Engineering Transactions, **66**(4): 375–390, 2018, doi: 10.24423/EngTrans.872.20180920
Polish Academy of Sciences • Institute of Fundamental Technological Research (IPPT PAN)
Université de Lorraine • Poznan University of Technology

Research Paper

Bogie Steering System Improving Alignment of the Urban Railway Vehicle in a Track

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Urban rail systems are characterized by low-radius curves which are very problematic to negotiate for modern rail vehicles. There are several inventions developed throughout time to cope with that problem. One group of them are bogie steering systems, responsible for the improvement of the alignment of carbodies in a curve, increasing ride comfort and reducing wheel and rail wear. The principle of those systems is to correct the relative settlement of bogies and carbodies during curve negotiations, to lower the angle of attack. One of such systems is described in this paper in terms of design, operation and verification. Some experimental and simulation results are presented and discussed.

Key words: tramway; bogie steering; rail; track.

1. Introduction

Low radius curves are one of the biggest challenges for tram engineers. The lowest curve radius can be even ten times lower than the one present in railway tracks. Such narrow curves result in the occurrence of high values of friction between rails and wheels leading to excessive wear, vibration and annoying noise disturbing the city inhabitants. All these problems led the rail vehicle engineers to focus on some solutions to solve the problem. For many years short bogie and wagon bases were used and wheelset radial steering was introduced. Flange lubrication devices are widespread nowadays, reducing friction between the wheel flange and rail gauge corner. Most of the wheel and rail wear comes from flanging contact, which in turn is typical for riding through curves. However it can also be found on heavily worn track (poor track alignment). Usually, while riding through a narrow curve, a two-axle bogie sets itself diagonally – the first wheelset is pushed to the outer rail, while the second to the inner rail. This implies considerable big values of angle of attack, which is mostly responsible for improper wheel-rail interaction on the curves. To avoid that one can use radial steered wheelsets (Fig. 1) or bogies. The latter can be achieved by application of the proposed bogie steering system.

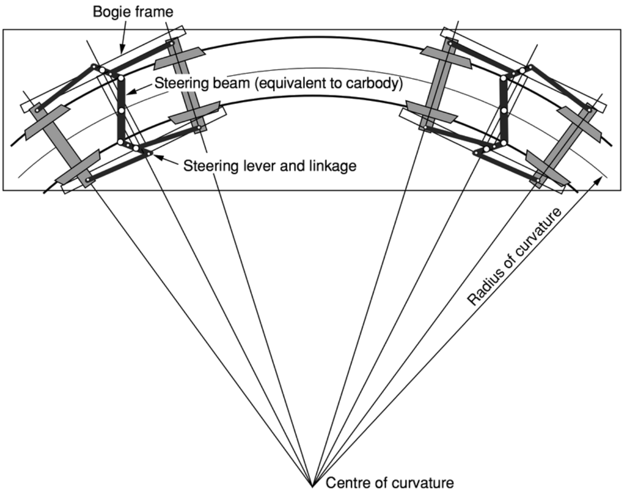

Fig. 1. Radial steered wheelsets [1].

The first implementation of a tram bogie steering system was done by Liebherr Transportation Systems in vehicles manufactured by former Adtranz in 2000 (Fig. 2). The solution was called anti-buckling system.

Fig. 2. Adtranz tram equipped with bogie steering system [2].

The Liebherr Transportation Systems equipped a vehicle with all necessary components of the hydraulic system coupling carbody and bogie, that is pressure transducers, electronic steering elements and hydraulic parts (actuators, cylinders, regulators, accumulators). Figure 3 presents the main hydraulic components of the anti-buckling system installed on Solaris Tramino tram in Braunschweig.

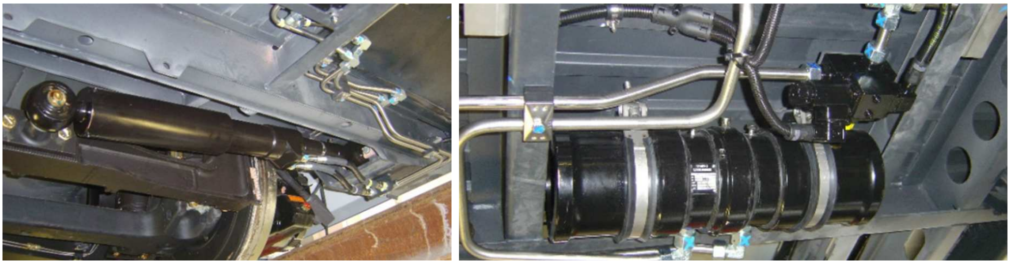

Fig. 3. Left: hydraulic damper connecting bogie and carbody, right: hydraulic damper's cylinder [3].

One of the main advantages of this solution is the improvement of kinematic gauge compatibility by using the hydraulic steering in coupling the bogies and carbodies. Furthermore, the system was also intended to amend the ride comfort and reduce the uneven wheel wear caused by intense friction between wheel and rail during curving. All the features contribute to the rising interest of rail vehicle manufacturers in such inventions in the last years.

In a newly designed tramway, it was not possible for Solaris to use the Liebherr System directly due to some construction aspects of the target vehicle; hence a new solution was needed. The principle of operation remained almost the same. A new system, designed by Solaris together with EC Engineering and Ponar Silesia, contained among others hydraulic dampers, damping and steering actuators and hydraulic accumulators. This particular bogie steering system (called SSTJ – Polish acronym for the system improving track alignment) is described in more details in the third section.

2. Related research

Such bogie steering system concepts are not entirely new to the market, which was described in the previous section. Also some research was done on this topic. Those systems can be divided into two groups: acting on wheelsets [4–8] and acting on whole bogies [9–13]. Both groups primarily tend to improve curving quality (lower wheel-rail wear, lower vibroacoustic emission), to assure higher ride quality and comfort. The latter of the two groups is more important to us due to the topic of this paper; hence some related works are described below in more detail.

In [9] an active yaw damper was proposed as a replacement for a classic, passive yaw damper in a railway car. Due to railway application it was fitted with two different control logics: one for running in straight track (stability priority) and the second for improving curving behavior. In the first case the active damper behaves like a viscous damper. The curving mode is focused on assuring proper ride comfort, safety level (due to derailment risk and track shift forces) and low wheel-rail wear. Authors of the solution emphasize that balancing the track shift forces is the most important goal in the system operation, as it is a problematic parameter limiting running velocity in highspeed trains. However, trams do not need to travel very fast, hence in the proposed SSTJ system the most important aim is lowering the vehicle's swept envelope. The novelty of the described design is the use of a brushless motor coupled with a recirculating ball-bearing screw in order to obtain a linear actuator.

There is also a patented solution for a steering railway bogie [10, 11], which is an active system, where both the bogie and the wheelsets yaw movement is controlled. In most of the passive steering systems wheelsets are rotating based on creep forces and are prone to partial steer lose under high traction conditions. Meanwhile actuated active systems require very robust design due to high accelerations at the bogie frame. In the proposed design wheelsets are steered through the yaw movement of bogie which is being steered by actuators, which contributes to the elimination of the mentioned flaws. The purpose of the invention is to minimize the creep forces non-originating from traction, as well as to even the distribution of lateral curving forces among wheelsets to reduce the wheel and rail wear and damage.

Another steering system [12] was a successfully implemented invention for Tokyo Metro, which contributed to the noticeable increase of the acoustic comfort of travel and decrease of lateral wheel-rail forces and wear. The system comprises of rod system between the bolster, bogie frame and wheelset, which matches the yaw angle of wheelsets automatically to the track curvature identified by the bogie-carbody yaw angle. This system is more likely to be marked as acting on wheelsets, but it is still worth mentioning because the yaw movement of the wheelsets is a consequence of yaw movement of the bogie and it was a successful application in Tokyo Metro.

Steering system proposed in [13] has the steering mechanism only between carbody and bogie frame but not between wheelsets and bogie frame. Authors of the design state that it is possible to reduce the lateral force between the leading-outside wheel and rail even to zero while running in tight curves and prove it with a successful experiment on rolling test stand. Yaw dampers were replaced with controlled actuators which steer the bogie towards the radial position. This solution is only a concept and was not implemented yet since it still requires some improvements (e.g. running in transition curves).

Most of the steering bogie systems are acting on wheelsets (the majority of research papers are devoted to that topic); still some successful inventions incorporating only the bogie versus carbody yaw movement exist. All the bogie steering systems have to deal with the conflict between ride stability and curving behavior [14]. It is necessary to maintain sufficient ride stability while running at high speed in a straight track; meanwhile improved curve negotiation ability is expected during running in curves at various velocities. Tram vehicles do not need to travel at such high velocities as trains, which simplifies the case. The proposed bogie steering system is described in the next section.

3. General description

The SSTJ bogie steering system automatically rectifies the vehicle alignment in the track both while riding in curves and on tangent track and this is accomplished by forcing particular radial setup of bogies in relation to carbodies and track direction. The main feature of the system is to improve kinematic gauge compatibility and curving ability and to assure the required level of ride safety. The hydraulic outline of the system is presented in Fig. 4.

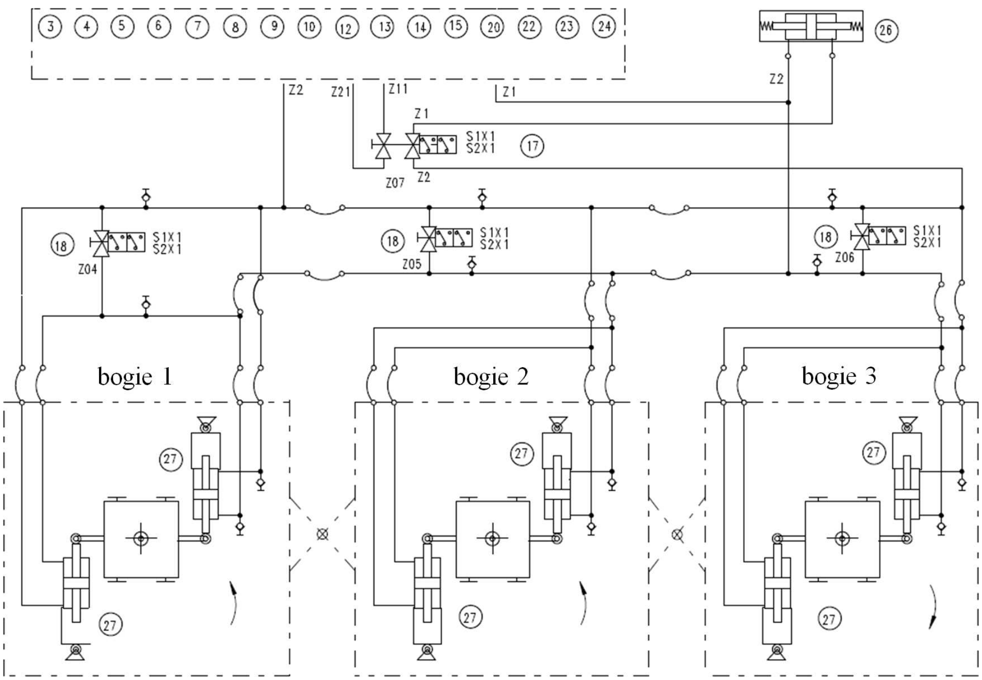

Fig. 4. Hydraulic outline of the system (description in the text).

The initial components belonging to the system are the following (markings relate to Fig. 4):

- hydraulic cylinders (27) integrating between bogie and carbody,
- damping actuator (26),
- ball valve with the position contacts (17),
- valve block with a pressure gauge in each circuit (pressure container, hydroline, pump, etc.) (18),
- pump with a reservoir (not shown in the above outline),
- accumulator equalizing the pressure level of the system (24).

In addition, the system is equipped with the following accessories:

- commissioning and diagnostic equipment (e.g. filling, emptying of the system, leaking detection),
- manual cleaning and filling of the system (runtime and service manual),
- software packages for the system.

The SSTJ steering system is based on a set of two hydraulic cylinders on each bogie, located orthogonally to the vehicle, between the bogie frame and the carbody. The system aims to balance the steering angles of the bogies according to the following dependence: $\alpha_2 = \alpha_1 + \alpha_3$ (aiming to make the sum of angles α_1 and α_3 equal to α_2). The steering system is designed for all bogies of a three section bidirectional vehicle (Fig. 5).

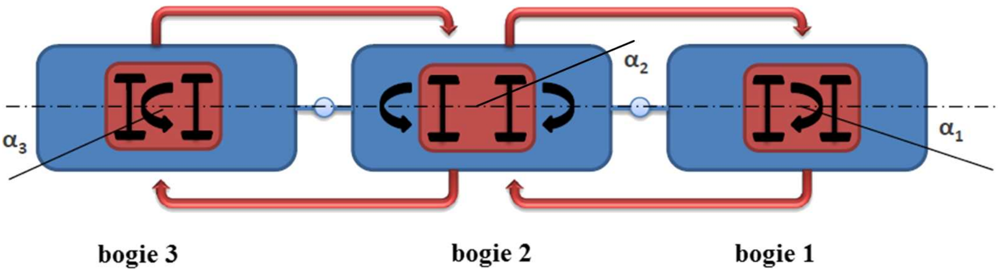

Fig. 5. General schematic of a bogie steering system.

4. General description

The system includes the following functionality:

- Prevent undesirable positions and motions of the individual car body modules in the following situations:
  - (a) entering and leaving the curves,
  - (b) running in curves,
  - (c) driving through S-shaped curves.

- Improving the alignment of the vehicle in the track to reduce the size of the swept envelope according to appropriate standards.

The system was equipped with an adjustable stiffness for different scenarios. In the normal mode the displacements of leading bogie and slave bogie are not the same, because the hydraulic connection between them is piped through a damping actuator. In case of a failure mode, i.e. towing or pulling situation the stiffness of the actuators is increased. The system is also equipped with a control unit, enabling to set the appropriate mode and report about diagnostic. Communication with tram central control unit is accomplished by CANopen bus. The system also contains a wire loop to activate brake in case of a critical situation (e.g. leakage) without controller participation.

5. Experimental verification

The aim of the examination was to assess the influence of SSTJ bogie steering system in various configurations on tram behavior and to evaluate correctness of hydraulic system operation. The test was based on the measurement of pressure on the hydraulic actuators and their operating displacements. Moreover the angle of rotation between particular carbodies was recorded. The test object was a three-sectional, low-floor tram showed in Fig. 6.

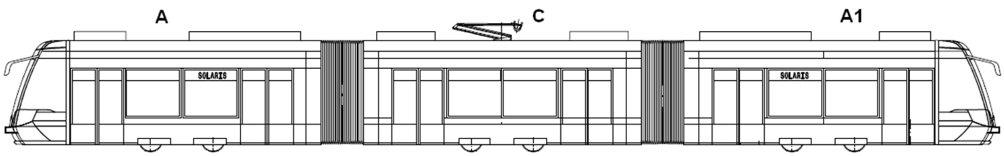

Fig. 6. Outline of the test tram.

Each car was supported by a bogie. Each bogie had two actuators responsible for the steering. Linear displacement sensor (1) was mounted on every hydraulic actuator. Pressure transducers (2) were installed in chosen circuits of the system (close to actuators, orifices, dampers). Angle transducers were fitted between the first and second car and between second and third. An exemplary arrangement of the measuring points is presented in Fig. 7.

Several rides in the depot and the city were carried out during this phase. The settings of the SSTJ system were changed during the test, including complete disconnection. Depot tracks (as very curved ones) were chosen for the assessment of system operation correctness. The test track consisted of a straight section and a curve (radius 22 m, length ca. 27 m) preceded and followed by a transition curve (radius 50 m, length ca. 6 m). Gathered results (rotation angles between cars for different track sections and system configurations) were

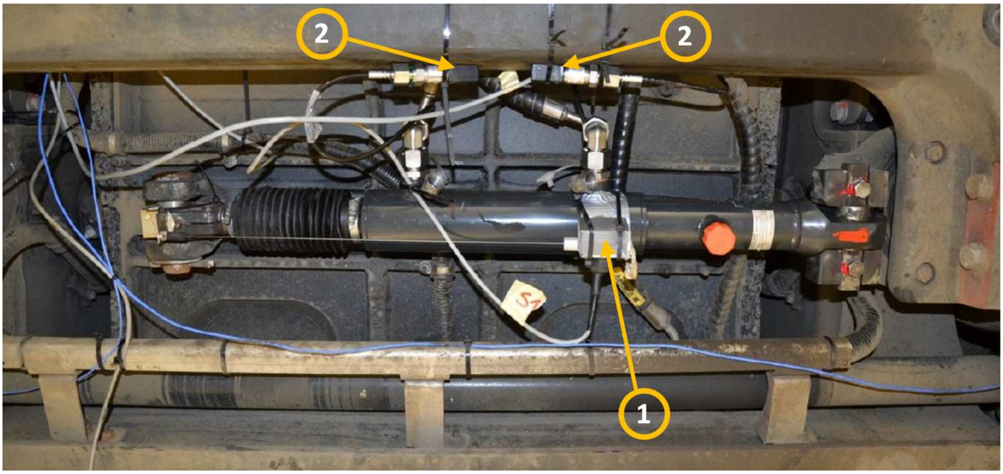

FIG. 7. Exemplary arrangement of the measuring points (described in text).

arranged into Table 1. Angles were measured around the vertical axis Z of the coordinate system.

Table 1. Rotation angles between cars for different track sections and system configurations.

Vehicle position in curve	Entering the curve $R = 22$ m (initial phase)		Entering the curve $R = 22$ m (final phase)		Whole vehicle in curve $R = 22$ m		Exiting the curve $R = 22$ m to transition $R = 50$ m	
Angle	A1 [°]	A2 [°]	A1 [°]	A2 [°]	A1 [°]	A2 [°]	A1 [°]	A2 [°]
System on, without damping cylinder	−10.07	−1.44	−25.99	11.33	−23.98	24.29	−18.76	26.07
System on, with damping cylinder	−9.66	−0.94	−26.33	11.13	−23.58	24.88	−18.74	26.08
System off	−8.91	−0.36	−26.71	11.13	−23.97	24.59	−18.35	26.44

Figure 8 presents a visualization of a ride through the curve for different states of the system to compare the kinematic gauge compatibility. For the extreme cases there is a 22 mm difference in protrusion of the first car towards the gauge.

Figure 9 shows the time history of pressure in the circuit for different system states. Red color indicates ride with system switched on without damping cylinder, green – system switched on with damping cylinder, blue – system switched off.

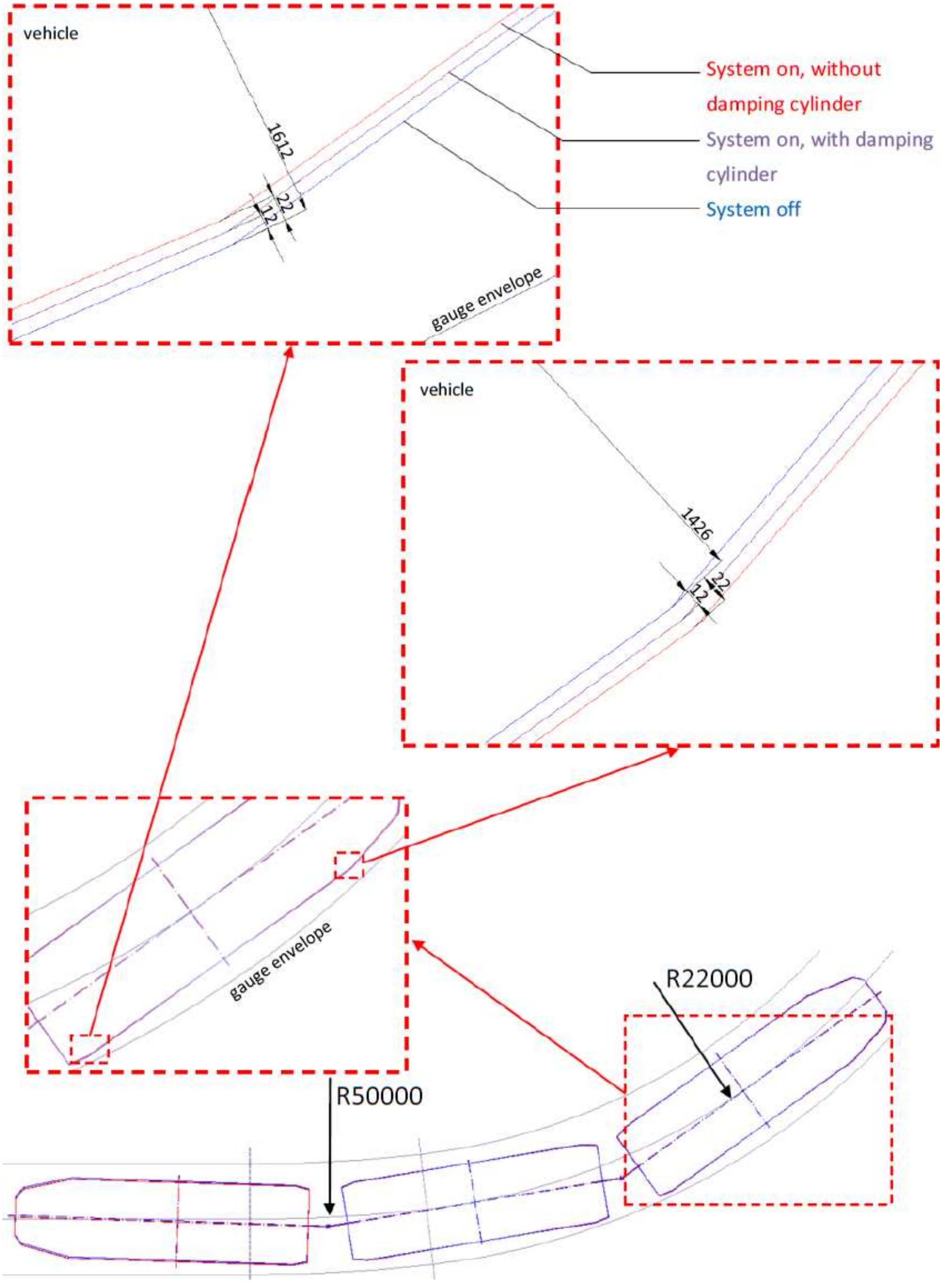

Fig. 8. Kinematic gauge compatibility check for various system states
(in mm, description in text).

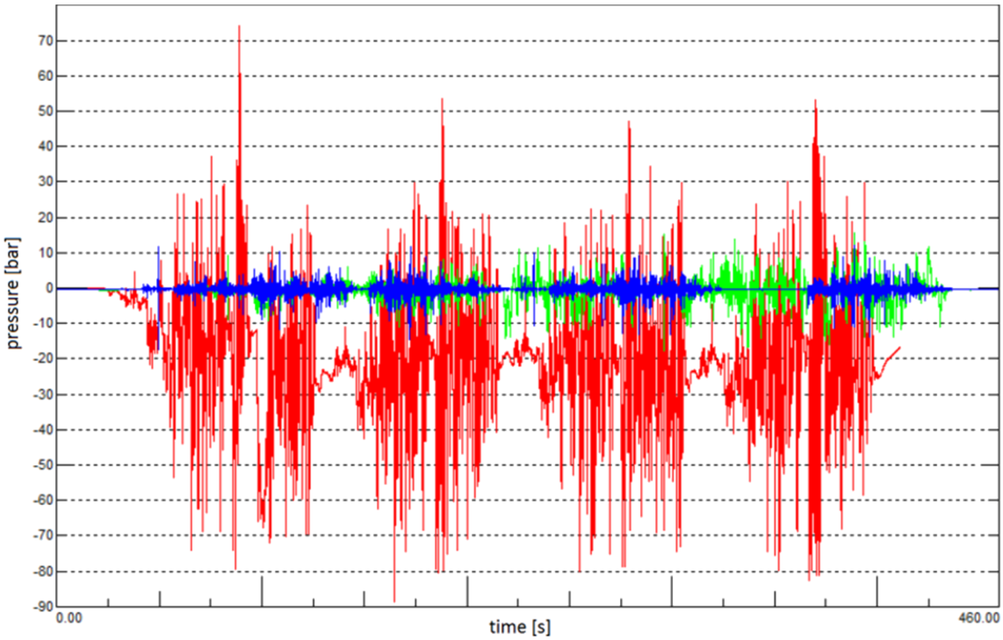

Fig. 9. Time history of pressure in the circuit for various configurations of the system.

It can be clearly noticed that omission of the damping cylinder while the system is on contributes to a significant increase of pressure value in the hydraulic circuit. Consequently it should cause stiffening of the system.

It was proved experimentally that implementation of the system does not affect negatively the ride safety and ride comfort (Tables 2 and 3). Ride safety was examined due to [15], for outer wheels while running in curve track. The presented Y/Q derailment coefficient ratio parameter is a quotient of maximum observed value to limiting value which was 0.8. Y/Q derailment coefficient ratios

Table 2. Ride comfort N_{MV} indexes [m/s^2].

System status	Car A1	Car C	Car A
On	0.81	0.73	0.84
Off	0.81	0.73	0.84

Table 3. Y/Q derailment coefficient ratios for outer wheels.

System status	WS1	WS2	WS3	WS4	WS5	WS6
On	0.96	0.57	0.66	0.66	0.95	0.59
Off	0.96	0.56	0.66	0.67	0.95	0.59

were almost the same for loaded (5 pass./m^2) and overloaded (6.67 pass./m^2) cases. Hence, only the first case is shown. Ride comfort was measured according to [16] at the geometrical centers of cars. Results were almost the same for loaded (5 pass./m^2) and overloaded (6.67 pass./m^2) scenarios. All mentioned results come from the second test case (see Table 5).

6. Validation of the numerical model

One of the most important phases during the designing process of the bogie steering system was its simulation based on the model of the target vehicle. The simulation was carried out using multibody simulation software SIMPACK. Ride safety, ride quality, curving behavior (regarding various curve radii and kinematic gauges) and ride comfort were assessed during the numerical analysis according to [15–17], for the purposes of vehicle certification. Track gauge was equal to 1435 mm, rail profile set to 59R2 or 49E1, wheel profile – PST (a typical Polish wheel profile for tramways). The coordinate system and vehicle model outline were set as in Fig. 10.

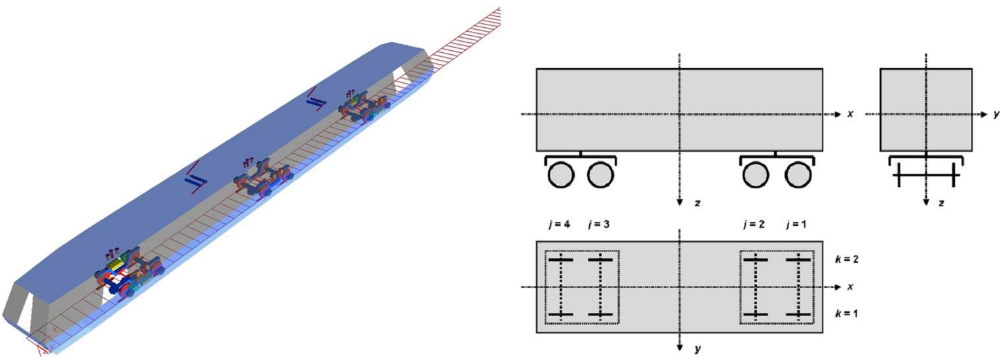

Fig. 10. Vehicle model view and coordinate system adopted for simulation [15].

Basic vehicle parameters are summarized in Table 4.

The model was equipped with the bogie steering system which may be activated or deactivated during the simulation. The numerical analysis consisted of several rides through established test cases (Table 5). All tracks comprised irregularities measured on reference tram track. Simulations were made both for loaded (5 pass./m^2) and overloaded vehicle (6.67 pass./m^2). On the basis of the experimental results it was possible to validate the simulation model.

The bogie steering system influences the relative position of carbodies based on the hydraulic coupling of their rotations over bogies, lowering at the same time the protrusion of tram contours against the kinematic gauge. The operation

Table 4. Vehicle basic parameters.

Total length	29.3 m
Total height (current collector down)	3.8 m
Total width	2.5 m
Number of bogies (motor/trailer)	2/1
Motors	4×120 kW
Wheel diameter (new/worn)	682/602 mm
Medium angle for rotation	40°
Bogie base	1.85 m
Wagon base	9.45 m

Table 5. Simulation test cases.

Test case	Vehicle speed	Curve radius	Superelevation
1	70 km/h	Max. 400 m	Max. 40 mm
		Min. 300 m	Min. 20 mm
2	40 km/h	Max. 100 m	Max. 140 mm
		Min. 75 m	Min. 60 mm
3	20 km/h	Max. 40 m	Max. 130 mm
		Min. 25 m	Min. 80 mm

of the system is intended to decrease the likelihood of non-tangent settlement of cars against the track, which results in similar values of angles in A1 and A2 articulations while traveling on the same track section. The angles of rotation between the cars were determined during the passage through the curve with a radius of 25 m (the smallest radius of the curve on the test route) to define the impact of the SSTJ system on the behavior of the vehicle. In order to eliminate the possible differences between measurements and simulations caused by the non-ideal tram setting on a straight track section during physical tests (setting the zero position on the angle transducers), the difference of rotation angles in the joints was used for the assessment. In order to match the model with the actual vehicle, it was necessary to determine the reduced stiffness of the steering system, which describes the stiffness of this system resulting from the susceptibility of actuators and their attachments (supports), liquid compressibility and elasticity of the pipe walls (susceptibility to elastic deformation due to pressure change in the hydraulic system). The comparative results for three selected values of reduced steering system stiffness with values obtained during physical object tests are summarized below (Fig. 11).

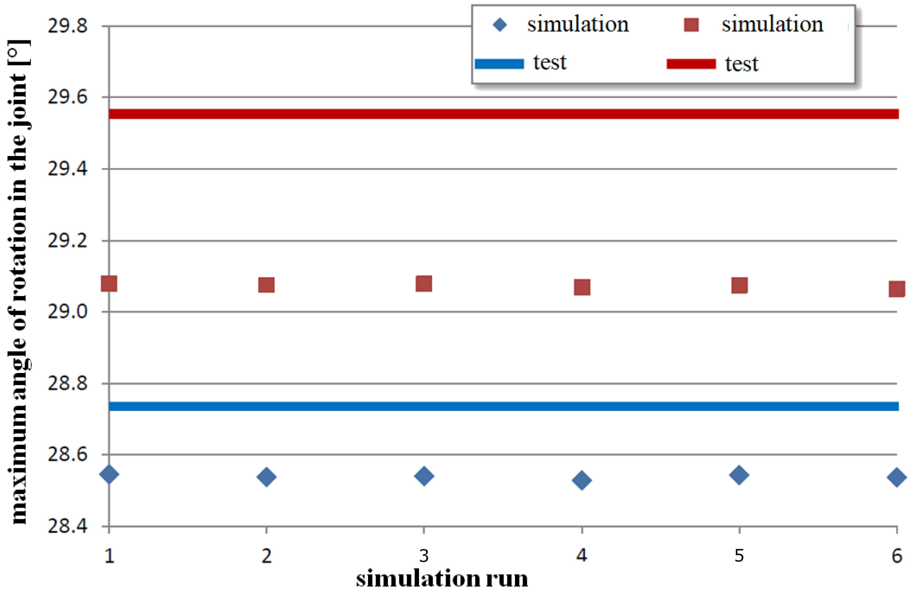

FIG. 11. Angle of rotation between cars – reduced equivalent stiffness of the system (100 kN/mm).

For a very high equivalent stiffness of the steering system equal to, e.g., 100 kN/mm, the maximum rotation in the joints is very dependent on the ride dynamics (small changes for six different speed profiles). The obtained angles of rotation between the cars depend mainly on the geometry of the traveled track. Thus, the values of angular displacements on both joints are almost constant and differ by an average of 0.53°. The bogie steering system with such high stiffness can cause significant pressure jumps in the hydraulic system and increase the forces acting on the track. The analogous results for the model with equivalent stiffness equal to 0.48 kN/mm (Fig. 12) are presented below, as well as the values of the angles between the members for such reduced stiffness (Table 6).

Table 6. Values of angles between cars for reduced equivalent stiffness of the system (0.48 kN/mm).

Parameter	Measurement	Simulation
The average difference between the maximum angles of rotation in the joints on the curve $R = 20$ m [°]	0.81	0.81
Standard deviation of the difference of the maximum angles of rotation in the joints [°]	0.04	0.06

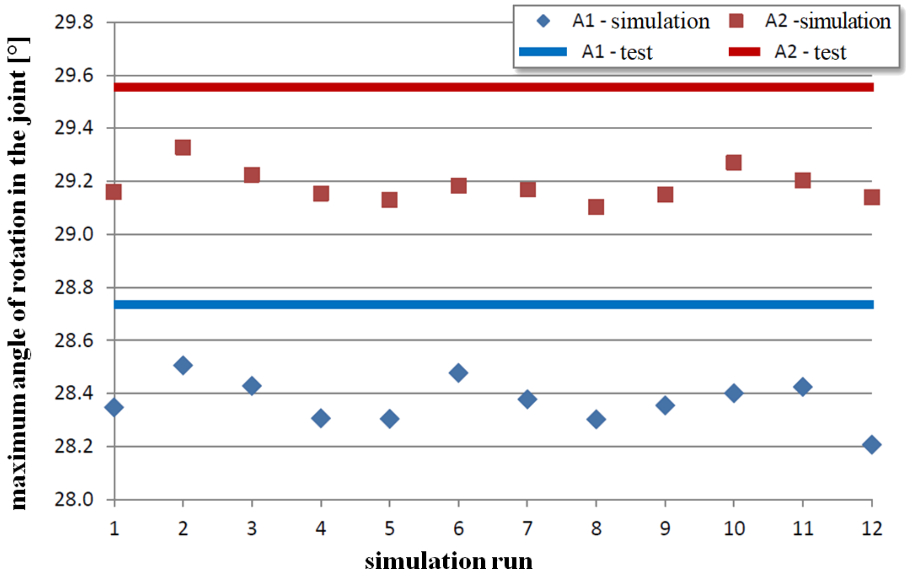

FIG. 12. Angle of rotation between cars – reduced equivalent stiffness of the system (0.48 kN/mm).

For the equivalent stiffness of the system equal to 0.48 kN/mm, the maximum swivel angles in the joints depend on the speed profile used. However, the difference between these angles for individual passes does not show such a high variation from the driving conditions – on average it amounts to 0.81°. The above equivalent stiffness value was considered to be the closest to the actual value.

7. CONCLUSIONS

The bogie steering system is a hydraulic system that affects limiting the yaw movement between individual carbodies and bogies of the vehicle. Its impact was mostly visible in situations where large angular displacements of the bogie relative to the carbody occurred during rapid changes of the curvature of the track. When running on a straight section of track or in a curve with a constant radius, the influence of the system was smaller, because the torsional flexibility of the secondary suspension in quasi-static situations causes the same effect.

The system ensures correct driving of the vehicle within the boundaries of the kinematic gauge and minimizes mutual undesirable movements of the carbodies while driving.

The greatest impact of the bogie steering system was visible during the initial phase of entering the curve. The least influence was observed during running on a track with a constant curvature or with a small change in curvature. The best results regarding system operation were obtained during tests carried out with the damping actuator switched off. For such a system configuration, the multibody numerical model was validated.

Based on the measurements results, it can also be stated that the correct system operation having the greatest impact on limiting the yaw angle between the bogie and carbody occurred for the situation of maximum stiffening of the hydraulic system (switching off the damping cylinder and disconnecting the damping nozzle). For this configuration, the greatest pressure differences were obtained between the circuits of the hydraulic system, but not exceeding the pressure values set at the safety overflow valves.

It was proved experimentally that the SSTJ system does not affect negatively the ride safety and ride comfort.

As part of the work carried out, the team managed not only to design, test and manufacture a prototype of the bogie steering system, but also to launch its successful serial production for one of the Polish cities.

Acknowledgment

All work was realized as a part of the research project "Innovative package of subsystems improving the functional and operational properties of light rail vehicles" (POIG.01.04.00-30-336/13), financed from the European Regional Development Fund under the Innovative Economy Operational Program.

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Received December 31, 2017; accepted version June 6, 2018.