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STUDY OF THE DERAILMENT SAFETY INDEX Y/Q OF THE LOW-FLOOR TRAM BOGIES WITH DIFFERENT TYPES OF GUIDANCE OF INDEPENDENTLY ROTATING WHEELS

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Abstract: *Modern tram designs use different conceptions of how to implement the low-floor functionality. The key construction part is the bogie running gear which has to accommodate the lower part of the tram body. To adjust the low-floor level, many low-floor tram bogies have different types of guidance of independently rotating wheels with no central axle between the two wheels. Lack of self-steering mechanism in the form of central axle coupling or an external guiding device creates several inherent problems, such as insufficient guiding and excessive wear. Another important context is the safety against derailment when the vehicle negotiates a curved track. In this study the dynamic behaviour of non-powered bogies with different types of guidance of independently rotating wheels are presented using computer simulation models. The simulation results of the Y/Q index are compared for the two track configurations (curved and tangent sections) and four different kinds of bogie running gear.*

Key words: *simulation, independently rotating wheels, derailment safety*.

1. Introduction

The low-floor trams are increasingly popular; they improve the accessibility of the tram for the public, and also may provide other comfort improvements like larger windows and more airspace. The most modern 100% low-floor designs typically accommodate bogies with independently rotating wheels (IRW) while some intermediate floor level solutions may use conventional wheelsets. Apart from the low-floor capability, the IRW concept also showed promise in other aspects (Dukkipati R. V., Narayana Swamy S., Osman M.O.M., 1992):

- reducing severe hunting present in high-speed railway vehicles with conventional wheels,
- reducing wear of rail and of the wheel tread and flange,
- improving the performance in curves by virtually eliminating longitudinal components of creep force.

Further studies in the last decades have proved the concept is feasible if appropriate guidance system is used, especially active one (T.X. Mei & R.M. Goodall, 2003). It is also possible to use solutions with mixed guidance method i.e. on tangent track a dedicated device stabilizes the independent rotating wheels by coupling them, while on the curved track the device is in the limited slip mode or turned off. This device could be in a form of simplified controller for the motors powering independent wheels, another example of such a device is clutch-type limited slip differential device (Wu et al., 2014). Therefore there are some ranges in which the IRWs could be used without fully active control mechanism, especially in medium radius curves. In this article, the dynamic behaviour of different kinds of IRW bogies is studied in the context of derailment safety, using non-linear vehicle model and tram track configuration of medium radius curve. The results are compared to the conventional bogie equipped with wheelsets. The bogies are not connected to the vehicle body.

Wheels mounted on a common solid axle must rotate at the same speed. When the wheelset shifts laterally, one wheel runs with a larger rolling radius than the other wheel. The resulting longitudinal creep forces at the wheel–rail interfaces on wheels of the same axle form a moment that gives the bogie a basic self-steering ability. Flange climb studies (Wu, H., Elkins, J., 1999) have shown that as the ratio of longitudinal force T_x to vertical force Q increases, the limiting value of the lateral to vertical force Y/Q ratio required for derailment also increases. Therefore, the Nadal flange climb criterion can be relaxed based on the level of longitudinal force. Longitudinal steering forces cause the available friction to saturate which reduces the effective friction coefficient for flange climbing, increasing the *Y/Q* ratio required for flange climb (TCRP, 2005).

Independently rotating wheels can rotate at different speeds and therefore produce no longitudinal forces to form a steering moment. This can lead to higher wheelset yaw angles, consequently higher lateral forces (before reaching to the saturation), higher *Y/Q* ratios, and increased wheel and rail wear. In addition, since there are no longitudinal creep forces, the wheel–rail friction acts entirely in the lateral direction, resulting in the shortest distance to climb and greater flange climb risk (Shen G., Zhou J., Ren L., 2006) (Allen P., Bevan A., 2008) (TCRP, 2005).

Another aspect of the running safety performance is the influence of the bogie frame suspensions characteristics and the wheels guidance method (Chudzikiewicz A., Sowiński B., 2015) (Kuba T., Lunger P., 2012). In this article the focus is put on the relation between the passive guidance method and the bogie performance in the context of safety against derailment according to Nadal's criteria (Kardas-Cinal, 2014).

2. Description of the models

In the comparison there are four bogies with different types of running gear arrangements taken into account:

a) conventional bogie with two self-steering wheelsets (each wheelset has two wheels connected by a solid, stiff axle), model of the bogie has 11 degrees of freedom, each wheelset has 3-DOF (lateral, pitch, yaw),
b) bogie with four independent wheels on two axle bridges (cranked axles), 23 degrees of freedom, each wheel has 3-DOF (lateral, pitch, yaw), each pair of wheels is connected elastically through the axlebridge which has 2-DOF (lateral, yaw),
c) bogie with four independent wheels individually mounted to the frame, 17 degrees of freedom, each wheel has 3-DOF (lateral, pitch, yaw),
d) bogie with four independent wheels mounted on four radial-arm axle boxes (swingarms), 33 degrees of freedom, each wheel has 3-DOF (lateral, pitch, yaw), each swing arm has 3-DOF (lateral, pitch, yaw).

Models are implemented in computer simulation program Simdel (Opala M., Melnik R., 2015) in the form of a system of rigid bodies connected with springs and dampers of linear characteristics. Equations of motion are generated automatically for any given structure of the system. It is also possible to generate 3D view of the system structure, which is presented in figure 2. System of rigid bodies interacts with the track through the higher kinematic pairs of wheels and rails profiles which are provided in the form of coordinates measured on real PST/Ri60n profiles shown in figure 1.

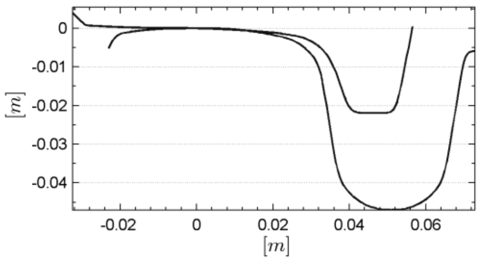


Fig. 1. PST wheel / Ri60n rail profiles

Model of contact is based on Kalker's simplified theory and FASTSIM algorithm. In order to calculate tangential contact forces the algorithm requires such input data as normal contact forces, coefficient of friction (assumed equal to 0.4), length of the semi–axes of the contact ellipses (calculated using Hertz theory), creep values which are given in the form of relative rigid slip:

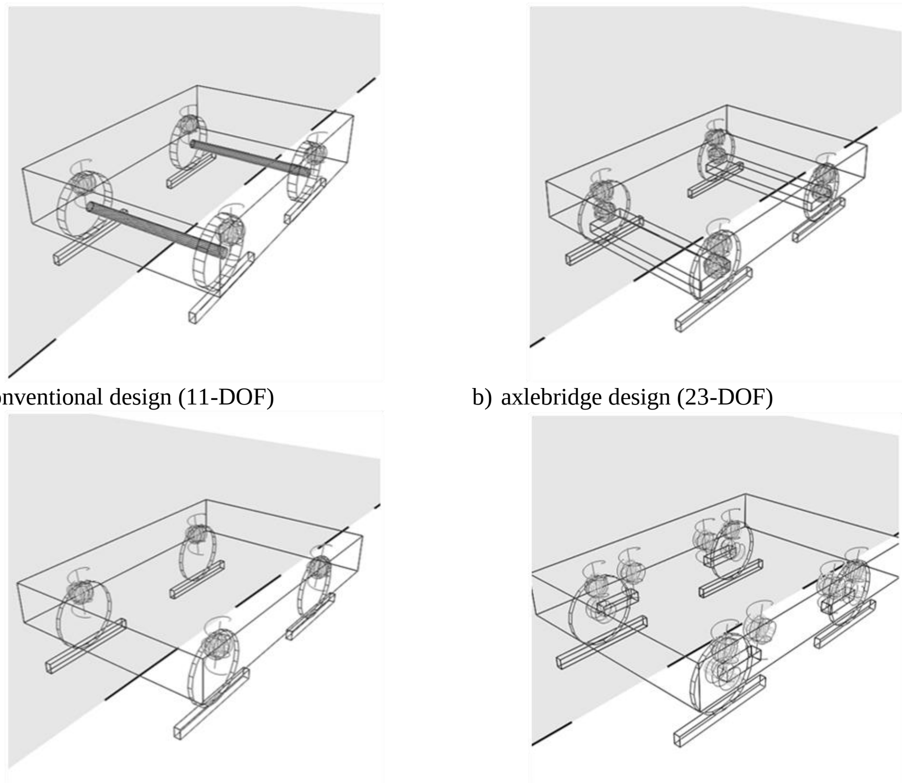
$$\begin{bmatrix} rs_x \\ rs_y \\ rs_z \end{bmatrix} = \frac{1}{vu_x} \begin{bmatrix} sv_x \\ sv_y \\ sv_y * \sin(\alpha) + sv_z * \cos(|\alpha|) \end{bmatrix} \tag{1}$$

where:

rs_x, rs_y – creepages (relative rigid slip) in longitudinal and lateral direction, rs_z – spin; α – contact angle; vu – speed of the moving reference frame (equal to the vehicle speed); sv – slip velocity:

$$\begin{bmatrix} sv_x \\ sv_y \\ sv_z \end{bmatrix} = \begin{bmatrix} vu_x \\ 0 \\ 0 \end{bmatrix} + \begin{bmatrix} 0 \\ vr_y \\ 0 \end{bmatrix} + \overline{\omega}_w \times \overline{r} \tag{2}$$

ω_w – relative angular velocity of the wheel; r – coordinates of the contact point in the reference frame connected to the wheel mass centre; vr – relative velocity of the wheel mass centre (in the moving reference frame).



a) conventional design (11-DOF) b) axlebridge design (23-DOF)

c) separate independent wheels (17-DOF) d) independent wheels on swingarms (33-DOF)

Fig. 2. Types of the running gear of the tram bogies in study

Intention of the study is to take into account the differences in the wheels guidance method and the structure of the bogie, keeping the other parameters such as masses, inertias and suspensions stiffness similar between the four presented models of the bogies as long as possible. Selected parameters of the models are given in tables 1 and 2.

Table 1. Masses and inertias data

Masses and inertias	*Wheel*	*Axle*	*Wheelset*	*Bogie frame*
Mass [kg]	335	90	774	2340
Roll inertia [kgm^2]	9.1	17	315	506
Pitch inertia [kgm^2]	18,2	2,2	38	422
Yaw inertia [kgm^2]	9.1	17	315	860

Table 2. Primary suspensions characteristics

Primary suspension	*Frame-wheelset axlebox*	*Frame-wheelmount*	*Frame-swingarm*
Longitudinal stiffness [kN/m]	4000	4000	4000
Lateral stiffness [kN/m]	3000	3000	3000
Vertical stiffness [kN/m]	1200	1200	1200
Yaw stiffness [kNm/rad]	–	2000	300
Damping [kNs/m]	30	30	30

The geometry of the bogies is also similar between the models; wheel base is 1.8 m, wheel nominal rolling radius 0.33 m, swingarm length 0.4 m, lateral semi-spacing of the axleboxes is 0.8 m.

3. Comparison of the results

3.1. General description

First part of the simulation studies comprise a ride through a smooth right circular arc with radius of 200 m without gauge widening (constant gauge 1435 mm) and without superelevation, the track layout is depicted in figure 3. No transition curve is present, only short insert of 1 m between the straight and curved section to avoid numerical issues. The vehicles ride with a constant speed of 30 km/h and after entering the curved section the cant deficiency is 0.053 m. The results of this part are given it the following paragraph 3.2.

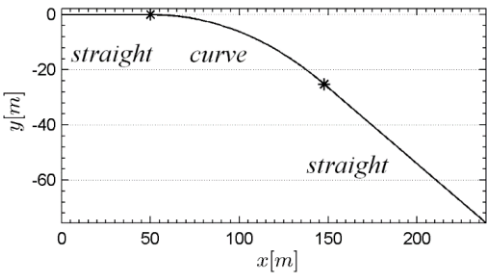


Fig. 3. Curved track section layout

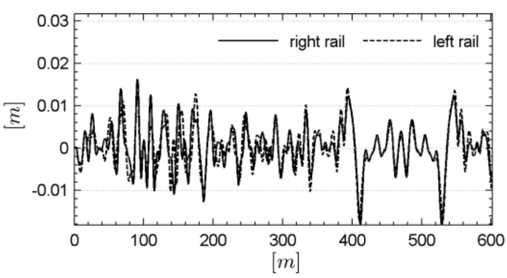
Second part of the study uses non-smooth tangent track section with lateral irregularities only, characteristics of the irregularities is given in figure 4. Maximum amplitude of the lateral irregularities is almost the same for the left and right rail, which is 0.018 m and the standard deviation is 0.005 m. Dominating wave lengths of the irregularities are 9 m, 15.4 m and 28.6 m. Irregularities have been measured on existing tram line.

3.2. Curving performance

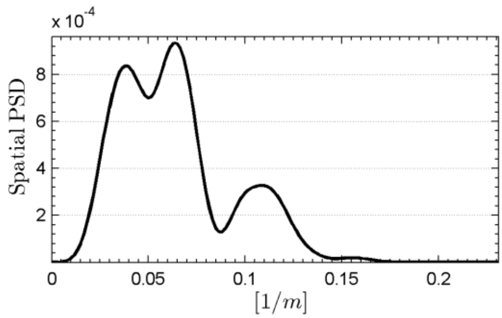
The results presented in figure 5 show the lateral position of the leading outer wheel relative to its initial position in the track, the wheel yaw angle relative to the track centre line and the bogie frame yaw angle relative to the track centre line. The track right-handed reference frame has the positive tangent axis congruent to the direction of the vehicle motion and the vertical axis' upward direction is opposite to the gravity direction.

The lateral position result is typical for the particular bogie design; wheelset of the conventional bogie (*a*) returns quickly to the central position in an oscillatory motion while the bogies with independently rotating wheels (IRW; *b*, *c*, *d*) perform a slow one-sided convergent motion. Among the IRW designs in the study, the bogie with swingarm guidance (*d*) shows the quickest convergence due to the small, non-zero value of the wheel yaw angle while the bogie frame is in the central position.

Figure 6 shows that conventional design has the largest amplitude of the wheel yaw angle when curving. It is connected to the fact that this bogie also has the largest amplitude of the frame yaw angle while the IRW designs in study have smaller amplitude of the frame yaw angle. The yaw angle of wheel in the axlebridge design is significantly smaller than in the model of separate independent wheels.

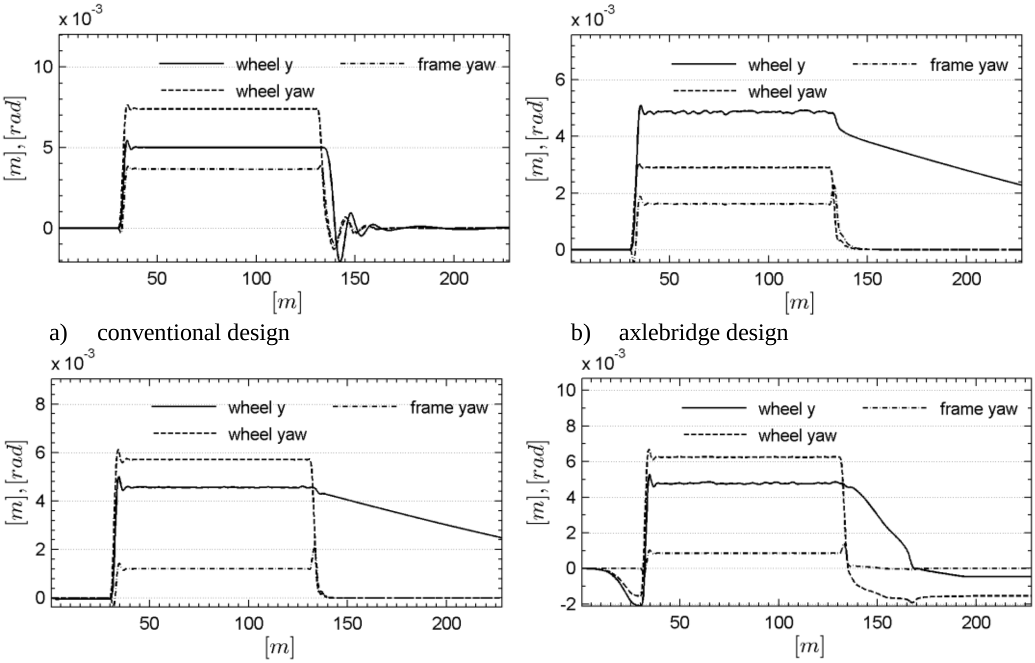


a) Amplitude



b) Spatial power spectrum density

Fig. 4. Lateral irregularities of the left and right rail



a) conventional design
b) axlebridge design
c) separate independent wheels
d) independent wheels on swingarms

Fig. 5. Comparison of the running gear kinematics for the leading outer wheel, relative to the initial position (lateral y position, yaw angle) and yaw angle of the bogie frame

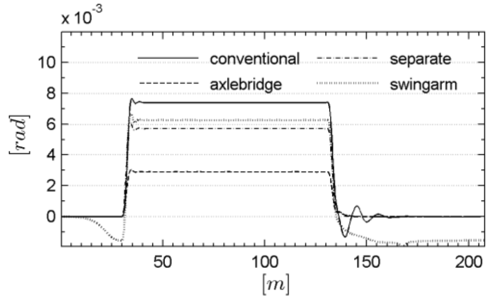
When the conventional bogie enters the track curved section, the front wheelset move immediately to the outer rail and the rear wheelset, immediately to the inner rail. In the IRW designs the front and the rear wheels also tend to move in the opposite directions but the rear wheels have smaller lateral displacement than conventional bogie. Directly after the curve exit an IRW bogie can take one of the two orientations: with close to zero yaw angle of the bogie frame or with a non-zero remaining yaw angle. The causes of a non-symmetric resetting of the IRW bogie after the curve exit are connected to the lack of longitudinal creep forces; further analysis of this mechanism is not carried out in this paper.

In all the cases, the amplitude of the lateral position of the leading wheels is similar when the bogies are running on the curved section. Figure 6 presents yaw angles of the leading and trailing wheels of the bogies; their values are correlated to the magnitudes of the lateral creep forces.

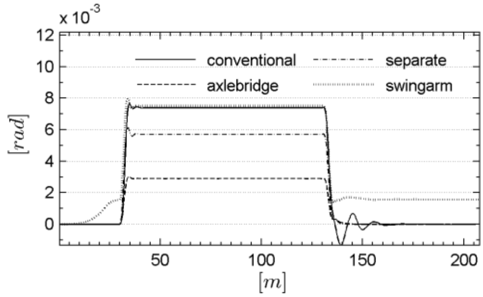
Although the IRW bogies have smaller values of the yaw angle of the frame and the front wheels, the *Y/Q* index values are generally higher in the same range as the conventional design or higher. This behaviour could be related to fact that the IRW wheels produce no longitudinal contact forces and allow for the higher saturation limit of the lateral creep forces. High amplitudes of the lateral creep forces add up to the higher value of the total lateral force *Y*.

The comparison presented in figures 7 and 8 shows the values of *Y/Q* derailment index of the leading outer wheels and the trailing inner wheels of the bogies in study. Figure 8 shows the IRW bogies have generally larger *Y/Q* index value than conventional bogie, at every wheel with one exception of the leading outer wheel where the differences are less evident. IRW bogies have larger *Y/Q* index value at the trailing inner wheel than the leading outer wheel (figure 8) while the conventional bogie have larger *Y/Q* value at the front outer wheel.

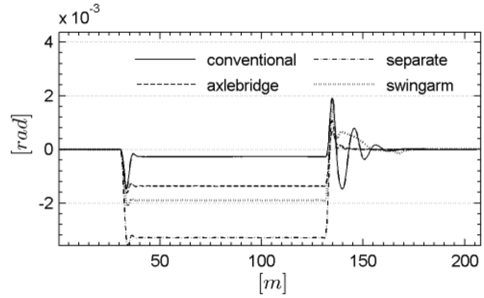
Despite some differences in wheels guidance mechanism of the IRW bogies, their curving performance is similar. In most of the cases it is easy to distinguish between the results obtained from the IRW and conventional bogie simulation.



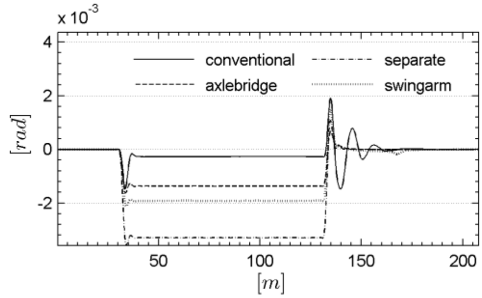
a) leading outer wheel (left)



b) leading inner wheel (right)

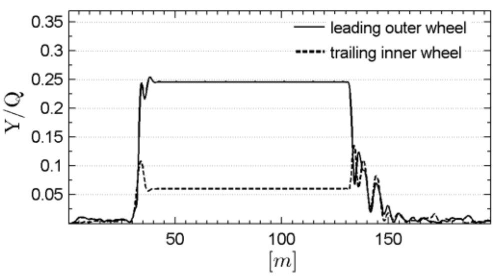


c) trailing outer wheel (left)

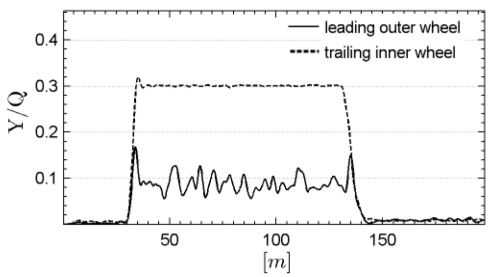


d) trailing inner wheel (right)

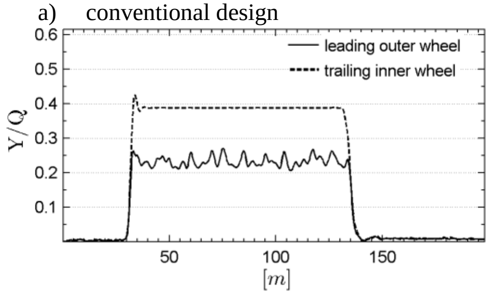
Fig. 6. Comparison of the wheel yaw angles



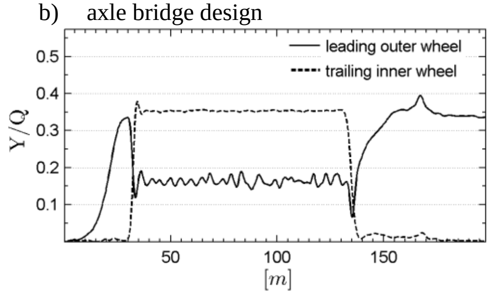
a) conventional design



b) axle bridge design



c) separate independent wheels



d) independent wheels on swingarms

Fig. 7. Values of the Y/Q derailment index for the leading outer wheel and the trailing inner wheel of the bogie

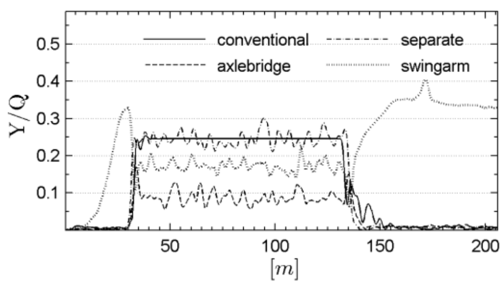
When the bogies enter the tangent section of the track there are visible differences between the bogie with swingarms and other bogies. In the figure 7 diagram (d) the leading outer wheel for independent wheels on swingarms significantly differs from the other diagrams. The same behaviour is visible in figure 8 (a) and (b). Due to the primary suspension stiffness configuration the leading wheels in this model have non-zero yaw angle on tangent track (the leading swingarms are allowed to an inward convergent alignment). Hence the leading swingarm wheels are rolling in slightly convergent direction, while the trailing swingarm wheels have the divergent direction of rolling. Resulting lateral tangential forces act in directions which further increase the yaw angle of leading swingarm wheels and decrease the yaw angle of trailing swingarm wheels. Therefore the *Y/Q* ratio of the both leading swingarm wheels is significantly higher on the tangent section than other wheels.

In real application when the yaw stiffness of the swingarms could be higher, such a behaviour would be less evident and the dynamics would be closer to the case of the separate independent wheels.

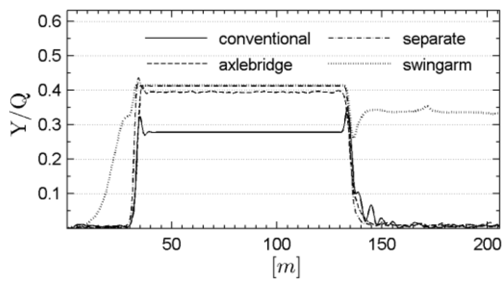
3.3. Bogies performance on tangent track with lateral irregularities

The track configuration used in this section is described in details at the beginning of the paragraph 3. The vehicles travel with a constant speed of 30 km/h along the tangent track section with lateral irregularities. Detailed statistical evaluation of the *Y/Q* index values for each of the bogie wheels are given in table 3.

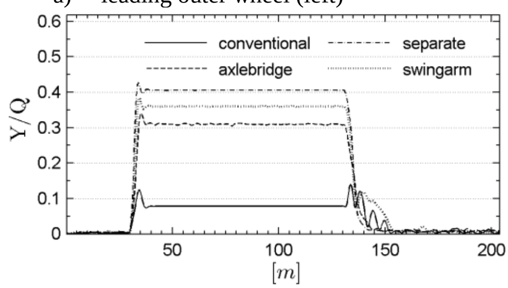
Initial analysis show little difference between the mean values of the Y/Q index between the left and the right wheels while running on the tangent track with lateral irregularities. More differences exist between the front and the rear wheels. Leading swingarm wheels have the highest mean value yet they have the smallest standard deviation value. The leading wheels have generally higher standard deviation values than the trailing wheels. The index value of the leading wheels is higher for the IRW bogies while the difference for the trailing wheels is less evident. The differences are mostly due to the individual peaks of the values while the mean values are in the same range.



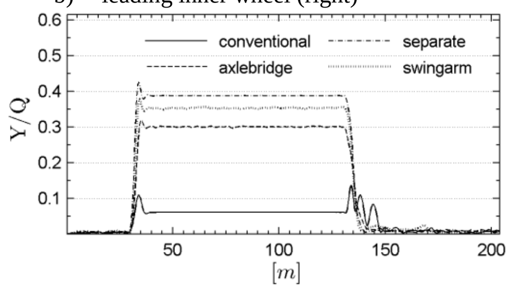
a) leading outer wheel (left)



b) leading inner wheel (right)



c) trailing outer wheel (left)



d) trailing inner wheel (right)

Fig. 8. Combined plots for the Y/Q derailment index of the bogies' subsequent wheels; leading outer wheel (left), leading inner wheel (right), trailing outer wheel (left), trailing inner wheel (right)

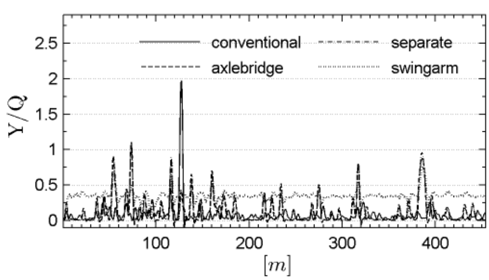
Table 3. Statistical evaluation of the Y/Q index for the bogies on straight track with irregularities

Leading left wheel			
bogie type	*max. estimated at 99.7%*	*mean*	*std. dev.*
conventional	0.56	0.08	0.16
axlebridge	0.68	0.11	0.19
separate	0.65	0.10	0.18
swingarm	0.60	0.35	0.08
Leading right wheel			
conventional	0.49	0.08	0.14
axlebridge	0.69	0.11	0.19
separate	0.68	0.11	0.19
swingarm	0.60	0.34	0.08
Trailing left wheel			
conventional	0.46	0.07	0.13
axlebridge	0.41	0.08	0.11
separate	0.37	0.08	0.10
swingarm	0.25	0.05	0.07
Trailing right wheel			
conventional	0.62	0.07	0.18
axlebridge	0.39	0.08	0.10
separate	0.38	0.08	0.10
swingarm	0.29	0.05	0.08

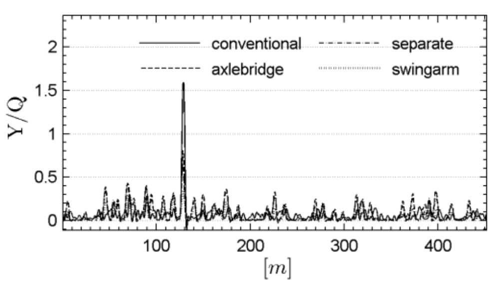
Results presented in figure 9 show an example plot of the *Y/Q* index values of the leading left wheel and the trailing left wheel. The plotted index values for the right side wheels are similar due to the tangent track configuration. The single biggest spike in the plot is related to the conventional wheelset, while the majority of the middle valued amplitudes are related to the IRW models.

4. Summary

In this study, a comparison of the bogie concepts used in the low-floor tram designs – bogies with independently rotating wheels and bogies with wheelsets – has been carried out. The investigation allows for a characterization of their dynamic behaviour in the context of derailment safety according to Nadal criteria, the simulations has been carried out using models for two configurations of track and four non-powered bogie designs which differ in relation to the wheels guidance system. First track configuration describes a smooth circular arc with radius of 200 m without transition curve and cant. Second track configuration describes the tangent track with lateral irregularities. The results of the *Y/Q* index and selected variables which describe the bogie motion have been shown for all of the four bogie wheels. The general conclusion that emerges from the comparison between the IRW bogies is that despite some differences in their passive guidance mechanism of the wheels, their performance in the context of *Y/Q* index is similar. The magnitude of the *Y/Q* index is in most of the cases larger for the IRW bogie than conventional bogie. Among the IRW bogies negotiating the curved section, the axlebrige design has the Nadal index values smaller than the bogie with separate independent wheels, while on the tangent section the results are similar. The results are obtained for free bogies (not connected to the vehicle body), what is intended for elimination of the influence of secondary suspension and the vehicle structure configuration.



a) leading left wheel



b) trailing left wheel

Fig. 9. Derailment index values on tangent track with irregularities

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