Coupled single-axle running gears—a new radial steering design

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Abstract: New railway vehicle concepts with broader and shorter carbodies necessitate new running gear concepts. One of the possibilities, the single-axle running gear, offers several advantages. The disadvantage of the conventional single-axle running gear during curving can be counteracted with a simple coupling between the single-axle running gears of the neighbouring carbodies.

This paper presents parameter analysis and design principle of the coupled single-axle running gears. They can be constructed for an almost ideal curve negotiation in a great range of curve radii. The coupling of the running gears not only improves the running characteristics in a curve but also increases the stability limit. Bombardier Transportation Winterthur has developed the coupled single-axle running gears called FEBA. The test runs with prototype as well as with serial running gears in the Norwegian commuter train Class 72 have fully confirmed the anticipated running characteristics.

Keywords: single-axle running gear, radial steering, wheelset coupling, vehicle dynamics, stability, curving

NOTATION

a	longitudinal distance between the carbody centre and the wheelset
a_{lat}	uncompensated lateral acceleration at track level
b	longitudinal distance between the vehicle coupling and the wheelset
$c_{\mathrm{S}x}$	damping of the yaw damper in the secondary suspension
D	residual damping (damping of the smallest damped eigenmode)
F_{S}	longitudinal force in the secondary suspension
$k_{\mathrm{D}x}$	serial stiffness of yaw damper
$k_{\mathrm{P}x}$	longitudinal stiffness of the primary suspension (per wheel)
$k_{\mathrm{P}y}$	lateral stiffness of the primary suspension (per wheel)
k_{rad}	radial stiffness of a spherical rubber element in the running gear coupling
$k_{\mathrm{S}x}$	longitudinal stiffness of the secondary suspension (per wheel)
$k_{\mathrm{S}y}$	lateral stiffness of the secondary suspension (per wheel)
k_x	longitudinal stiffness of the running gear coupling
k_y	lateral stiffness of the running gear coupling
$k_{\varphi z}$	yaw stiffness of the running gear coupling around the vertical axis
l	longitudinal distance of the spherical rubber elements in the running gear coupling
M_{φ}	moment around the vertical axis in the running gear coupling
R	curve radius
v_{cr}	critical speed
w	half the lateral distance of the secondary suspensions
Y	guiding force (lateral force) between the wheel and rail
α	steering angle between the wheelsets of the single-axle running gears of one carbody
β	steering angle between the wheelsets of the coupled single-axle running gears

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1 WHY COUPLE THE RUNNING GEARS?

In the case of regional and commuter trains the trend is increasingly towards broader and shorter coaches. In comparison with conventional vehicles they are shown to have better parameters, such as the number of seats or the utilizable area per weight unit. In the case of short carbodies with conventional bogies the permissible wheel set force is not utilized, and the share of the running gear in relation to the total weight is high. A better utilization of the permissible wheelset force can be achieved with the Jakob bogie (see Fig. 1 on the left). Using the Jakob bogie to support two neighbouring carbodies, the number of wheelsets per carbody is reduced to two instead of four using conventional bogies. However, this solution can only be implemented in articulated train sets.

Another possibility, until present rarely utilized, is presented by the single-axle running gears. However, they possess the disadvantage of unfavourable running characteristics in curves. Until the present, the radial steering of the single-axle running gear was realized with hydraulic steering systems, using the bending angle between the carbodies as an input signal [**1**, **2**] or with steering linkages between carbodies and wheels [**3**]. A theoretical study of passive and active steering systems for articulated vehicles with single axles is presented in reference [**4**].

Radial steering can also be achieved more simply by way of a coupling between the single-axle running gears of the neighbouring carbodies (Fig. 1 on the right). The coupled single-axle running gears ideally combine the characteristics of bogie and single axle. They can be used for articulated train sets independent of the type of carbody coupling. The radial steering utilizes the advantage of the running gear concept and requires no steering mechanisms between the wheelset and carbody or active elements. The design and technical execution of such innovative running gears will be described in more detail below.

2 VEHICLE DYNAMICS ANALYSIS OF RUNNING GEAR PARAMETERS

Coupling of the single-axle running gears of neighbouring carbodies should improve the running characteristics during curving, as well as heightening their running stability. These characteristics have been theoretically examined in a parameter analysis. The coupling of the running gears has been modelled using a coupling element with three translational stiffnesses and three torsional stiffnesses. The examined parameters of the running gear coupling are shown in Fig. 2.

The shear stiffness and the bending stiffness of the coupled single-axle running gears have significance for the stability analysis. The bending stiffness is determined through the yaw stiffness $k_{\varphi z}$ around the vertical axis and the shear stiffness by the lateral stiffness k_y of the coupling. The longitudinal stiffness of the carbody coupling k_x does not influence the examined characteristics. However, it does influence the type and construction of the carbody coupling. The yaw movement of the running gears around the vertical axis is damped by way of yaw dampers installed between the carbody and the single-axle running gear.

2.1 Curving

Through the coupling of the single-axle running gears, a combination of forced and passive steering of the wheelsets is achieved. Owing to yawing of the running gear versus the carbody during curving, the longitudinal stiffness of the secondary suspension k_{Sx} acts in one

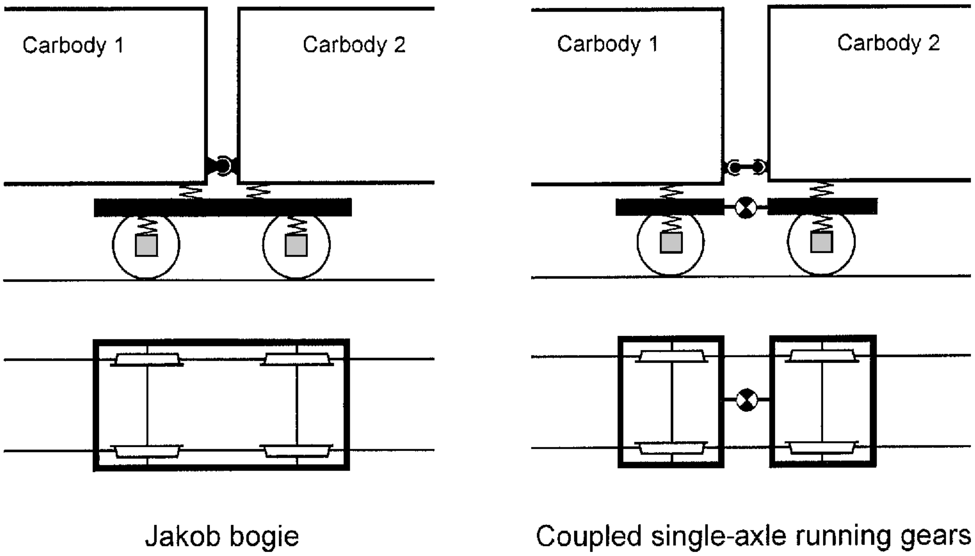


Fig. 1 Jakob bogie (on the left) and coupled single-axle running gears (on the right) supporting the neighbouring carbodies of an articulated vehicle

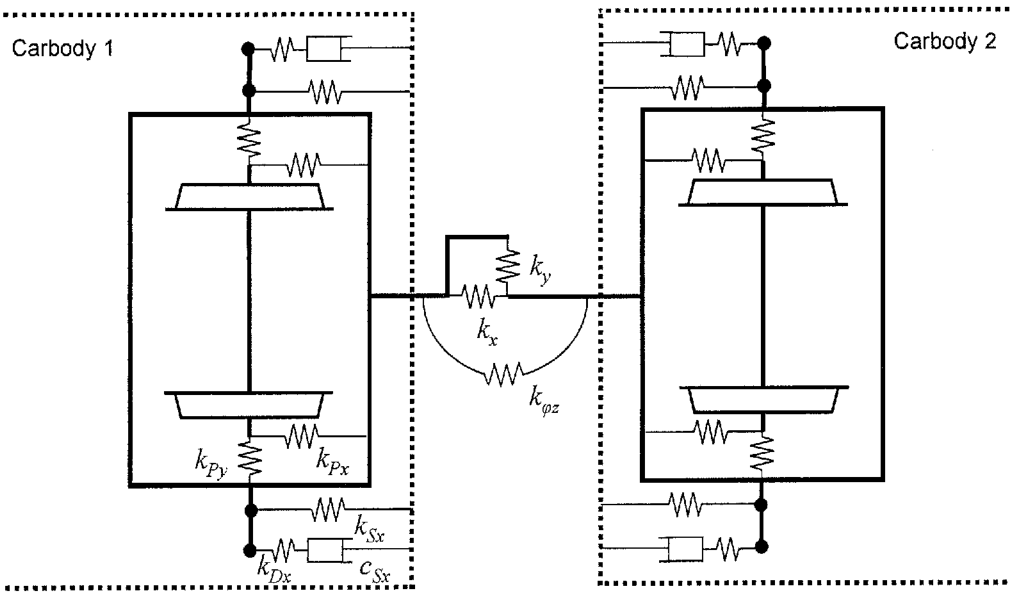


Fig. 2 Investigated parameters of single-axle running gears and their coupling (dampers in parallel to springs to model the eigendamping of rubber elements are not shown in the figure)

direction and the yaw stiffness of the coupling $k_{\varphi z}$ acts in the opposite direction. The single-axle running gear balances itself out in a position that lies between the stiff steered wheelset of a two-axle vehicle and the wheelset of the Jakob bogie with rigid axle guidance. If a sufficiently soft yaw stiffness of the running gear coupling is chosen, the wheelsets possess additional freedom to steer themselves even better in the radial position through the effect of longitudinal creep forces between the wheel and rail. Figure 3 illustrates the forces and moments acting on the single-axle running gear. The longitudinal stiffness of the primary suspension is assumed to be rigid. A ‘perfect steering’ of the wheelsets running through the curve in a radial position will now be investigated. Assuming the wheelset is in a radial position, there are zero longitudinal creep forces between the wheel and rail. Without the effect of the forces between the wheel and rail, the wheelset would remain in the radial position if the effective moments in the secondary suspension and in the coupling are balanced out:

$$M_{\varphi} = 2F_{S}w \tag{1}$$

It is assumed that a secondary suspension is symmetrical about the vertical axis (air spring, flexicoil spring). The longitudinal stiffness resembles the lateral stiffness ($k_{Sx} = k_{Sy}$), whereby the lateral stiffness is determined as a result of running comfort optimization. Assuming the ‘perfect steering’ using equation (1), the optimum yaw stiffness of the running gear coupling can be found by solving the equivalence of moments acting on the secondary suspension and on the running gear coupling during ‘perfect steering’:

$$k_{\varphi z} = \frac{a}{2b} w^2 k_{Sx} \tag{2}$$

If the condition (2) is fulfilled, the single-axle running gears will be radially steered during curving by the forces in the secondary suspension and in the wheelset coupling.

2.2 Stability

To investigate parameter influence on running stability, a vehicle dynamics parameter study is necessary. The results presented in this paper are based on the linearized multibody model of the real running gear and real vehicle. The objects investigated in this parameter study are the coupled single-axle running gears FEBA, developed by Bombardier Transportation Winterthur, formerly Swiss Locomotive and Machine Works Limited, and used in the commuter trains NSB Class 72. Descriptions of the running gears and vehicle mentioned can be found in Sections 4 and 5.

In the parameter study, the investigated parameters were varied whereas other parameters remained the same as those used in the vehicle mentioned. Using other default parameters of the single-axle running gear and of the vehicle, the results of the parameter study could vary quantitatively, but the qualitative correlation and determined tendencies would remain similar.

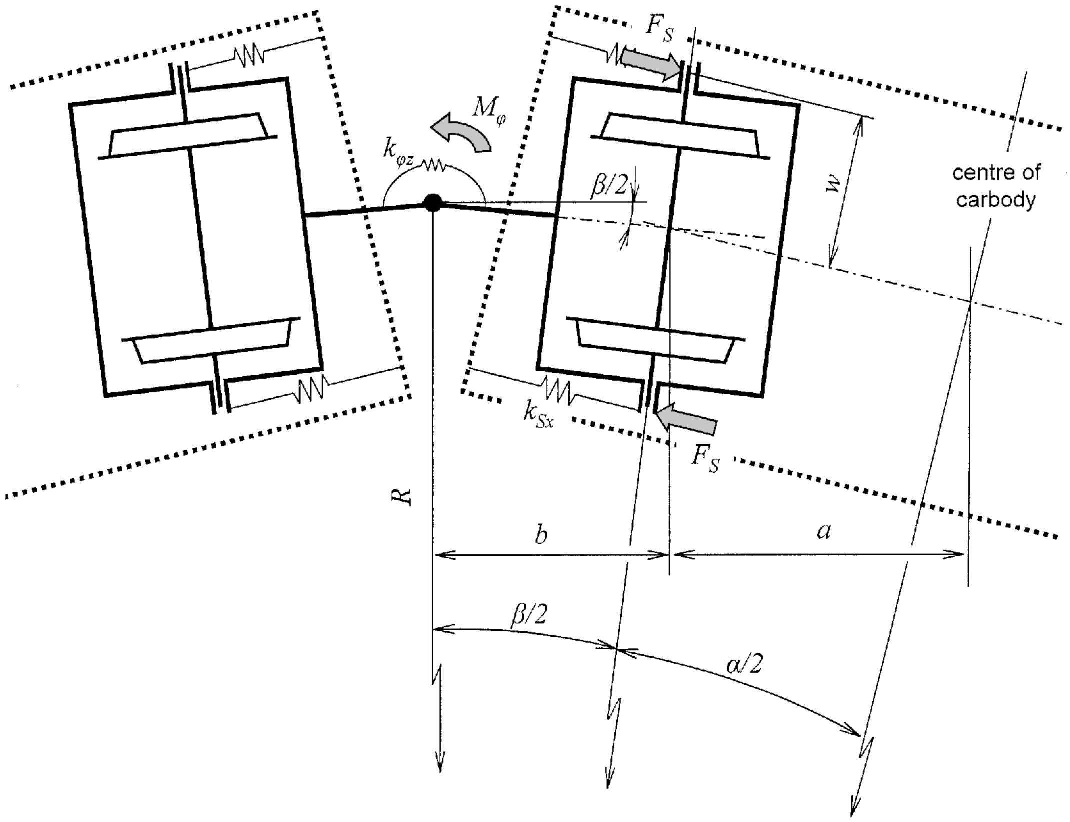


Fig. 3 Forces and moments acting on the coupled single-axle running gears during curving

The results of the parameter analysis are represented by stability contour plots for a residual damping $D = 0$ per cent at a wheel–rail conicity of 0.4 (the upper limit of the conicity for the testing and acceptance of the vehicle according to UIC-518 [**5**] for a speed between 140 and 200 km/h). At other conicities qualitatively similar results were observed.

In order to take into consideration a reduced effectiveness or failure of the yaw damper, the results for the vehicle with and without yaw dampers are discussed. The yaw dampers are installed between each single-axle running gear and the carbody supported on it. The yaw damper model considered serial stiffness to take into account the influence of internal flexibility and rubber end bushings. The parameter of the yaw damper was not varied.

The influence of the running gear coupling can be seen in Fig. 4. The stability increases with the gaining of yaw stiffness $k_{\varphi z}$ and the lateral stiffness k_y of the running gear coupling. In order to achieve a radially steering design, the yaw stiffness $k_{\varphi z}$ should be in the vicinity of the value according to condition (2), and therefore relatively low. Under this condition the stability can only be increased by the lateral stiffness k_y.

The analysis without yaw dampers shows that the critical speed of the single-axle running gear without coupling ($k_y = 0$, $k_{\varphi z} = 0$) and without yaw dampers is below 60 km/h. The coupling of the single-axle running gears increases the running stability. If the running gear coupling is designed with a higher lateral stiffness k_y, the stability of the running gear can also be ensured during a partial failure of the yaw damper or without yaw dampers for a low maximum speed.

For a vehicle with yaw dampers, similar tendencies can be observed as in the case without yaw dampers. A high critical speed together with good running behaviour in curves can be achieved for $k_y \gg k_{\varphi z}$. In comparison with the vehicle without yaw dampers, the lateral stiffness does not play such a significant role.

The influence analysis of the primary suspension (axle guidance stiffness) is shown in Fig. 5. In the case of a vehicle without yaw dampers, higher stiffness of the wheelset guidance in the longitudinal and lateral directions increases the critical speed. A more important role is played by the longitudinal stiffness k_{Px} of the axle guidance. An increase in the lateral stiffness k_{Py} firstly contributes to a heightening of the critical speed; however, from certain values onwards the stability limit remains constant.

In the case of yaw dampers, the stability limit is determined by the longitudinal stiffness k_{Px}; the lateral stiffness k_{Py} plays a subordinate role.

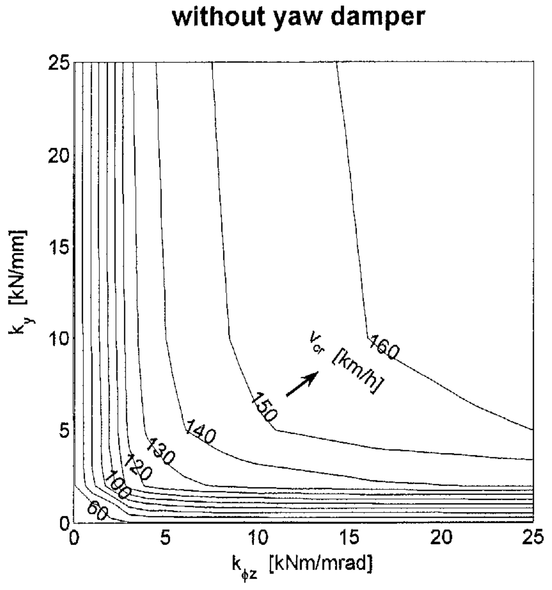


Fig. 4 Influence of coupling stiffness on the critical speed

2.3 Design principle for the running gear parameter

The theoretical analyses carried out determine the design philosophy of the coupled single-axle running gears. The areas of preferred parameters to achieve good curving performance together with high stability are shown in Fig. 6 for the stiffness of the running gear coupling (Fig. 6 on the left) and for the wheelset guidance (Fig. 6 on the right). The marked areas present preferred relations, where the absolute values have to be found from a detailed study of the function of design parameters and required properties.

The design principles for good curving performance were explained in detail in Section 2.1. The stiffness of the symmetrical secondary suspension $k_{Sx} = k_{Sy}$, defined by running comfort properties, is used to calculate the yaw stiffness $k_{\varphi z}$ of the running gear coupling required in respect to curving according to condition (2). However, the yawing stiffness value does not usually ensure an increase in running stability that is worth mentioning. Therefore, a higher value of yaw stiffness than that according to condition (2) can be used. For instance, if twice as much yaw stiffness of the running gear coupling was applied, half of the radial steering

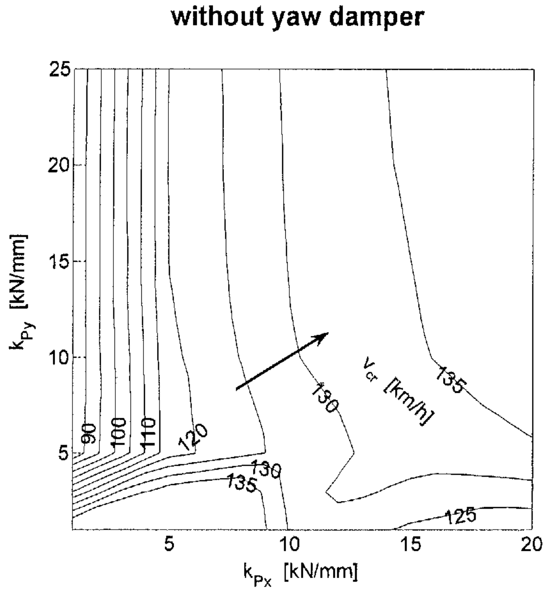


Fig. 5 Influence of axle guidance stiffness on the critical speed

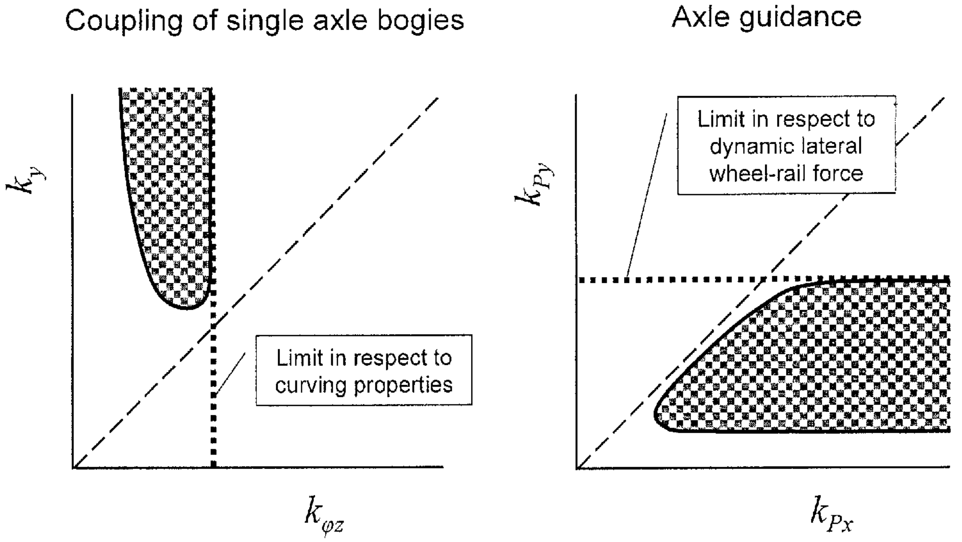


Fig. 6 Design principle for the coupling of single-axle running gears. The marked areas correspond to the prioritized parameters used to achieve a high stability limit on straight track and radial alignment during curving

would be achieved by the forced steering and half through the self steering of the wheelset caused by the creep forces between the wheel and rail. This radial steering—although partially dependent on the conditions in contact between the wheel and rail—functions considerably more efficiently than a radial steering of the wheelsets in a conventional bogie, which must act against the relatively high forces of the axle guidance. Increasing the value of yaw stiffness $k_{\varphi z}$ of the running gear coupling causes the stability to improve but the curving properties to become worse. To achieve some defined curving properties, e.g. not to exceed a limit of lateral wheel–rail force or a limit of angle of attack, the yaw stiffness parameter $k_{\varphi z}$ is limited as shown in Fig. 6 on the left.

The requirements regarding the running stability result from the parameter study. If the yaw dampers are not under surveillance, a reduced effectiveness of the yaw damper is more critical than the case of an intact vehicle. In the coupling of running gears, an increase in the critical speed can be achieved by increasing the lateral stiffness of the coupling k_y (see Fig. 6). An increase in the yaw stiffness $k_{\varphi z}$ would improve stability as well, but the value of $k_{\varphi z}$ is limited by the curving properties, as already mentioned. Therefore, to achieve good stability, the lateral stiffness of the vehicle coupling k_y should be higher than the yaw stiffness $k_{\varphi z}$. In the primary suspension, a very high longitudinal stiffness $k_{\mathrm{P}x}$ should be chosen, as the radial adjustment of the wheelsets will be realized in the secondary suspension. Using high longitudinal primary stiffness $k_{\mathrm{P}x}$, the lateral stiffness $k_{\mathrm{P}y}$ can be relatively soft. This allows the lateral dynamic forces to be reduced between the wheel and rail. Increasing the lateral stiffness $k_{\mathrm{P}y}$ causes the lateral dynamic wheel–rail forces to increase. If there is a limitation of lateral dynamic forces between the wheel and rail, the lateral stiffness $k_{\mathrm{P}y}$ of the primary suspension is limited as well, as shown in Fig. 6 on the right.

3 TECHNICAL SOLUTION

The design of the single-axle running gear coupling can be either:

(a) longitudinally stiff (rigid) or
(b) longitudinally soft.

The first solution can only be utilized for vehicles where no significant longitudinal displacements occur in the coupling between the carbodies. This design is mostly realized by a joint that also transfers the vertical forces, so that the weight force of the carbodies will be balanced out in the joint. A simple decoupling of the vehicles is scarcely possible in this case. To solve this problem Jakob's bogies are usually the preferable choice.

In the case of a longitudinally soft running gear coupling ($k_x \rightarrow 0$) various types of carbody couplings can be used without restriction. The construction enables a simple decoupling of the vehicles, allowing them to be shunted for maintenance reasons without the help of an additional auxiliary device. The longitudinally soft coupled single-axle running gears, called FEBA, have been developed by Bombardier Transportation Winterthur as a modern solution for regional service. They are suitable for a top speed of 160 km/h and maximum axle load of 20 t.

The technical principle of the single-axle running gear FEBA coupling is shown in Fig. 7. The single-axle running gears are coupled by way of two horizontal parallel aligned transverse rods, so that the single

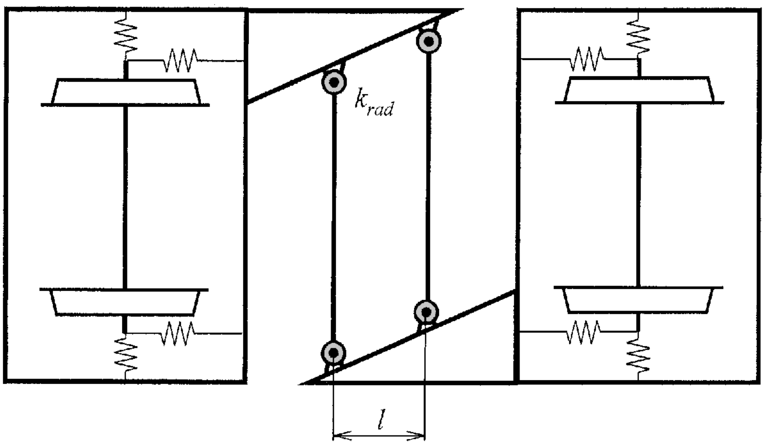


Fig. 7 Principle of the single-axle running gear coupling using two parallel lateral rods. The design allows free longitudinal and vertical motion of running gears to each other

running gears can move towards each other in a longitudinal and vertical direction. The yaw stiffness of the running gears around the vertical axis is determined by the radial stiffness of the spherical rubber elements k_{rad} and by the longitudinal distance of the coupling rods:

$$k_{\varphi z} = \frac{l^2}{4} k_{\mathrm{rad}} \tag{3}$$

The lateral stiffness of the running gear coupling is

$$k_y = k_{\mathrm{rad}} \tag{4}$$

Apart from the important parameters given in the equations (3) and (4), the torsional stiffness of the spherical rubber element and the flexibility of the frames of both running gears should be taken into account in the exact layout of the yaw stiffness and the lateral stiffness of the running gear coupling.

The coupling of the running gears enables optimum running behaviour during curving and increases the running stability, as detailed in Section 2. In comparison with the Jakob bogie, both running gears demonstrate a high torsional flexibility towards each other, providing better safety against derailment on bad track quality.

The design of the prototype running gears is based on components already extensively tried and utilized in railway vehicles (Fig. 8). The primary suspension of the single-axle running gear FEBA is constituted by rubber Chevron springs. Air springs with an auxiliary air volume serve as the secondary suspension. Two disc brakes provide the necessary braking power. The braking force transmission is realized by two traction rods, which couple each running gear longitudinally on its carbody and also support it against pitching. Two rubber elements centrally aligned over the axle constitute the lateral bump-stops and restrict lateral movement between the running gear and carbody. The

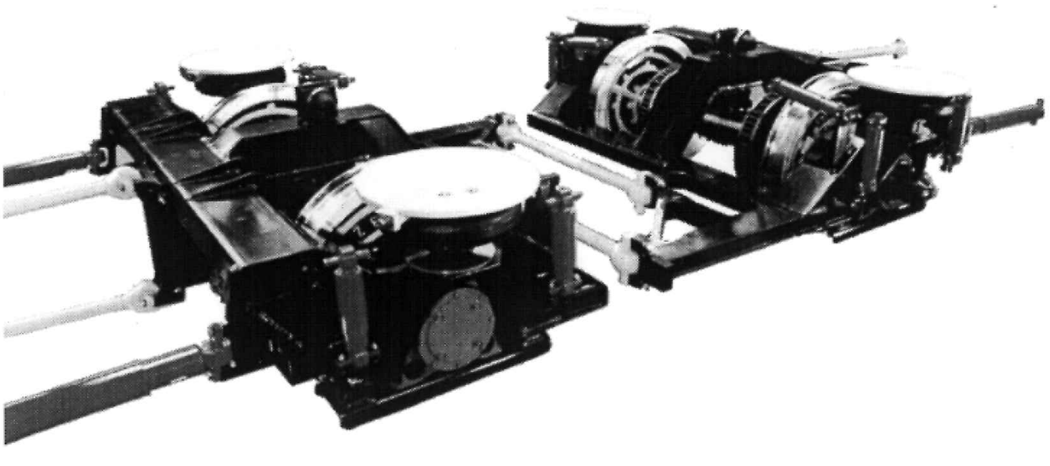


Fig. 8 The prototype of the coupled single-axle running gear FEBAs with measuring wheelsets to obtain the forces between the wheel and rail. The prototype was equipped with several additional dampers to test the optimal damper position

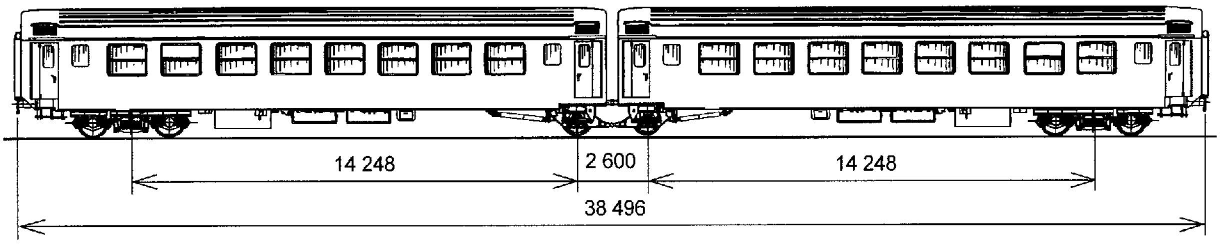


Fig. 9 Testing vehicle composed of two rebuilt short coupled passenger train coaches. The prototype of the coupled single-axle running gear FEBAs is assembled in the middle of the test vehicle

vertical, lateral and longitudinal dampers ensure quiet running behaviour and ride comfort.

4 TESTING

Prior to series application, two prototype running gears were subjected to extensive tests [**6**]. They were built into a testing device comprising two shortened SBB (Swiss Federal Railways) passenger train coaches (Fig. 9). The carbodies were coupled with a short coupling and supported in the middle on the single-axle running gear FEBA. The original bogies were retained on the ends.

The test vehicle was equipped with measuring sensors in order to test and to optimize the running behaviour. The wheel–rail forces were found by measuring the wheelsets. With further acceleration, displacement and force sensors, a total of approximately 90 measuring quantities were measured, calculated and stored. These data provided a complex picture of the running gear characteristics achieved.

The running behaviour on a track having a high number of curves as well as straight track was investigated. The curving test line possessed a high number of radii between 300 and 500 m. The tests were concluded with runs up to a speed of 176 km/h—a top speed of the running gears in the foreseen application increased by 10 per cent.

The test runs have completely confirmed the anticipated running characteristics. No unstable running behaviour could be observed in all test runs with an intact vehicle, notwithstanding the high conicity sometimes occurring between the wheel and rail in certain sections (up to 0.8). The running gears also remained stable during partial failure of the yaw dampers.

The capability of the running gears to steer themselves radially in a curve was judged by measuring the steering angle (Fig. 10) between the wheelsets of the coupled

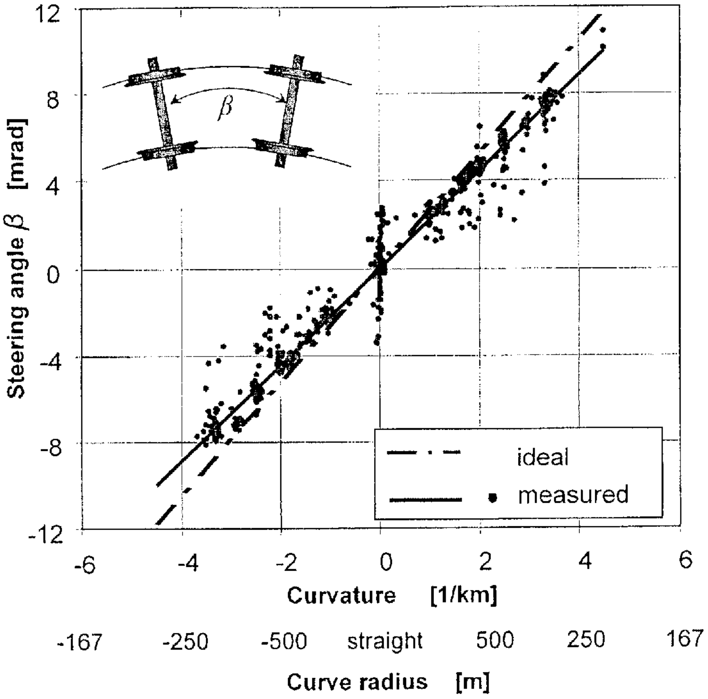


Fig. 10 Steering angle between the wheelsets of the coupled single-axle running gear FEBAs as a function of the curve radius. Measured values and their regression line in comparison with calculated ideal values (curved track, axle load 13 t)

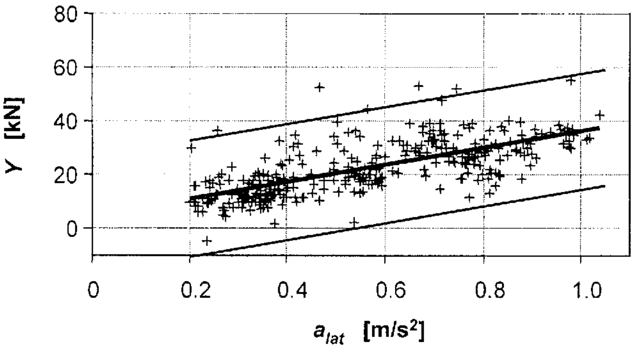


Fig. 11 Measured maximum dynamic lateral wheel–rail force on the leading wheel as a function of uncompensated lateral acceleration at the track level, evaluated according to UIC-518 [5] (curved track, axle load 18 t)

running gears. The ideal steering angle β_i can be easily calculated from the curve radius and the vehicle geometry:

$$\beta_i = \frac{2b}{R} \tag{5}$$

where

$2b$ = longitudinal axle distance of coupled running gears
R = curve radius

The closer the measured steering angle comes to the ideal steering angle, the better are the curving properties of the running gears. The measurements have confirmed a statistically almost ideal radial alignment of the wheelsets on the curved test line (see Fig. 10). Subsequently, the wheel–rail forces in curves with radii between 300 and 500 m are low, as can be seen from the maximum dynamic guiding forces between the wheel and rail measured according to the vehicle acceptance leaflet UIC-518 [5] (Fig. 11). It can even be observed that the maximum dynamic guiding forces lie beneath the quasistatic guiding force limit of 60 kN.

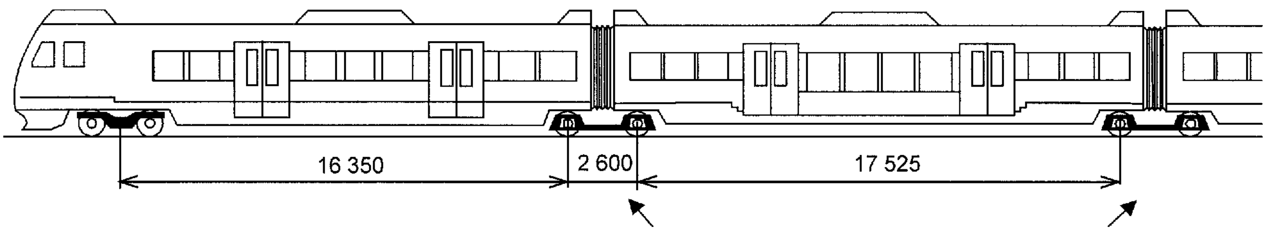
The running tests with the coupled single-axle running gear FEBAs have demonstrated that this running gear concept for articulated trains achieves a very good running behaviour. Particularly on track with a high number of curves, its characteristics clearly surpass the conventional design solutions.

5 SERIES APPLICATION

The single-axle running gear FEBA was chosen by the Norwegian State Railways for the new electrical units Class 72 (Fig. 12). The four-part commuter train with a top speed of 160 km/h was built in Consortium by ANSALDOBREDA and Bombardier. Two each of single-axle running gear FEBAs are coupled beneath the coach ends of the centre coach. On the ends of the composition, motor bogies enabling radial steering of the wheelsets by way of soft wheelset guidance are used.

The serial design of the single-axle running gears [7] can be seen in Fig. 13. Contrary to the prototype, the running gears possess three disc brakes and an anti-roll device. The primary suspension is constituted by rubber Chevron springs. The weight-optimized running gear frame, comprising two longitudinal beams and two cross-beams, is of a hollow girder design. The lower cross-beam is positioned in the direction of the coach end. On this girder the support for the laterally aligned coupling rods is positioned and the torsion rod of the anti-roll device is fixed. The upper cross-girder on the opposite side is of a tubular design, and serves simultaneously as a support for the mounting of the traction rods and the brake lever unit and as an auxiliary air container for the air suspension system. The air supply occurs through the bogie frame from the under side of the air spring through the rubber–metal spring of the emergency suspension. A mounting plate is provided above the air spring bellows on which the carbody-side connections of the secondary dampers in the vertical and lateral directions, as well as the yaw dampers and the pendulum of the anti-roll device, are positioned. Two lateral bump-stops, which have the task of limiting the lateral suspension clearances, are positioned in the running gear frame above the centre brake disc.

In the autumn of 2000, the first vehicle NSB Class 72 was subjected to a provisional running dynamics type test in Norway. At that time, the safety-relevant criteria



Coupled single-axle running gear FEBAs

Fig. 12 Half of the four-part commuter train Class 72 of Norwegian Railways

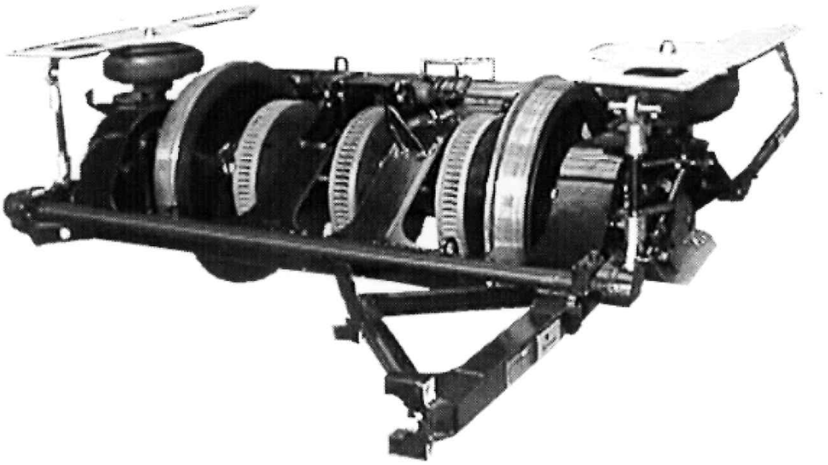


Fig. 13 Serial design of the single-axle running gear NSB Class 72

and the track requirements for a fully loaded vehicle were tested. The test demonstrated the fulfilment of the anticipated design results and compliance with the limiting values. In the summer of 2001, the final type test of commuter train NSB Class 72 was successfully completed.

6 SUMMARY

The coupled single-axle running gear FEBA constitutes an attractive solution, mainly suited for articulated train sets with a conventional bogie or an active or force-steered single-axle running gear on the vehicle end. In contrast to the Jakob bogie, the train parts can be simply decoupled and individually shunted for maintenance purposes.

The single-axle running gear FEBAs steer themselves radially in curves without steering mechanisms between the wheelset and carbody or active systems. They can be designed for almost ideal running in curves in the complete range of traversable curve radii. Through the utilization of these running gears on lines with a high number of curves, a significant reduction in wear and the avoidance of squealing in the curves can be achieved. The coupling of the single-axle running gears not only improves the running characteristics in curves but also increases the stability limit. When used for applications with a low maximum speed, a yaw damper is unnecessary. When a yaw damper is used, a higher running speed is permissible, even in the case of reduced operational effectiveness of the damper or failure of the same.

The prototype of the running gear FEBA was tested extensively in a test vehicle. The test runs with series running gears in the Norwegian commuter train Class 72 have fully confirmed the anticipated running behaviour.

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