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IMPROVING THE ENERGY EFFICIENCY OF A TRAM'S RUNNING GEAR

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Abstract. This research analyses the influence of some design features of an undercarriage of a tram on the energy efficiency in terms of mechanical energy losses during its operation. The work includes the comparison of results of the research from two main points of view, namely from a running gear design and a railway wheel design. Two variants of a tram's bogie are investigated. A standard bogie and a bogie with a system that allows a radial adjustment of the wheelsets in curves. Two designs of a railway wheel are compared, a wheel with the traditional construction scheme and a wheel with a perspective construction scheme. The values of mechanical energy losses due to slippage in the contact between the wheels and rails are analysed. These losses are obtained with reference to a specific route and the value of the average power dissipated. Moreover, an analysis of advantages and disadvantages of bogie designs has made it possible to consider the most appropriate bogie design in terms of ensuring the energy efficiency. In this case, the bogie design with the wheels with the perspective construction scheme can be considered as the optimal option.

Keywords: Energy efficiency, tram's bogie, simulations, MBS model, railway wheel.

1. Introduction

The successful functioning of large cities is only possible with an efficient public transport system. One of the most important types of street rail-based public transport, usually with electric traction, used mainly in large cities to transport passengers along fixed routes, is the tram [1–5].

In some places in Europe, the tram has now even begun to go beyond the classical concept of urban transport, as it can drive on the tracks of a conventional railway and operate in suburban areas, covering distances of up to 80 kilometers outside of the city limits. In some places where there is no subway, the tram can pass under the busiest streets through tunnels. Tram transport is therefore actively developing [6–12].

Currently, the transport industry is faced with the urgent task of ensuring the energy efficiency of vehicles, including rail vehicles. The urgency of this issue is heightened by rising prices of electricity and fuel resources. Therefore, even a slight decrease in energy consumption required to move trams can significantly reduce operating costs, since the main part of these costs is the provision of their movement.

According to [13], energy efficiency can be understood as the comparative ability to use less energy for the same level of energy supply for technological processes [14–16].

One of the main indicators of the energy efficiency of a tram as a rail vehicle is the amount of energy required to move along the rail track, i.e. to overcome the resistance to its movement. Among several ways to create rail vehicles with competitive energy efficiency indicators, one of the most promising is the use of innovative bogie designs [17–21].

For example, it is well known that the use of radially mounted bogies and wheelsets can significantly reduce the energy required to overcome the resistance to movement. The energy required to move the rolling stock is reduced while at the same time providing resistance against wobbling of the bogies. This resistance depends primarily on the bending stiffness (resistance to the angular rotation of the wheelsets) and the shear stiffness of the bogies (resistance to the mutual lateral movement of the wheel sets). High shear stiffness provides stable movement on straight tacks, and low bending stiffness allows to negotiate curved track sections of the railway without flange guidance [22–24]. Finding the optimum combination of these characteristics will lead to a reduction in energy required to move rail vehicles on both straight and curved tracks [25].

There are known technical solutions, in which, a wheelset does not consists of a pair of wheels rigidly mounted on a common axle, but of three independently moving components, i.e. two wheels rotating on an axle independently of each other [26]. This technical solution is known as the IRWs (independently rotating wheels). On the one hand, this reduces the wear of the wheel/rail pair in curves with small radii and partially, depending on the application, also helps to reduce noise of a driving urban railway vehicle. On the other hand, releasing the rigid coupling between the wheels and the axle leads to unstable rotation of the wheelset, or, rather to unpredictable movement of the IRW wheelset. It means that the standard and necessary sinusoidal movement of the wheelset is no longer present. Many technical solutions have been developed to eliminate the described disadvantages of the standard IRWs wheelset. Number of them includes less or more complicated mechatronic systems [27–30], which increase the complexity of the wheelset and thus the entire bogie (running gear) [30–33]. Another related problem is the braking system, which also needs adequate modifications [34–37]. The question is, therefore, whether it is possible to design a wheelset (mainly for urban railway vehicles – trams), which will be able to reduce the negative effects of the traditional wheelset, mainly wear and energy losses and at the same time eliminate the disadvantages of the IRWs.

One of the perspective construction scheme (PKS) solutions in this direction is the use of control systems for the installation of running gear in the rail track [38, 39]. For example, in some of them, the input parameter is the angle between the bodies of two cars or between the car body and the bogie. Although such systems cannot accurately operate when entering and leaving curves, their operation does not depend on the geometry of the profiles of wheels and rails. If the rails are in a good condition, radial adjustment systems can be used, depending on the geometry of the connected profiles wheel and the rails, with partial use of the mass inertia. However, due to the predominantly worn state of the rail track, a negative effect of using this technical solution is possible and consists in an increased uneven wear of the wheels [40–45]. The operation of the railway vehicle and the application of the proposed PKS wheel design relate not only to the running of the rail vehicle through curves, but also to running through crossings and switches. A research focused on the phenomenon of the lifetime of the wheel/rail pair components was made and is included in [46, 47]. They mainly focus on monitoring the condition of the most critical part of turnouts (common crossing) as well as the research of predicting the crossing geometry deterioration. Future research with the proposed TKS may also demonstrate the contribution in terms of reduced wear and deterioration effects on the surfaces of the railway wheel and the rails.

The mechanism of radial installation of wheelsets cannot be used advantageously in the modernisation of a rolling stock [48]. On the new rolling stock, the implementation of this measure does not require additional high costs. According to [48], the use of such devices is expedient almost everywhere, except for lines with a small number of curves.

Taking into account the predominant contribution of the kinematic movement resistance to the level of the overall resistance to the movement of the railway vehicle, another PKS technical solution that can significantly reduce the resistance to the movement of the railway vehicle in curved sections of the track and reduce the wear of the contact surfaces is the use of independently rotating wheels in the running gear [49, 50]. A further development of the use of such technical solutions is, for example, the design of a rail vehicle wheel with the PKS wheels proposed and justified in [51, 52], allowing the possibility of independent rotation of its supporting rolling surface and guide surface. This technical solution makes it possible to minimise the amount of kinematic resistance to the movement of the rail vehicle.

2. A Method of the Problem Solving

An important generalising indicator of the energy consumption during the movement of a transport unit is the total specific resistance to its movement w''_{t_srm} [N·kN^{-1}].

Based on [53–57], the total specific resistance to the movement of a railway vehicle:

$$w''_{t\_srm} = w''_{m\_srm} + w''_{ad\_srm}\,, \tag{1}$$

where w''_{m_srm} [N·kN^{-1}] is the main specific resistance to movement of the railway vehicle and w''_{ad_srm} [N·kN^{-1}] is the additional specific resistance to movement of the railway vehicle.

Among the well-known works on determining the components of the main specific resistance to the movement of railway vehicles, the studies of P.N. Astakhov stand out [53, 54], where it is indicated that the main components of this resistance is the specific resistance from friction in bearings w''_{fb} [N·kN^{-1}], the specific resistance from rolling friction of wheels on rails w''_{rfw} [N·kN^{-1}], the specific resistance from sliding friction of wheels on rails w''_{sfw} [N·kN^{-1}], the specific aerodynamic drag w''_{sad} [N·kN^{-1}], the specific resistance from energy dissipation in transit w''_{edt} [N·kN^{-1}], and the specific resistance from dissipation of energy into the environment w''_{dee} [N·kN^{-1}], i.e.:

$$w''_{m\_srm} = w''_{fb} + w''_{rfw} + w''_{sfw} + w''_{sad} + w''_{edt} + w''_{dee}\,. \tag{2}$$

As the wheels rotate, frictional forces are created in the bearings, depending on the type of bearing, the quantity and quality of the lubricant, the air temperature, and the speed of the crew. Modern axle boxes use cylindrical or tapered roller bearings, which provide a significant reduction in drag as compared to plain bearings. The value of the friction coefficient of roller bearings is from 0.001 to 0.005.

The specific aerodynamic drag w''_{sad} [N·kN^{-1}] of the movement of the car mainly depends on the factors associated with the design of the body of the rail vehicle, its speed, axial load, and ambient temperature.

It is known that the condition of the railway track significantly affects the overall resistance to the movement of the vehicle, particularly as the speed of movement and axial loads increase. In a number of works, when determining the specific resistance to the movement of a rail vehicle from energy dissipation along the way, the indicator of energy dissipation in the track is used, which is determined experimentally [55, 56]. The use of generalised empirical formulas for calculating the value of this indicator is problematic due to the presence of a large number of influencing factors.

The value of the specific resistance to movement from the dissipation of energy into the environment w''_{dee} [N·kN^{-1}] is also difficult to quantify using generalised empirical formulas for the same reason. In [57, 58], it was proposed to take the value of this indicator in comparative calculations, considering the assumption of unwearable elements of the running gear.

The value of the specific resistance to the movement from the rolling friction of wheels on rails w''_{rfw} [N·kN^{-1}] also depends on many factors: the arrangement and loading of the rolling stock, the type of rails, sleepers, and their number per 1 km of the track, the type and condition of the ballast, etc. The better the quality and technical condition of the track, the lower the rolling resistance of the wheels on the rails. This indicator is also difficult to quantify using generalised empirical formulas, because under the influence of large loads and plastic deformations of the material, microprocesses of sliding friction and wear of the contact surfaces occur simultaneously with rolling friction. The friction coefficient for pure rolling is from 0.001 to 0.01.

When the wheel is rolling, in addition to the rolling friction, there also is an elastic sliding of the wheel along the rail. The dimensionless coefficient of elastic sliding of one body over another or creep is defined as the deviation from pure rolling conditions. In addition, in some cases, inelastic sliding of the rolling surfaces of wheels and ridges along the rails also occurs.

The value of the specific resistance to the movement of the car from the sliding friction of the wheels on the rails w''_{sfw} [N·kN^{-1}] is determined by converting the absolute values [N] of the forces of resistance to movement from the sliding of the wheels of a railway vehicle along the rails into specific values [N·kN^{-1}] [59, 60].

The additional specific resistance to the movement of the car w''_{ad_srm} [N·kN^{-1}] generally includes the resistance to movement in the curve w''_R [N·kN^{-1}], specific resistance caused by rail track inclination w''_I [N·kN^{-1}], and specific resistance caused by the action of wind load w''_B [N·kN^{-1}].

It should be noted that it is not possible to influence the values of the last two components through the use of innovative designs of the running gear.

One of the most significant components of the resistance to the movement of a railway vehicle is the so-called kinematic resistance to movement, which is associated with slips at the contact points of the wheels with the rails, leading to the dissipation of mechanical energy during the movement of the vehicle.

A review of scientific papers on the study of the kinematic resistance to the movement of railway vehicles showed the dependence of its value on a significant number of factors: the presence of curves of a small radius and the specific length of these curves on a given test site, the presence of lubrication on the contact surfaces, the technical condition of the vehicle and the railway industry.

The presence of a large number of curves on a certain polygon and the specific length of these curves increases the kinematic resistance to movement and the wear of the contact surfaces. This is especially true for curves of a small radius. This factor cannot be influenced.

To reduce the kinematic resistance to movement and wear of the contact surfaces, a widespread measure is the lubrication of the contact surfaces of wheels and rails. The result of its application is an increase in traffic safety, improved conditions for fitting into curves and passing through turnouts, and a reduction in the consumption of fuel and energy resources for train traction, wear of rolling stock wheel flanges and rails and noise levels.

The method of lubrication and the conditions of use affect the complex nature of the interaction processes between the wheel and the rail when the crew moves in curved sections of the track, the wear of the running gear, and rails. However, a number of serious issues remain unresolved, such as the environmental friendliness of lubricating oils and the ingress of sand and dust into lubricant compositions, which causes additional resistance to movement and increased wear of the wheel-rail contact surfaces.

An important factor in reducing the kinematic resistance to the movement of rail vehicles is the maintenance of the rail track in an appropriate technical condition. However, these measures require significant material costs, which makes the simultaneous improvement processes impossible. Also, the reason for the unsatisfactory technical condition of the rail track is the discrepancy between the geometric parameters of the track and the parameters of the wheels, which also affects the indicators of wear and traffic safety [61, 62].

In a short theoretical review, it was found that the existing methods for calculating the resistance to movement of railway vehicles do not take into account its dependence on the design features of their running gear. This does not allow a direct possibility of determining this characteristic at the design stage of the crew. It is advisable to study and evaluate the influence of these design features on the energy efficiency of the crew by means of simulation.

The characteristics of the movement of a rail vehicle along the section are influenced by many random fac-

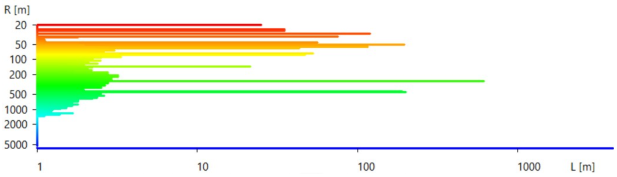

Figure 1. A bar graph of the curved sections of the route.

tors, this causes certain difficulties in determining the possible effect of the use of certain technical solutions from the standpoint of energy efficiency. Therefore, in order to calculate the energy costs for the movement of a tram vehicle when comparing competing options for technical solutions of its components, it is advisable to determine the main characteristics of energy consumption with a mandatory reference to a specific route.

This requirement is especially relevant when conducting research on the influence of the design features of tram running gear on the level of kinematic resistance to their movement.

It should be taken into account that the values of most of the abovementioned components of the resistance to movement of a rail vehicle are practically independent of the design of its running gear. Therefore, the study considered the impact on the reduction of energy consumption during the movement of the tram is precisely the component that is determined by the forces generated when the wheels slip on the rails (kinematic resistance to movement). In fact, the magnitude of this component can be influenced through the use of innovative designs of undercarriage.

In order to determine the impact on the energy efficiency of trams of the possibilities of using innovative technical solutions in their running gear by reducing the kinematic resistance to their movement, the simulation of the movement of several variants of the crew was carried out on the example of the Tatra T3 tram car. The simulation was carried out with reference to a real tram route (part of route No. 12: Ukraine, Kharkov, Yuzhny Station – Lesopark, Appendix 1, Figure A1). This route consists of straight sections of the track and curves of different radii, the minimum of which is 20 m. A map-scheme of the part of the route in relation to where the simulation was performed is shown in Figure 1.

The map in Figure 1 shows a distribution of curves with various radii along the entire length of the track section. The colours of the bars indicate curve diameters in the following manner, the red colour means the smallest radius of a curve and the blue colour the biggest radius if a curve.

The tramcar motion modelling was carried out using the Simpack software package.

The main components of the resistance to the movement of a rail rolling stock are associated with the forces generated when the wheels slip on the rails on straight and curved sections of the track. To reduce

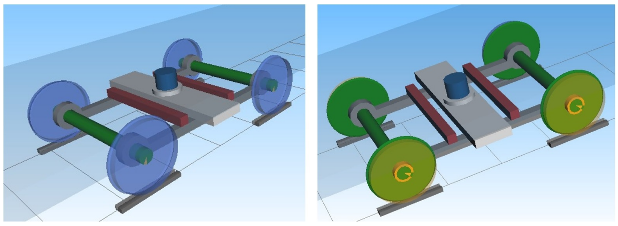

Figure 2. A railway running gear with the TKS wheels (left) and with the PKS wheels (right).

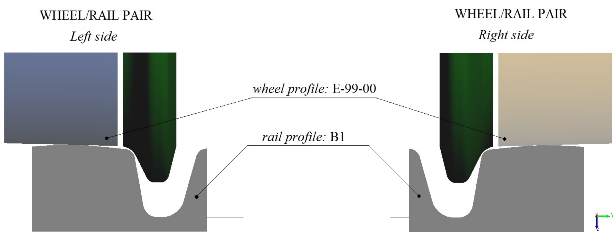

Figure 3. A visualisation of the contact zone of a wheel of a PKS wheel with a rail.

them, it is necessary to create innovative undercarriages, which use, for example, advanced wheel designs or devices for radial installation of bogies or wheelsets.

The study considered the movement of the running gear of a tram car, taking into account the following design features:

- a tram car with bogies and wheels of a standard design,
- a tram car with bogies of a standard design and wheels with the PKS, which have the possibility of separate rotation of the supporting and guiding surfaces,
- a tram car with bogies with a radial installation of wheelsets and wheels of a standard design.

Figure 2, 3 and 4 show diagrams of the main design features of the tram running gears under consideration.

The designs of carts shown in Figure 2 are standard, so there is no detailed description of them. The difference between them is only in the design schemes of the wheels. As noted above, in Figure 2, the cart has wheels of a standard design. A feature of the wheels of the bogie shown in Figure 3 is the possibility of separate rotation of the supporting and guiding surfaces. This mean s that the wheel flange is rigidly mounted on the axle and the tread surface can rotate separately in relation to the flange and the wheelset axle. In this design, the tread surface rests on bearings mounted on the axle. Due to the specified design, the amount of kinematic slip of the contact surfaces is reduced, especially in the ridge contact, and the corresponding work of the friction forces is also reduced. Figure 3 shows the visualisation of the contact zone of a wheel of a perspective design scheme with a rail, formed in Simpack. The track gauge of the model is 1520 mm, the wheel diameter is 680 mm, the wheel profile is

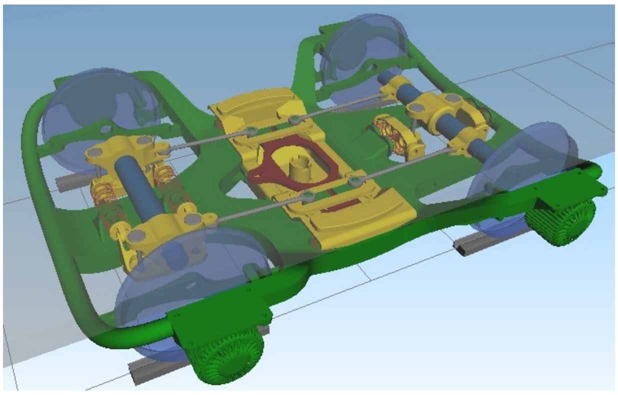

Figure 4. A scheme of a tram car running gear with a radial installation of wheelsets and with wheels of a standard design.

E-99-00 and the rail profile is B1. The wheel/rail contact surface is calculated by means of the FASTSIM contact algorithm.

The bogie presented in [63–65] was accepted as the bogie of the tram car with radial installation of the wheelsets A feature of such a bogie (Figure 4) is the fastening of the axle frame with the help of three bearing housings and the presence of a lever mechanism for adjusting the radial position of the axes when moving along a curve [66–68]. The key feature of the suspension is kinematic independence from the axis positioning system.

3. Results and Discussion

In general, the consumption of mechanical energy at the points of contact of the wheels with the rails during the movement of the vehicle has been calculated by determining and summing the mechanical work of the friction forces at each contact point of the wheels of the tram vehicle with the rails.

The described types of the tram bogies were analysed. The analyses have been focused on investigating the energy consumption during running on a selected track line (Section 2). There are many quantities and output parameters, which can be assessed. In the case of such a complex model of a tram bogie or an entire tram, it is possible to focus on various outputs. Some limits, which have been considered regarding the evaluation of the outputs, should be noted.

The simulations were carried out for the running on a track with no irregularities. This means that the mechanical system of a bogie/tram was not excited by the track irregularities and these dynamic effects were neglected during the simulations.

Mechanical energy E_{abi} [J], which is dissipated when the wheels slip on the rails in the corresponding contact point (equal to the work A_{abi} [J] of the creep forces in the corresponding contact), was defined as the scalar product of the corresponding component of the creep force F_{abi} [N] in the corresponding contact point and of the slip on the rail at the contact point in this direction:

$$E_{abi} = A_{abi} = -(U_{abi} \times S^U_{abi} + V_{abi} \times S^V_{abi}) \,, \quad (3)$$

where a, b are the number of the wheel pair of the vehicle in the direction of travel and the side (left or right) of the tram running gear, respectively, U_{abi} [N], V_{abi} [N] are the longitudinal and lateral components of the creep force in the i-th contact of the corresponding wheel and the rail, respectively, S^U_{abi}, S^V_{abi} are sliding in the i-th contact of the corresponding wheel and the rail in the longitudinal and lateral directions, respectively.

In order to take into account the rapid changes in the values of the forces acting at the corresponding contact points of the wheels and the rails, their values have been modelled at a specific frequency (simulation frequency f_s [Hz]).

The corresponding slip was calculated taking into account the components of the slip velocity at the contact, i.e.:

$$\begin{aligned} S^U_{abi} &= v^U_{abi} \times T_{f_s} \\ S^V_{abi} &= v^V_{abi} \times T_{f_s} \,, \end{aligned} \quad (4)$$

where v^U_{abi}, v^V_{abi} – components of the sliding speed at each contact, in the longitudinal and lateral directions, respectively, T_{f_s} [s] is the simulation time period, taking into account the specific simulation frequency f_s (accepted in the calculations $f_s = 200$ Hz), that is:

$$T_{f_s} = \frac{1}{f_s} \,. \quad (5)$$

The total consumption of mechanical energy due to sliding at the points of contact of the wheels with and rails during the movement of the vehicle is equal to the sum of the consumption of mechanical energy E_{sum} [J] during sliding at each contact point of each wheel of the railway vehicle with the rail:

$$E_{sum} = \sum_{a=1}^{4} \sum_{b=1}^{2} \sum_{i=1}^{2} E_{abi} \,, \quad (6)$$

where E_{abi} [J] is the mechanical energy dissipated when the wheels slip on the rails in the corresponding contact point.

The average power dissipated when the wheels slipped on the rails while moving along the route $\overline{N}$ [W] was determined as follows:

$$\overline{N} = \frac{E_{sum}}{T} \,, \quad (7)$$

where T [s] is the time of the movement of the vehicle along the considered route.

As a result of processing the simulation data, the following values of total mechanical energy losses (work of tangential forces in the contact points of wheels and rails) from sliding at the points of contact of wheels and rails and the average power dissipated when a tramcar moves on a given route:

- a tram car with bogies and wheels of a standard design 297.3 kJ,

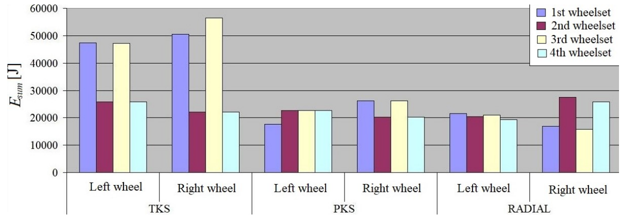

FIGURE 5. Total loss of mechanical energy E_{sum} [J] due to slipping of the tram wheels and the rails during the passage of the considered route at a speed of 10 km·h^{-1}; TKS – a bogie with the traditional construction scheme, PKS – a bogie with the perspective construction scheme, RADIAL – a bogie with the radial setting system.

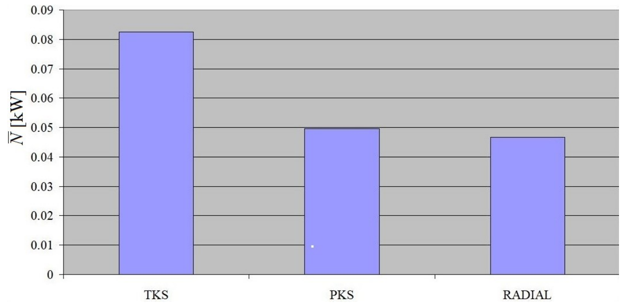

FIGURE 6. The average power $\overline{N}$ [kW] dissipated when the wheels of the tram car slip on the rails during the passage of the considered route at a speed of 10 km·h^{-1}; TKS – a bogie with the traditional construction scheme, PKS – a bogie with the perspective construction scheme, RADIAL – a bogie with the radial setting system.

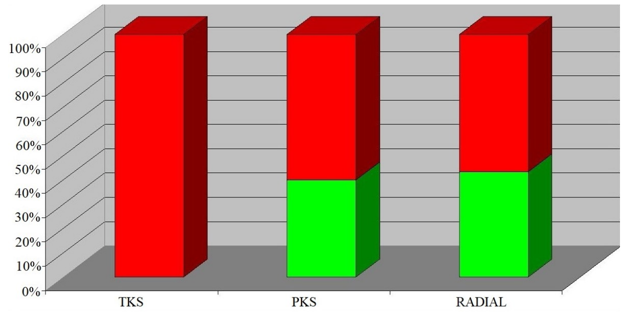

FIGURE 7. Possible effect of energy saving by using the innovative technical solutions at a running speed of 10 km·h^{-1}: red colour – the amount of energy dissipated due to wheel slippage on the rails when the tram moves along the route, green colour – energy saving effect; TKS – a bogie with the traditional construction scheme, PKS – a bogie with the perspective construction scheme, RADIAL – a bogie with the radial setting system.

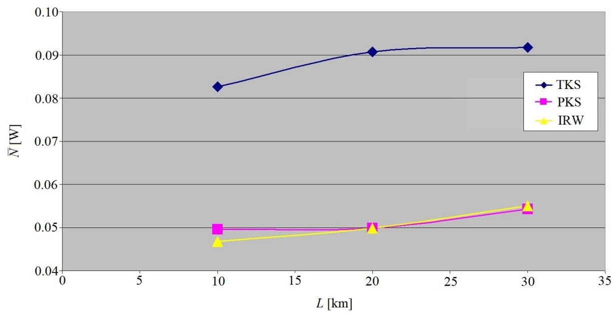

FIGURE 8. The value of the average power $\overline{N}$ [kW] dissipated when the wheels of the tram cars slide on the rails during the passage of the considered route L [km]; TKS – a bogie with the traditional construction scheme, PKS – a bogie with the perspective construction scheme, RADIAL – a bogie with the radial setting system.

- a tram car with bogies of a standard design and wheels capable of separate rotation of the supporting and guiding surfaces 178.6 kJ,
- a tram car with wheels of a standard design and the possibility of radial installation of wheelsets 168.1 kJ.

The average power consumption to overcome the kinematic resistance to movement when the tramcar vehicle variants move along the indicated route was:

- a tram car with bogies and wheels of a standard design 0.083 kW,
- a tram car with bogies of a standard design and wheels capable of separate rotation of the supporting and guiding surfaces 0.05 kW,
- a tram car with wheels of a standard design and the possibility of radial installation of wheelsets 0.048 kW.

Figure 5, 6, 7 and 8 show, as an example, the results of several studies on the effectiveness of applying innovative technical solutions in the running gear of a tram to reduce energy losses when it moves at a speed of 10 km·h^{-1} are shown.

Figure 8 shows the results of a study of the power dissipated when the wheels of tram cars slide on the rails during the passage of the considered route with the speed ranging from 10 km·h^{-1} to 30 km·h^{-1}.

The analysis of the obtained data allows us to state that the use of wheels with the PKS wheel design as part of standard tram car bogies can reduce the consumption of mechanical energy to overcome the resistance to movement as effectively as the use of bogies with the possibility of radial installation of wheel sets.

The future research in this field will be focused on an analysis of other dynamic effects, which relate with the proposed technical solution of the wheel design. It is considered, that the simulations will be carried out for other running conditions, which will include track irregularities. They will cause an excitation of the mechanical system of a bogie and it will be possible to assess related valuable outputs. Additional considered activities will be aimed at performing simulations and evaluations of energy consumption for other railway tracks (depending on the availability of the geometry). Furthermore, the implementation of a flexible body (a bogie frame) as a part of a multi-body model of a bogie is considered, which will lead to more realistic results. It will then be possible to compare the results of experiments carried out both on a section of a real track and on a test stand.

4. Conclusions

An analysis of the data obtained allows us to state that, by using innovative technical solutions in the running gear of a tram, it is possible to achieve a reduction in the loss of mechanical energy dissipated in the contact of the wheels with the rails. These are the possibilities of radial installation of wheel sets and the use of wheels with the capability of separate rotation of the supporting and guiding surfaces. The energy efficiency improvements for these running gear variants are almost the same. The results of the results of the simulations are as follows. The total mechanical energy loss due to sliding in the wheel/rail contact, in the case of the tram with the bogie equipped with the PKS, was 297.3 kJ. However, the TKS wheels can reduce these losses. The reduction indicated for the analysed track section is 118.7 kJ and the installation of the mechanism for adjusting the wheelset to the radial position in the track even reduces these losses by 129.2 kJ.

The comparison of the average power consumption has also shown that the most favourable technical solution of the bogie seems to be the bogie with the mechanism for adjusting the wheelset in the radial position under the analysed conditions. It can reduce this power by almost half, to the value of 0.048 kW, compared to the bogie with the TKS wheels (0.083 kW). The installation of the PKS wheels has a similar effect on the average power consumption. The value for this technical solution is 0.05 kW.

An analysis of the advantages and disadvantages of the running gear options under consideration allows us to conclude that, in this case, the option of the tram bogie with wheels of the PKS design can be considered the most appropriate in terms of ensuring the energy efficiency of the tram car.

List of symbols

w''_{t_srm} Total specific resistance [N·kN^{-1}]

w''_{m_srm} Main specific resistance [N·kN^{-1}]

w''_{ad_srm} Additional specific resistance [N·kN^{-1}]

w''_{fb} Specific frictional resistance of bearings [N·kN^{-1}]

w''_{rfw} Specific rolling resistance of wheels on rails [N·kN^{-1}]

w''_{sfw} Specific sliding friction resistance of wheels on rails [N·kN^{-1}]

w''_{sad} Specific aerodynamic drag [N·kN^{-1}]

w''_{edt} Specific resistance resulting from energy dissipation in transit [N·kN^{-1}]

w''_{dee} Specific resistance resulting from dissipation of energy into the environment [N·kN^{-1}]

w''_{R} Specific resistance resulting from motion in the curve [N·kN^{-1}]

w''_{I} Specific resistance resulting from rail track inclination [N·kN^{-1}]

w''_{B} Specific resistance resulting from the action of wind load [N·kN^{-1}]

E_{abi} Mechanical energy [J]

A_{abi} Mechanical work of the creep forces in the corresponding contact [J]

F_{abi} Corresponding component of the creep force [N]

U_{abi} Longitudinal component of the creep force in the i-th contact between the corresponding wheel and the rail [N]

V_{abi} Lateral component of the creep force in the i-th contact between the corresponding wheel and the rail [N]

s^U_{abi} Longitudinal slip [–], [%]

s^V_{abi} Lateral slip [–], [%]

f_s Simulation frequency [Hz]

v^U_{abi} Longitudinal component of a sliding speed [m·s^{-1}]

v^V_{abi} Lateral component of a sliding speed [m·s^{-1}]

T_{f_s} Period of the simulation time [s]

E_{sum} Sum of the mechanical energy consumed [J]

$\overline{N}$ Average dissipated power [W]

T Time of movement of a vehicle [s]

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A. Appendix

Figure A1. A map showing the route of a tram.