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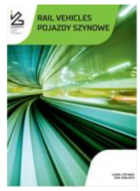

Characteristics of selected running gear design solutions that affect the traction performance of freight locomotives

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This paper presents an analysis of selected design solutions for the running gear of freight locomotives and their impact on the vehicles' traction characteristics. The first part discusses the basic concepts related to traction properties, including the relationships derived from the train motion equation and the traction characteristics. Next, the design of freight locomotives and their operating conditions were described. The main section of this paper reviews the design solutions used in the running gear of modern locomotives in operation on the European market, including suspension systems, wheelset guidance, and the transmission of traction forces and torques. Their importance in ensuring adequate traction performance, driving safety, and the structural durability of the vehicle was highlighted.

1. Introduction

Locomotives are traction vehicles designed to haul passenger and freight cars. They perform their function by pulling or pushing a vehicle or group of vehicles that, by design, lack their own power source. These vehicles are currently essential to the smooth operation of passenger and freight transport.

The use of locomotives in passenger transport has declined in recent years due to changes in carriers' rolling stock policies and the adoption of other types of rolling stock; however, they remain among the most commonly used traction vehicles in passenger transport. Despite the many advantages of multiple-unit trains and articulated trains, only locomotive-hauled train sets offer the significant flexibility needed to adapt a train's configuration to temporary changes in passenger demand. According to data from the Central Statistical Office (GUS), the total number of electric and diesel locomotives of various types stood at 3500 units at the end of 2024 [7, 18].

When it comes to freight transport, locomotives are essentially the only type of traction vehicle capable of providing comprehensive service for freight trains. Current trends in the development of rail freight transport do not suggest that any significant changes are likely to occur in this area in the long term. It goes without saying that the operating conditions for freight and passenger transport differ significantly. This means that the capabilities of the locomotives must be adapted to the specific nature of the tasks at hand. This additional classification of mainline vehicles divides them, based on their intended use, into those designed to haul passenger trains and/or freight trains. Adaptation to the operation of a specific type of train is primarily due to the design features of the vehicle's control and power systems, as well as its running gear. This, in turn, affects the locomotive's basic characteristics, such as weight, maximum speed, and tractive force (effort) [19].

2. Traction characteristics of locomotives

Traction characteristics refer to a set of features and indicators describing a train's ability to generate and transmit traction force from the wheels to the rail, and to overcome resistance to motion under specific operating conditions, which vary depending on factors

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such as the route layout and profile, the speed achieved, the mass of the train being hauled, and the variable adhesion of the wheel sets to the track. In the classical sense, traction characteristics must be considered in close connection with the train's equation of motion and the traction characteristics of the traction vehicle in question, as only this approach allows for a comprehensive description of the train's motion as a system moving along the railway track. One form of the equation of motion in question is the relationship given by equation [8, 10]:

$$m \cdot \frac{dv}{dt} = F_t(v) - W(v, s) \quad (1)$$

where: m – train mass, $F_t(v)$ – the vehicle's tractive force (effort), W(v,s) – total rolling resistance depending on the driving speed v and road conditions s.

Each component of the above equation may vary in level of detail, depending, among other things, on the nature of the analyses conducted. For example, when considering the effect of rotating masses, the train's mass m must be expressed in terms of the so-called equivalent mass m_z according to equations [8–10]:

$$m_z = m(1 + \delta) \quad (2)$$

where: δ – the mass coefficient of rotating parts, ranging from 0.05 to 0.15 depending on the design of the vehicles in question.

The key element linking the equation of motion to a vehicle's traction characteristics is the so-called traction curve, defined as the relationship between the tractive force (effort) generated by the vehicle and its speed. This relationship is also represented graphically, and this graphical representation is considered one of the fundamental tools for the overall assessment of traction characteristics [1, 10, 12, 16, 17, 20].

A vehicle's traction characteristics are typically determined based on certain assumptions, including, among others:

– vehicle operation with a constant power P [kW] allocated for traction purposes
– uniform and constant distribution of the Q [kN] loads on individual wheels and wheel sets while driving under load
– the assumed variation in the wheel-rail adhesion coefficient as a function of vehicle speed.

Issues related to load distribution, the coefficient of adhesion, and the force of adhesion are directly relevant to the subject of this paper and will be discussed in greater detail in the following sections. The requirement for a constant power output for traction purposes leads to the simplifying assumption that the vehicle generates a constant power output P [kW] across the entire range of operating speeds. The equation for determining the traction force $F_t(v)$ is shown below [16]:

$$F_t(v) = \frac{P}{v} [kN] \quad (3)$$

where: P [kW] – vehicle power for traction purposes, v [m/s] – vehicle speed.

The relationship given by Eq. (3), when plotted on a graph, takes the form of a hyperbola, whose values asymptotically approach zero as the speed increases. In its simplest form, a vehicle's traction characteristic consists of two curves representing the variation of adhesion force and the traction force that can be generated under the given assumptions. However, the final form of the traction characteristic can be significantly expanded by supplementing it, for example, with a rolling resistance curve for a train set of a specific mass and under specific operating conditions. Figure 1 shows an example of the traction characteristics of a typical four-axle locomotive. The gray line illustrates the variation in the traction force that the vehicle in question can achieve. The variation in traction force is shown in red.

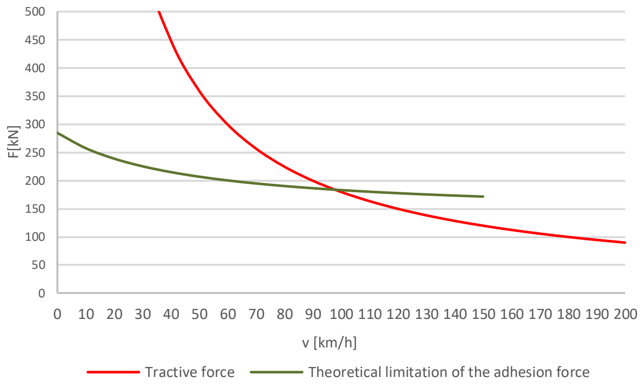

Fig. 1. Example of a theoretical traction characteristic (author's own work)

Very often, the traction curve provides more information. An example of such a characteristic is shown in Fig. 2, onto which the following were applied in sequence [4]:

– normal operation mode – the horizontal section and the blue curve – the variation in traction force for a constant power setting
– booster mode – the portion of the graph shown as a red broken line – a different pattern of traction force variation for short-term operation
– limitations of adhesion – black dashed line – a schematic representation of the variation in a vehicle's adhesion force
– limitations on the network current of 2500 A when working at direct current – the turquoise dashed line – the variation in traction force for a limited supply current in the traction network.

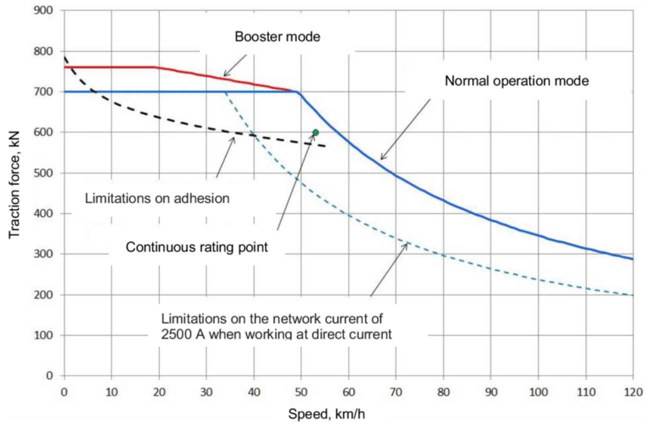

Fig. 2. Traction characteristics of the 2EV120 locomotive [4]

The characteristics shown in Fig. 2 could be further supplemented with rolling resistance curves reflecting example train compositions of specific masses operating under the assumed conditions. In such a situation, the vehicle's traction characteristic would also serve as a graphical representation of the equation of motion in a quasi-steady state context, since the vehicle's operating point at any given moment (traveling at a specific speed and with a specific value of traction force) would be determined by the intersection of the traction force curve and the resistance curve. For example, when driving uphill, the resistance curve would shift upward, which would result in a reduction in speed or the need to increase traction power (if such an option were even available). Conversely, when traveling on sections of track with low rolling resistance (the resistance curve would shift downward on the characteristic curve), it would therefore be possible to achieve a higher speed or reduce the amount of power used for traction.

The assessment of the initial range of a vehicle's traction characteristics refers to a curve representing the adhesion force, which, as the speed argument increases, intersects the traction force graph. In this case, the adhesion force should be understood as a certain conventional limit; if the traction force exceeds this limit, it may cause the vehicle's wheel sets to slip.

The complex nature of the adhesion between the wheel and the rail makes it impossible to specify a fixed and unambiguous load value at which wheel set slippage begins; nevertheless, determining the theoretical value of the adhesion force between these components is crucial for assessing the vehicle's basic traction characteristics. Modern drive systems control the operation of traction motors independently for each electric motor and based on input signals from other vehicle systems, such as the traction control system. When starting the locomotive and requiring a high level of traction force, the vehicle's drive system controls the motor's operation so that it achieves the highest possible traction torque. If, during this process, the anti-slip system detects slippage on the wheel set connected to the motor, the torque produced by the machine will be temporarily limited (and the sanding system may be activated). Once the slippage has ceased, the drive system will begin to gradually increase the torque on the traction motor in question in order to reach its target value. This solution offers a realistic opportunity to temporarily make full use of the available traction of each wheel set. Furthermore, when conditions are favorable - such as a locally high wheel-rail adhesion coefficient - modern traction systems allow for short-term overloading of the traction motors, enabling the wheelset to transmit a higher traction force to the track locally than its nominal equivalent. However, this phenomenon is temporary, as the overload capacity of traction motors is limited in duration.

3. Design and operating conditions of freight locomotives

Freight locomotives are a special type of locomotive designed primarily to pull trains carrying cargo rather than passengers. What sets them apart is:

- high tractive power – they can pull very heavy trains
- a lower top speed compared to passenger locomotives
- robust construction – designed for long-term and intensive use
- more drive axles – better traction on the tracks.

In general terms, a freight locomotive consists of a body and undercarriage, which are connected in a flexible manner; this allows the vehicle, among other things, to safely navigate various types of track curves in both plan and profile while simultaneously carrying all types of loads resulting from the operation. The design features of the locomotive's body and undercarriage generally reflect the vehicle's intended use and its anticipated operating conditions.

The vehicle body integrates the entire vehicle by combining all assemblies and components into a functional whole. In addition, it features a weather-protected interior space that houses two cabins for the vehicle's crew and engine compartments designed to accommodate the necessary equipment. The body also provides external mounting points for equipment, which are located, among other places, in the area of the front bumpers and the vehicle's front panels, under the bumper, and on the vehicle's roof. Ultimately, the body structure bears all loads resulting from the vehicle's interaction with the track, interactions between coupled vehicles, or those resulting from derailments or collisions with other vehicles or objects.

The freight locomotive has an undercarriage consisting of bogies that support the body. The running gear typically consists of two drive bogies, each equipped with two or three wheel sets. The design solutions used in the undercarriage depend entirely on the intended use of the traction vehicle, the expected performance parameters, and the anticipated operating conditions; in the case of freight vehicles, these solutions should be simple.

The operating conditions for freight locomotives are particularly harsh. This is the result of a number of factors, including, among others:

– navigating infrastructure in varying states of technical conditions
– long-term work on a daily basis
– limiting the frequency and scope of maintenance work to the absolute minimum
– operating train formations with a total weight exceeding 3000 tons
– a high number of startups
– the generation and relatively long-term maintenance of high traction forces [15].

Freight locomotives are widely used on rail lines of all categories, ranging from main lines to lower-class lines and ending with typical local lines. The infrastructure of the aforementioned railway lines varies significantly in terms of technical condition, which determines the differing operating conditions for the vehicles in question. Traveling on track surfaces with noticeable signs of deterioration (irregularities in the track's plan and profile) exposes the structure of these vehicles to various types of forces, both fatigue-inducing and dynamic. In simple terms, the direction of the forces exerted by the aforementioned constraints coincides with the direction of the track irregularities; however, due to the flexible connection between the locomotive body and its running gear, the loads acting on individual structural nodes of the vehicle are more complex in nature [10].

Freight locomotives are vehicles that operate for relatively long periods of time on a daily basis. This is due, on the one hand, to the specific nature of domestic freight transport and, on the other hand, to economic factors related to the costs of purchasing and maintaining this type of vehicle. The average operating speed of freight trains in Poland was approximately 34 km/h in 2024 [6]. This is a relatively low figure, especially when compared to the corresponding figure for other EU countries, which stands at approximately 44 km/h. Several factors contribute to this, the most notable of which include:

– the limited technical condition of the track infrastructure, particularly the track surface, which restricts the maximum speed of freight trains
– the organization of the transport process, which involves coupling together in a single train groups of cars traveling on different routes, thereby requiring additional work at intermediate marshaling yards
– limited capacity on certain railway lines where passenger and freight trains run in parallel – in most cases, this limitation stems from the technical condition of the track surface and the capabilities of the national rail traffic control system.

The specific nature of the service described above necessitates frequent train stops and imposes local speed limits, which in turn results in an increased number of starts. On the one hand, these operations place additional stress on the locomotive's structure and its assemblies and components; on the other hand, they result in the traction vehicle being in service for a relatively long period while operating a single train.

The economic factor is also significant in the daily operation of a freight locomotive. Taking into account the acquisition and maintenance costs of this type of traction vehicle, it is expected that downtime resulting from maintenance and repair work will be kept to a minimum. Consequently, maintenance plans for freight locomotives provide for relatively long intervals between successive maintenance levels, while limiting the scope of such work to the minimum necessary to ensure the safe operation of these vehicles.

The manufacturer's specified service life for freight locomotives should be at least 30 years; however, experience shows that in practice this period can be significantly longer. It is therefore expected that the design of these vehicles will be highly resistant to adverse operating conditions. This requirement applies both to the locomotive's load-bearing structures (e.g., the body's load-bearing structure and the bogie frame) and to the components used in the mechanical, electrical, and power electronics systems. The use of modern, simple, and proven vehicle systems and components is particularly important for vehicles exposed to the various adverse factors mentioned above.

The primary load on the load-bearing components of these vehicles is caused by the act of pulling a freight train. This is primarily due to the need to generate high levels of traction force required to overcome the resistance encountered when moving a train of cars. Due to the specific nature of domestic rail freight transport, the components of a train's traction system are subjected to significant stress essentially throughout the entire journey of the locomotive pulling the train. This is due, among other things, to the significant weight of the trains being handled, as well as the number of starts (accelerating a train from a standstill to a set speed) during which it becomes necessary to generate and maintain relatively high traction forces for an extended period of time. These loads take the form of longitudinal tensile forces; however, due to the design solutions used in the connection between the bogies and the locomotive body, they will also generate internal forces acting in various directions [8, 13, 16].

4. Design features of the running gear that affect the traction characteristics of freight locomotives

The primary functions of the running gear include, first and foremost, enabling the vehicle to move, as well as generating traction and braking forces and effectively transferring them to the body. It is essential that the locomotive's undercarriage ensures an even distribution of the vehicle's weight across the individual wheel sets, which will create favorable conditions for fully utilizing traction power and enable the vehicle to be operated on straight tracks, curves, and turnouts while maintaining the required level of operational safety and a smooth ride. The design of the bogies should also minimize the impact of the vehicle on the track and dampen vibrations caused by traveling over local irregularities in the track surface [13]. The locomotive's running gear should enable the performance of the above functions under a variety of operating conditions, which result primarily from the vehicle's intended use, that is, the type of work performed, the anticipated load, and the technical condition of the track infrastructure. The proper functioning of the above-mentioned features is primarily due to the solutions implemented in the main components of the bogie, including the following systems:

1. First-stage suspension with a damping system
2. Second-stage suspension with a damping system
3. Wheel set guides
4. The system for transmitting longitudinal forces between the bogie and the body
5. The suspension system within the drive unit's bogie frame and the system for transmitting traction torque to the wheel sets.

The description of the structural solutions used is limited to the aforementioned systems employed in locomotives currently manufactured for the European market and used to haul freight trains. Among these vehicles, four are four-axle locomotives:

– Alstom Traxx
– Newag Griffin
– Pesa Gama
– Siemens Vectron

and two six-axle locomotives:

– Newag Dragon
– Stadler Euro.

The specifications provided are intended to offer basic information about the solutions used in the running gear of the aforementioned locomotives.

Figures 3–7 show schematic views of the bogies of the selected locomotives mentioned above; brief descriptions of their key systems are provided later in this section.

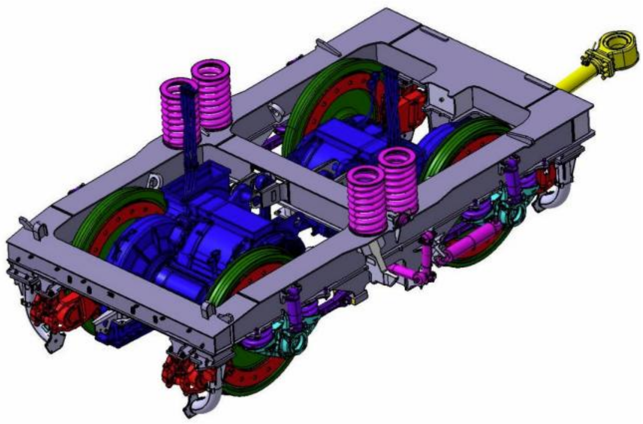

Fig. 3. General view of the TRAXX 3 Bombardier/Alstom locomotive bogie [5]

Fig. 4. General view of the Pesa Gama locomotive bogie [11]

Fig. 5. General view of the Siemens Vectron locomotive bogie [14]

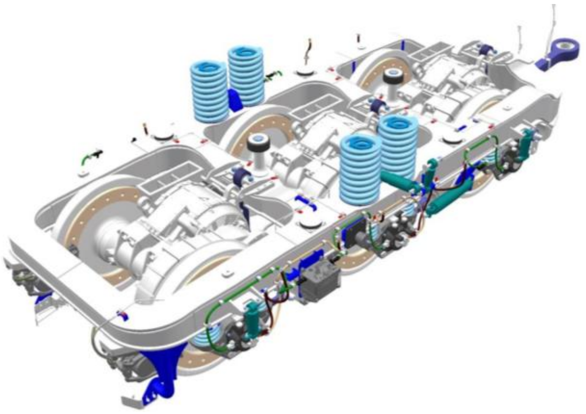

Fig. 6. Drawing of the Dragon Newag locomotive bogie [3]

Fig. 7. General view of the Stadler EURO locomotive bogie [2]

4.1. First-stage suspension system, including the damping system

All locomotives manufactured for the European market are equipped with a similar primary suspension system, which is based on compression-type steel coil springs. On the wheelset side, these components are mounted in sockets machined into the bearing blocks on both sides of the axle bearing. The upper ends of these springs engage with sockets machined into the lower flanges of the bogie frame.

Due to the lack of self-damping properties in the steel coil springs, the system also incorporates hydraulic vibration dampers that mechanically connect the bearing housings to the bogie frame. Vibration damping is applied in the primary direction of movement of the wheel set relative to the bogie frame, i.e., in the vertical direction.

The described first-stage suspension system, together with the damping system, has been used on the four-axle Alstom Traxx, Newag Griffin, Pesa Gama, and Siemens Vectron locomotives, as well as on the six-axle Newag Dragon and Stadler Euro locomotives [2, 3, 5, 11, 14].

4.2. Second-stage suspension system, including the damping system

Among all locomotives manufactured for the European market, a secondary suspension system consisting of so-called flexicoil springs is currently used. The Alstom Traxx, Newag Griffin, Pesa Gama, and Siemens Vectron four-axle locomotives, as well as the Newag Dragon six-axle locomotive, are equipped with large-diameter, dual-purpose Flexicoil steel coil springs, while the Stadler Euro locomotive uses metal-rubber springs. In all of the above cases, the number of springs and their arrangement depend, among other factors, on the weight of the body, the available space for their installation, and the anticipated range of movement of the bogie relative to the body. These springs are mounted from below in sockets cut into the upper flanges of the bogie frame (or, as in the case of the Vectron and Griffin locomotives, on additional metal-rubber pads). At the top, these components fit into sockets cut into the cross member of the body frame. The design and characteristics of the springs used allow them to operate under multi-axial loading conditions. As a result, they may be subjected to vertical, longitudinal, and transverse forces simultaneously.

The system also incorporates hydraulic vibration dampers that mechanically connect the bogie frame to the vehicle body. Vibration damping is provided in three directions: vertical, transverse, and longitudinal (to prevent the carriage from swaying). In the case of the Stadler Euro locomotive, vertical mufflers were not used [2, 5, 11, 14].

4.3. Wheel set guidance system

All locomotives manufactured for the European market feature a single-link wheelset guidance system, which, depending on the specific vehicle, is based on either a straight or triangular link. In the case of the Alstom Traxx four-axle locomotive, as well as the Newag Dragon six-axle locomotive, two-point (straight) longitudinal links were used, with two metal-rubber components mounted at their ends. The Newag Griffin, Pesa Gama, and Siemens Vectron locomotives use triangular (three-point) links, with three metal-rubber components mounted in their heads. In contrast, the Stadler Euro locomotive employs both variants of the described system, with two-point linkages used to guide the center wheel sets of each bogie, and three-point linkages used for the remaining wheel sets [2, 5, 11, 13–15].

4.4. System for transmitting longitudinal forces between the bogie and the locomotive body

Among the systems currently used in locomotive manufacturing to transmit longitudinal forces between the bogie and the body, the following should be noted:
– a single diagonal tie rod
– a single horizontal tie rod
– the yoke assembly and the horizontal longitudinal tie rods – known as Watt’s linkage.

A system for transmitting longitudinal forces based on single diagonal tie rods is a design in which each of the vehicle's bogies is mechanically connected to the body via a single tie rod. This component typically connects the rear crossmember of the bogie to a bracket mounted on the underside of the body frame. The tie rod in question is located along the vehicle's axis at a certain angle to the horizontal plane.

In most solutions of this type – in addition to the traction rod mentioned above – two pivots are also used, one of which is attached to the bogie frame via a bracket mounted in the lower belt area of the rear end plate. The second one, on the other hand, was attached in the same way to a welded bracket mounted on the underside of the body frame. The tie rod connects the journals using metal-rubber components that are mounted in the heads located at both ends. This type of solution has been used in the four-axle Alstom Traxx, Newag Griffin, and Pesa Gama locomotives, as well as in the six-axle Newag Dragon locomotive.

A system for transmitting longitudinal forces based on single diagonal tie rods is a design in which each of the vehicle's bogies is mechanically connected to the body via a single tie rod. This component typically connects the crossmember located in the center of the bogie frame to the vertical support bracket extending downward from the body pillar. The tie rod in question runs horizontally along the vehicle's axis. In this design, the tie rod has metal-rubber bushings fitted at both ends, which provide the required flexibility in the mechanical connection between the bogie and the body, while also allowing the transmission of longitudinal forces acting within the system. This type of solution is used in the six-axle Stadler Euro locomotive.

The longitudinal force transmission assembly, designed as a so-called Watt system – that is, a system consisting of a yoke and two horizontal longitudinal tie rods – has a different structure. This assembly also includes a pivot or bracket that is attached to the underside of the vehicle body’s support structure and connects to the yoke via a metal-rubber component or components in which its end is mounted. The yoke, in turn, is mechanically connected to the bogie frame via two horizontal tie rods, at the ends of which metal-rubber components are mounted. This type of solution is used in the Siemens Vectron four-axle locomotive [2, 5, 11, 13–15].

4.5. The suspension system of the drive unit in the bogie frame and the system for transmitting traction torque to the wheel sets

Locomotives available on the European market feature a variety of designs regarding the suspension systems of the drive units within the bogie frame and the method of transmitting traction torque to the wheel sets.

Some models feature traction motors that are rigidly mounted to the vehicle frame – this is the case, for example, with the Pesa Gama and Stadler Euro locomotives. In these vehicles, drive torque to the wheel sets is transmitted through gearboxes mounted on one side of the wheelset axle and flexibly mounted on the bogie frame on the opposite side. A flexible coupling is located between the traction motor and the transmission; it transmits the traction torque and compensates for relative movements between the two components.

The Alstom Traxx and Newag Dragon locomotives feature a simple suspension system for the drive unit and a straightforward method for transmitting traction torque. The traction motor and the transmission are rigidly connected via their housings. On the engine side, this assembly is flexibly mounted in the frame, while on the opposite side it is rigidly supported by the wheel set axle.

The most complex method of suspending the drive units was used in the Newag Griffin and Siemens Vectron locomotives. In the case of the first vehicle mentioned, the engine-transmission assembly is fully suspended within the bogie frame using flexible components. The torque is transmitted to the wheel set via a hollow shaft and two flexible couplings. In the second locomotive, the traction motor is fully suspended within the bogie frame using metal-rubber components. One end of the transmission is rigidly mounted on the wheel set axle, while the other end is connected to the traction motor block via a flexible drive shaft. The torque is transmitted between these components via a flexible coupling [2, 5, 11, 13–15].

5. Conclusions

The analysis showed that the design features of the running gear play a key role in determining the traction characteristics of freight locomotives. The proper selection and configuration of components such as suspension systems, wheel set guidance systems, and mechanisms for transmitting longitudinal forces and traction torque directly affect the vehicle’s ability to effectively utilize traction force and safely guide the train under a variety of operating conditions.

The article notes that modern freight locomotives are designed to withstand harsh operating conditions, including heavy loads, varying infrastructure quality, and high operational intensity. For this reason, the design solutions employed are characterized by a balance between simplicity, reliability, and the ability to transmit high traction forces.

A review of selected modern locomotives in operation on the European market has confirmed that, despite design differences, similar design concepts are used to ensure an adequate level of operational safety, durability, and energy efficiency. Proper design of the running gear remains one of the key factors determining the performance characteristics of freight locomotives and their suitability for modern rail transport operations.

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