guidelines, and research programs both within the EU and globally. Within the European Union, a kind of roadmap has been defined for research and development activities, identifying specific smart specializations for each financial framework period. This paper discusses industrial development prospects, among others in relation to production processes. It emphasizes the evolution of component design in rail vehicle manufacturing, which brings notable advantages in terms of both production efficiency (through simplified manufacturing technologies) and the processes of operation and maintenance. Moreover, the study outlines selected trends observed in railway infrastructure.

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1. Introduction

At the beginning it should be noted that trends in the development of technical solutions in rolling stock and railway infrastructure are traditionally dependent on a number of regulations, guidelines, and research programs in the EU and globally. Given the dynamically changing geopolitics and global economic situation, the European Union's new industry strategy, the Clean Industrial Deal, has been in force in February 2025 [6]. The Clean Industrial Deal is intended to be a roadmap for changes in EU regulations for 2025–2026. This represents a shift in certain priorities outlined in the earlier strategic document, the European Green Deal [5].

First, a more detailed action plan was presented for the automotive sector (which has been plagued by significant market volatility), followed by an action plan for other key sectors, such as steel, chemicals, and clean technologies. The European Commission is therefore focusing on improving the economic situation. It has established a budget of over €100 billion for this purpose. The Industrial Decarbonization Bank, among others, will coordinate the actions. This entire EU policy has a significant impact on rail transport, which is increasingly implementing new technologies for sustainable development and improved efficiency.

For safety reasons, the railway industry is particularly subject to legislative requirements. Therefore, the relevant standards are constantly updated. The basic requirements include technical specifications for interoperability (TSIs). Supervision is carried out by the European Railway Agency and individual national railway safety authorities. Among the issues and areas of approval that have become more important in recent years are: non-flammability of materials used, reduction of environmental impact (noise), cybersecurity, and vehicle accessibility for people with reduced mobility.

In the context of rail vehicle construction and operation, digitalization, or more precisely, the aforementioned cybersecurity, is gaining particular importance. The requirements of the NIS2 directive are fundamental in modern rolling stock design offices [8].

The prospects for industry development in the coming years were included, among others, in last year's Deloitte report "2024 Manufacturing Outlook. Prospects in production", which highlighted 5 main trends [15]: Smart factory (IIoT) – a journey towards the industrial metaverse; Digitalization of the supply

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chain; Electrification and decarbonization of production and products; Modern technologies in after-sales service; Integrated planning.

According to the Capgemini "TechnoVision" report, the 5 most important trends worth watching in 2025 are [14]: Artificial intelligence, including generative AI (Gen AI); cybersecurity; AI-based automation and robotics; nuclear energy; next-generation supply chains.

2. Investment conditions

As observed in Poland, the pace of investments is not very high. According to the report of Bank Gospodarstwa Krajowego (BGK) and the Polish Economic Institute (PIE) from December 2025, the main barriers include, among others: low propensity to invest and limited access to capital [13]. Companies generally invest from their own funds (sometimes saved for years), but they do not want to take greater risks related to loans or venture capital funds. This is not surprising due to the high costs of financing and real rates of return on investment.

One of the key conclusions of the report is the role of automation in industry. Investments in robotics are key to maintaining production and export competitiveness in the face of an aging society and rising wages [13]. However, although investment processes sometimes progress slowly, the development of production processes in the railway sector is noticeable (chapter 3 discusses the technologies and technical solutions most developed in recent years).

This is due to the need to ensure a quick delivery of rolling stock in the light of numerous orders placed by carriers and transport organizers [22]. This pace, in turn, is dictated by very large increases in passenger flows. In 2025, further records were broken in Poland in agglomeration and long-distance transport [7].

3. Modern support for the production of rolling stock

3.1. Laser welding

In recent years, several areas of intensive technological progress have emerged in the production and modernization of transportation vehicles. One of these is laser welding of rail vehicle bodies (both steel and aluminum). This type of bonding processes has recently gained popularity. This applies both to manual (welding sources only) and robotic applications (Fig. 1).

This is a highly efficient technology with a number of advantages in production (process changes). The main ones include (relative to manual welding) [24]:

- Switching from MAG welding to laser welding
- Using a filler metal in the form of wire
- Eliminating the use of gas shielding (cost optimization)
- Building a laser welding station (increasing competitiveness, repeatability, and competence)
- Transporting the station using special (autonomous) trolleys
- Changing the organization of workpieces (repeatable preparation process)
- Building new team competencies.

Fig. 1. Laser welding of a steel side wall of rail vehicle [24]

It should be mentioned that a popular solution are extruded aluminum panels several meters wide, intended for the construction of vehicles with aluminum bodies. Renowned European manufacturers, such as the Spanish CAF, already effectively use this type of components imported from China. Instead of connecting several strips of panels intended for side walls (large gate devices with efficient welding sources) as before, only window openings are made and then the finished wall is welded to the frame, roof and front wall. Classic 3-piece panels have been successfully used by key global manufacturers such as Alstom, Siemens, Skoda and Stadler.

3.2. Reverse engineering

Reverse engineering and 3D scanning are also becoming commonplace. During vehicle inspections and modernization, fast, accurate structural measurements are essential. Bogie frames, in particular, require top-notch metrology and the ability for assemblers and measurement operators to work in parallel (Fig. 2). The equipment meets accuracy and repeatability requirements, is insensitive to complex surfaces, and allows for flexible production work. During P4/P5 inspections, the scanner supports structural inspection of rail vehicles, paving the way for efficient reverse engineering and rapid prototyping.

The main application areas of reverse engineering include:

- Quality and conformity control, comparison of 3D scans with CAD models

– Post-accident analysis and wear diagnostics, scanning deformed elements, comparison with nominal geometry (Fig. 2)
– Interior design, for example ergonomic modernization of driver's cabs in accordance with TSI regulations
– Digital documentation and "digital twin" (creating digital twins of vehicles, infrastructure), integration of scans with CAD (Computer Aided Design), FEM (Finite Element Method) or dynamic simulations.

In the latter case, at least Siemens Mobility uses digital twins to create virtual replicas of rail infrastructure (including tracks, signalling, and electrification) combining IoT asset data with Building Information Modelling (BIM). This technology enables simulation, predictive maintenance, and optimized planning, improving system availability and reducing costs across the asset lifecycle.

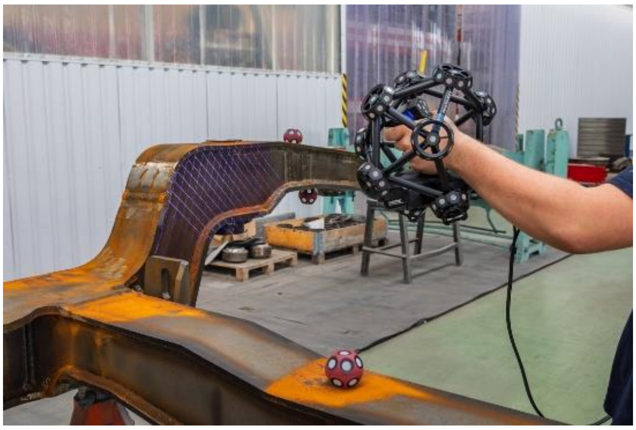


Fig. 2. 3D scanning of rail vehicles boogie – verification of dimensional accuracy [19]

3.3. Assembly work automatisation

The first stage on the way to improving the vehicle assembly process are adapted work platforms with the necessary equipment to increase their functionality (Fig. 3). This equipment includes: balancers to relieve the physical workload of employees, booms for installing doors and windows, loading elevators for delivered large components, control automation, etc.

Assembly work during rail vehicle production and maintenance at rolling stock maintenance facilities require also other efficient workshop infrastructure. An example of such flexible solutions is the system from the German company SIEMPELKAMP Transport Systems GmbH (formerly Strothmann) [10].

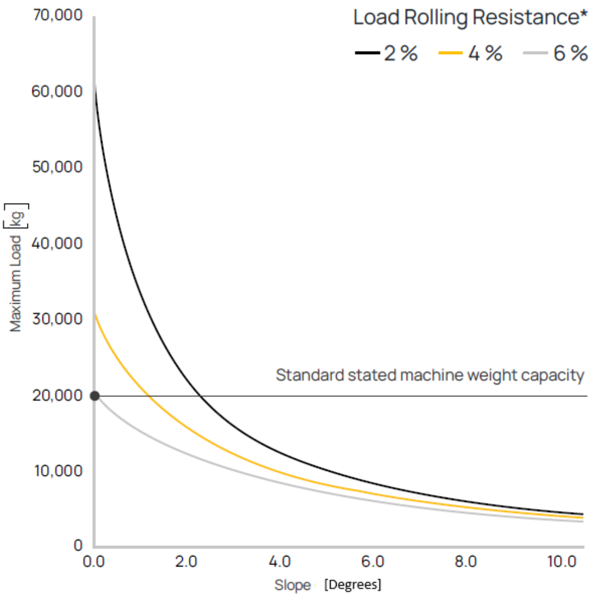
These modern technological trolleys allow for the rapid transport of vehicle bodies (Fig. 4). They also ensure excellent ergonomics and occupational safety for operators and other production workers.

Fig. 3. The first stage of installation of specialized assembly platforms [24]

Fig. 4. Platforms for moving rail vehicle structures (transport position) [11, 24]

Fig. 5. Ergonomic electric tug for shunting work [20]

Ergonomic and efficient, in terms of propulsion/traction, specialized electric tugboats are essential equipment for the stands (Fig. 5). Electric tugs and pushers enable rolling stock manufacturers and service providers to move heavy loads freely. Regardless of whether it is about moving trolleys and boxes in the final production process – assembling elements, or transporting them, e.g. for shot-blasting or painting in the plant.



* variables that affect rolling resistance include the quality of floor/terrain and the type/condition/quality of castor wheels

Fig. 6. Ergonomic electric tug for shunting work [20]

Table 1. The main technical parameters of TOW2000 ES – battery powered electric tow tug [20]

Parameter	Value
Maximum load (on castors | on rails)	20,000 kg | 80,000 kg
Maximum force (push | pull)	7845 N | 11,768 N
Machine weight	1711 kg
Battery weight (standard)	215 kg
Combined machine & battery weight (standard)	1926 kg
Drive type	Electric
Braking	Regenerative
Parking brake	Electromagnetic
Drive wheel type	Solid rubber
Castor wheel type	Non marking vulcanized elastic
Drive wheel diameter	350 mm
Point loading	Drive wheel 0.080 kg/mm²; 0.74 N/mm² Castor 0.083 kg/mm²; 0.81 N/mm²
Drive motor power	2 × 2 kW
Standard machine speed	2.0 km/h
Hare mode speed (With two speed selector switch)	3.0 km/h
Tortoise mode speed (With two speed selector switch)	1.2 km/h
Maximum slope	8º
Voltage	24 V
Noise level	Motor ≤80 dBA | Flashing light ≤ 85 dBA | Horn ≤ 112 dBA

In the case of slope performance the force required to move a load is based on load weight, slope angle and floor condition. Movement on a slope increases the force required to safely start, stop and move the load (Fig. 6). Therefore, the designs of this type of shunting devices are well-thought-out and have appropriate traction parameters, such as the example presented in the Table 1.

It's worth noting that projects involving the implementation of modern production solutions are becoming increasingly demanding. Clients expect contractors to provide comprehensive technological lines, including comprehensive preparatory work – construction, design (individual stations), and assembly, along with training.

3.4. Additive technologies and 3D printing

In many cases, the additive technologies can result in big advantages. Especially for low production volumes. Among such branches are aviation and railway industry. According to the literature, the additive manufacturing (AM) finds several applications in railway rolling stock sector, such as: replacement of spare parts, reparation of components and development of new designs or use of new materials with higher strength. In the case of spare parts, the main argumentation is to avoid the downtimes, especially when the parts are no more available on the market. In some cases the producers report also reduction in costs up to 80–90% [4]. The range of parts produced by AM of production is very broad, from the smallest and simple parts, like tablet holders, box shells, extinguisher covers through tram seat frames or front end covers for rolling stock (Fig. 7) up to gearbox housings, which weight even 540 kg [1, 4, 16, 21].

Fig. 7. Front-end parts of a tram produced by AM [1, 4]

In case of tram seats, the cost benefit was reported on a level of 90%, where the producer stated that taking into account the AM methods and optimizing the production process, can result in reduction of manufacturing and assembling process duration up to five times [23].

In rolling stock maintenance also very important issue is reparation of worn parts. That situation occurs especially when a surface of rolling elements, like wheel-set, gear seat, etc. is damaged. To avoid replacement of mentioned large and expensive elements, there can be adopted an additive technology – laser cladding [4, 18]. This technology can be adopted to repair surface damage locally by melting the original material and additional material in form of hot wire. As an example, the laser cladding can be used to repair locally the railway axle segment (Fig. 8).

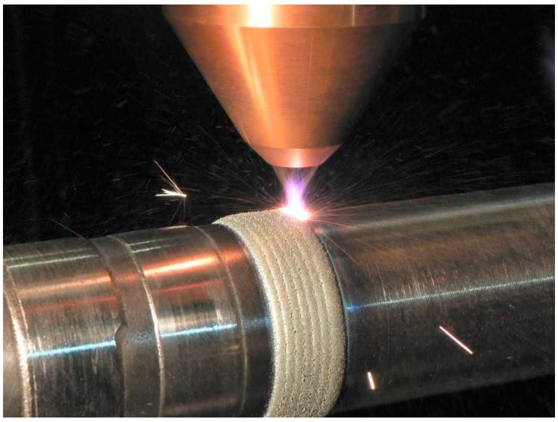


Fig. 8. Laser cladding of railway axle [4, 28]

An innovative technology is TIG 3D additive high performance welding with 3 wires, which enables printing and cladding of different materials. In cladding it is possible to obtain very good quality of material form metallurgic point of view. Additionally, cladding is technology which can be very precise and free of spatters, which enables minimum postprocessing work time. Additional advantage of TIG 3D (with 3 wires) method is high deposition rate, which reach values up to 10 kg/h with hot wire and vary between 1.6–3.3 kg/h with cold wire [25]. That is more than in traditional TIG with one wire, which enables deposition rates on a level of 1.2 kg/h (cold wire) and up to 5 kg/g (hot wire) [25]. That difference brings advantages in efficiency. Some other AM methods brings a lot of flexibility in case of materials and type of cladding geometry spot. For example in Laser Directed Energy Deposition (LDED) from Oscar the additive material can be feed as a wire (cold or hot) or powder and also enables different spot geometry, which can be adjusted by switching a different number of laser beams (Fig. 9) [26]. That possibility enables to adjust the shape of material spot during AM processes.

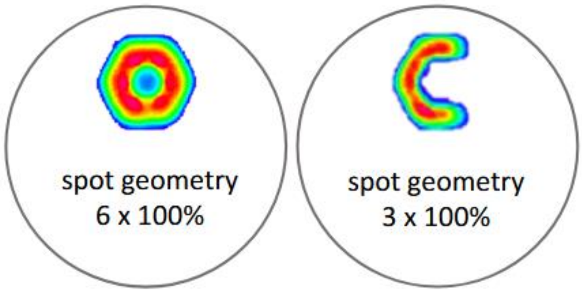


Fig. 9. Flexible spot geometry in LDED Profocus technology [26]

Sector, where AM brings the biggest gains in time reduction is prototyping and development of new designs. In traditional way, a new design will be obtained by hand crafting or firstly there should be designed and machined a mold when for example a molding molding process is used. Also in maintenance, where for example, the rail vehicle operator does not have documentation of part, the shape can be scanned with 3D scanner refined by rapid prototyping (RP) methods and produced with AM processes (Fig. 10) [3, 27].

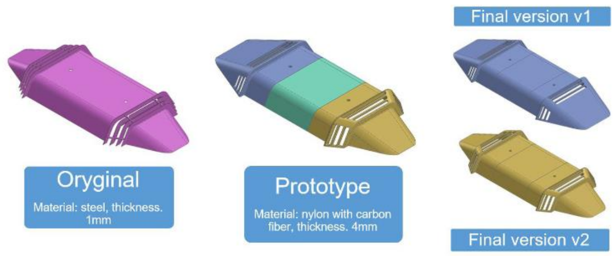


Fig. 10. Rail vehicle vent in different versions after RP processes [3]

The additive technologies can be used in standard manufacturing process and also as a solution for "just in time" deliveries to fix unplanned failure. According to [17], using the 3D printing enable to minimize downtimes and thus it helps to minimize the loss of revenue for rail operators. Some rail operators use the additive technologies from some time, like Deutsche Bahn, which reported to produce more than 200,000 3D-printed parts between 2015 and 2025. Over that period, DB reported also EUR 20 million savings, which result from that innovative technology in spare parts production [21]. Also Spanish tram producer CAF reports an advantage of 3D printing of rolling stock parts, because it allow not to be dependent from different molds for every part and gives more flexibility to the production process [1].

From a point of view of railway operator, the additive technology of 3D print is especially useful to produce parts which are no more available on the market and is still needed in maintenance the rolling stock [16]. Problem of parts availability can result from rolling stock durability which basically is 25–35 year and by proper maintenance and repairs it can be extended up to 45–50 years [2].

The 3D printing can be adopted for different materials from simply plastic used in holders, racks, etc. to materials used in rail vehicles construction, which consists of metal. It should be noted that in railway industry, the materials must meet the rail standard EN45545-2 and such materials are also available for 3D printing [17].

It should be mentioned, that AM methods have several disadvantages, like: high initial cost of 3D printer or another AM technology, slow processing (important in large scale production – e.g. automotive industry), emission of harmful components when the material is for example plastic.

4. Selected digital solutions in vehicle and infrastructure operation

4.1. Digital maintenance management systems

According to the Office of Rail Transport in Poland: the maintenance management system (MMS) includes a set of procedures and instructions aimed at minimizing the risk associated with maintaining a railway vehicle and, as a result, ensuring that the maintained vehicles are able to move safely on the railway network [12].

To improve the efficiency of rail vehicle maintenance processes (ECM certificates – Entity in Charge of Maintenance), specialized software (based on database systems) has been used. There are both tailor-made solutions (depending on the specifics of the vehicle fleet) and so-called "out-of-the-box" solutions (without the ability to modify the software or its functionality).

For example zedas®asset is the standard solution for the asset, fleet and maintenance management of rail vehicles. The EAM (Enterprise Asset Management) integrates all actors into one system and digitally maps all typical maintenance processes: planning (material, personnel, equipment), performance, management and controlling (Fig. 11).

The verification according to the Implementing Regulation (EU) 2019/779 is done automatically with zedas®asset ECM. The performing personnel, used materials and resources, the required time and measured values are documented in an audit-proof manner as part of the order processing. Personnel and equipment are managed directly in the system. The validity of qualifications and certificates can be monitored [29].

In summary, the system should ensure that vehicles are maintained in accordance with the vehicle's maintenance documentation and the guidelines and provisions arising from applicable regulations, including the TSIs. All entities responsible for maintenance are obligated to develop and implement a maintenance management system.

Fig. 11. Data range of computerized MMS [29]

4.2. Robotization of infrastructure maintenance

The railway infrastructure is mainly: superstructure (tracks, points), catenaries/overhead lines, trades of the control and safety technology (signals/signaling systems, level crossings), installations for traction current supply, buffer blocks, stops.

Robot-assisted, automated maintenance and repairs enables to extend mainly the service life of tracks (Fig. 12).

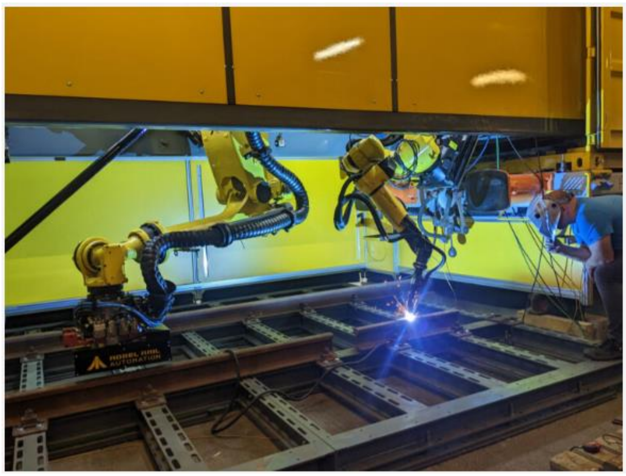


Fig. 12. Example of robotic rail head surfacing process [9]

The main advantages given by the creators of this system are [9]: less staff, reproducible results, shorter closure times. The local defect repair process means above all: fully automated, robot-assisted process (end-to-end); container as payload on standard container wagons; hybrid energy supply with battery storage; full digital documentation of processes and operating parameters; only 1 operator engagement. The typical technological processes are: scanning, milling, preheating, welding, grinding. Welding of R260Mn rails according to ISO15594 and RLN00451-2 is provided [9].

5. Summary

The technological transformation in companies producing rail vehicles is progressing. This applies to both strictly manufacturing companies (components and entire vehicles) and maintenance companies.

Mentioned technologies for rail vehicles manufacturing or their components help to gain the efficiency for the manufacturing companies. Additionally, the modern technologies, like AM help to minimize the production costs. The cost effectiveness in AM results mainly from the costs associated with traditional production methods (e.g. mold design and production). The AM methods are very helpful for spare parts production, especially for old vehicles, which are no more supported with spare parts by manufacturer or part supplier. This approach also aligns with a just-in-time strategy, eliminating the need for a spare parts warehouse. Also the described methods allow to avoid the need of new spare part production by cladding new material to the old part locally and thus extending the life of some parts. That assumption brings multi criteria benefits: environmental, energetic and cost reduction.

Additional advantages of additive methods include the dimensional range of the produced parts, but also the variety of materials from which the parts are made. Using AM methods, it is possible to produce plastic parts (such as body panels), but also metal parts of the drive system or frame. It should be emphasized that these methods also have several disadvantages, such as investment costs, slow production (important in large-scale production) and emission of harmful components during 3D printing.

The actual production trend for different technologies is automation of processes. Process automation, compared to manual work, allows for a number of advantages, such as repeatability, increased efficiency and minimizing the human factor, which is often the source of errors. For big scale production, the automation very often leads to time and money savings. The railway manufacturers have already implemented some process automation, but there is still space for improvements.

Nomenclature

AM	additive manufacturing
BGK	Bank Gospodarstwa Krajowego
BIM	building information modelling
CAD	computer aided design
EAM	enterprise asset management
ECM	entity in charge of maintenance
FEM	finite element method
IoT	internet of things
MAG	metal active gas
MMS	maintenance management system
PIE	Polish Economic Institute
RP	rapid prototyping
TIG	tungsten inert gas
TSI	Technical Specifications for Interoperability
UTK	Urząd Transportu Kolejowego

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