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# Wheel sets or independently rotating wheels – from theory to practice

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# Abstract

Bogies with independently rotating wheels (IRW) seem to be only a compromise because there is a lack of space for an axle. This paper explains the theory of track guiding by IRW and shows that IRW have some advantages over conventional wheelsets when these are used in tramway systems with their tight curves. These considerations are then backed up by field data, demonstrating that trams with IRW offer excellent ride quality and low levels of wheel/rail wear – if the particularities of this principle are considered.

## 1. Introduction

“Axle or no axle, that is the question!” This misquotation of Shakespeare aptly sums up what has to be considered for the guidance concept of tramway running gears. Whereas main-line railways almost exclusively make use of bogies with stiff wheelsets, there is disagreement in the tram sector. As tempting as the possibilities of independently rotating wheels (IRW) are for low floors all the way through the passenger compartment, there is equally great skepticism about giving up the wheel set axle principle that has been tried and tested in almost 200 years of service.

This paper should help, on a factual basis, to decide which guidance principle represents the best compromise for actual conditions of use. Whereas the surprisingly complex theory of the movement of independently rotating wheels was highlighted in [1] and [2], this paper establishes the relationship with the overall vehicle and presents results gained from practice. As good as our theoretical understanding of track guidance may be, only practice can show whether the compromise between the different requirements has succeeded. Using the example of the Siemens Avenio low-floor tram for Munich, this paper shows how a successful implementation with a high quality ride comfort and low wear can appear in practice.

## 2. Requirements for running gears

If different concepts are to be assessed, the requirements must first be clarified. The focus here shall be on requirements that differentiate between concepts. For example, reliable guidance is a fundamental prerequisite and features in every approved vehicle. Wear behavior and ride comfort, however, are strongly influenced by the track guidance concept.

### 2.1 Low wear

The re-profiling and replacement of tires due to wear is one of the most expensive individual items in vehicle maintenance. It is clear that the guidance principle has a considerable influence on this. Particular attention will be paid to this subject in the following.

### 2.2 High level of ride comfort

Influenced by the design criteria of the main-line railways, vibrations in the z-direction (vehicle vertical axis) are key to the assessment of ride comfort. In the case of trams, however, due to the frequency of changes in the track curvature, the comfort in the y-direction (vehicle transverse axis) is at least as important. It is essential here to demonstrate how and to what extent this is influenced by the guidance concept.

### 3. Assessment of the guidance of wheelsets and IRWs

#### 3.1 What is guidance?

Guidance is the specification of the direction of movement of vehicles by the guideway. This requires that the bogies must automatically be able to free themselves from incorrect orientations. Possible incorrect orientations are a lateral offset, a misalignment within the track or the combination of the two (Fig. 1). The wheel-rail contact forces necessary for the centering can be geometrical profile forces or frictional forces.

Frictional forces occur in the case of a rolling wheel when there is a relative movement – a slip – between the wheel and rail contact surfaces. This may be in the longitudinal direction, as in the case of a driven or braked wheel (Fig. 2, right) or in the lateral direction. A slip in the lateral direction occurs when the wheel, as shown in Fig. 2, left, is not aligned parallel to the rail. The overall movement in the contact point is not totally aligned with the rolling direction, and thus, the lateral component results in slip. Longitudinal and lateral friction forces can be used for guidance, but are associated with wear, as slip and force both point in the same direction and thus perform work – wear work.

Geometrical profile forces are understood to mean the normal force at the rail-wheel contact point. If this force has a component in the lateral direction (designated  $S_y$  in Fig. 3), this may be used for guidance. As the main direction of wheel movement follows the rail in the longitudinal direction of the track,  $S_y$  is perpendicular to this and thus does not perform any work. Guidance with geometrical profile forces is therefore practically free from wear.

#### 3.2 Running on straight track

##### 3.2.1 The wheel set

The guidance mechanisms of the wheel set on straight tracks are generally well known. If a wheelset is offset laterally, the wheel radii at the contact point of the wheels are different. Due to the rigid rotational speed coupling, one wheel becomes the driving wheel and the other becomes the braking wheel. This leads to a “steering movement” that guides the wheel set back to the track centre. The movement continues beyond the centerline, until a situation arises that is the mirror image of the starting position – and the process begins again (see Fig. 4).

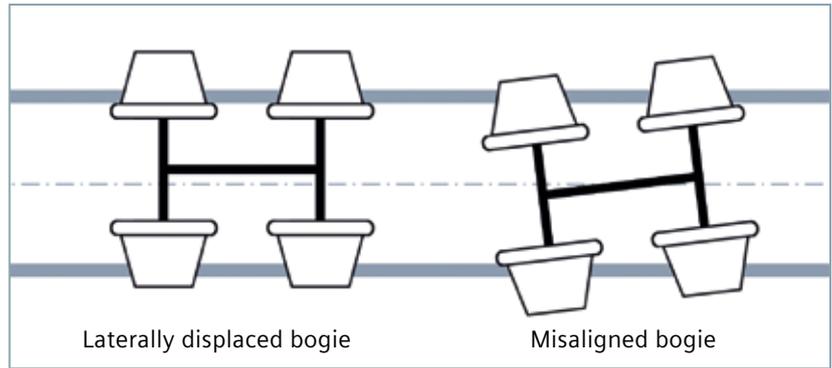


Fig. 1: Possible incorrect positions of the running gear on the track

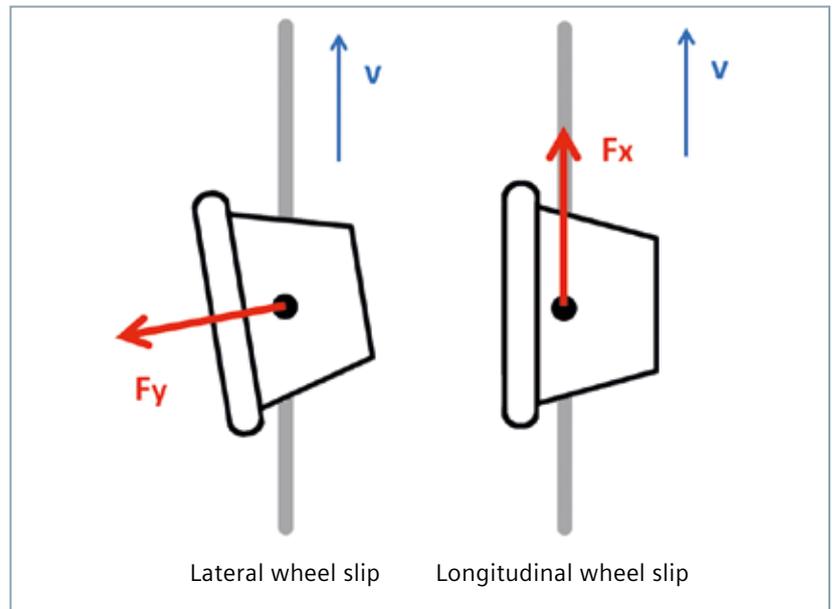


Fig. 2: Friction forces in transverse and longitudinal direction at the wheel/rail contact point  
 $v$ : Running speed  
 $F_x, F_y$ : Friction forces

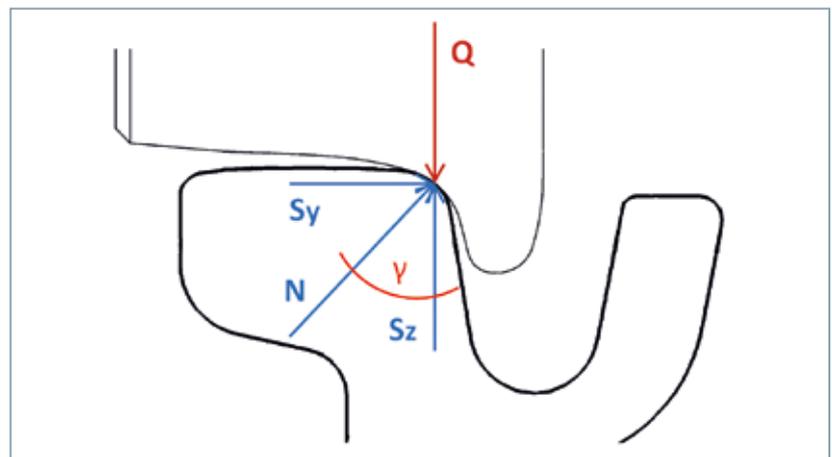


Figure 3: Breakdown of the geometrical profile forces at the wheel/rail contact point  
 $Q$ : Wheel load  
 $N$ : Normal force in the contact surface  
 $S_y, S_z$ : geometrical profile forces in y and z direction  
 $\gamma$ : Contact surface inclination

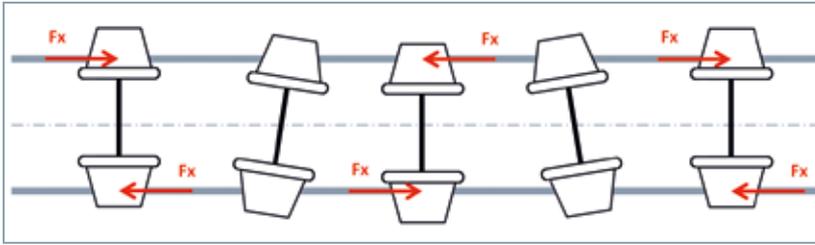


Fig. 4: Hunting motion of the wheel set  
 $F_x$ : Longitudinal friction force

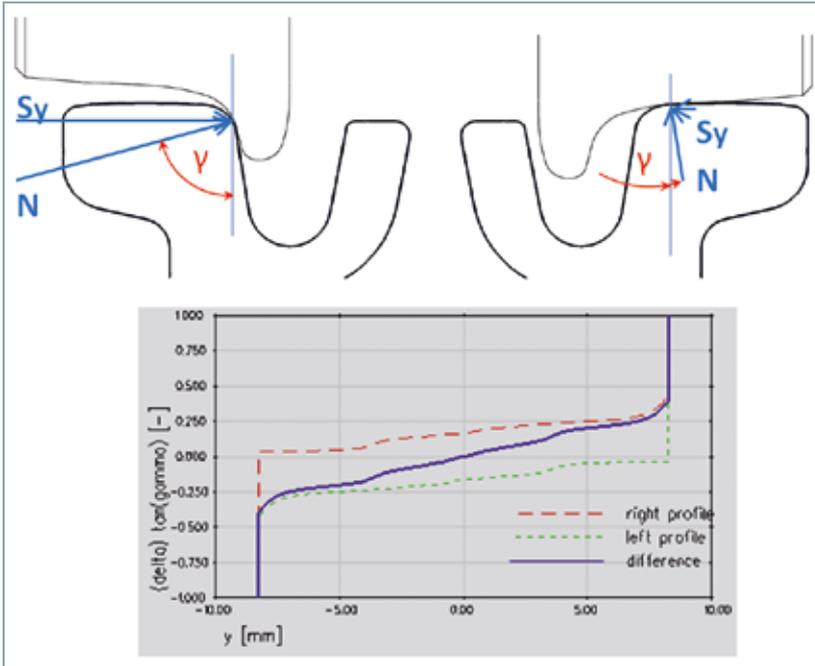


Fig. 5: Balance of forces on laterally offset pair of single wheels  
 $N$ : Normal force in the contact surface  
 $S_y$ : Geometrical profile forces in  $y$  direction  
 $\gamma$ : Contact surface inclination  
 $\text{delta tan}(\gamma)$ : Centering factor

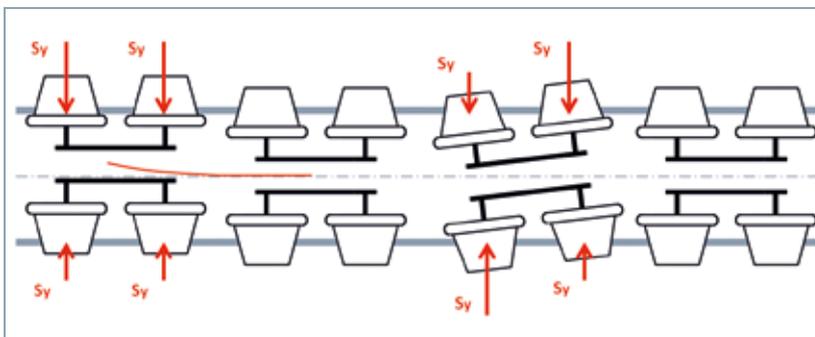


Fig. 6: Release of IRW from lateral offset and misalignment due to geometrical profile forces  
 $S_y$ : Geometrical profile forces in  $y$  direction

This repeated movement is called “sinusoidal or hunting motion” [3] and was described for the first time by Johannes Klingel in 1883.

It is clear that this mechanism alone is sufficient to correct not only a lateral offset, but also a misalignment within the rail. This functions just as well for a single wheel set as for two wheel sets combined to form a bogie.

“Hunting motion” on straight tracks results in a largely evenly distributed abrasion of the wheel treads, whereby however only longitudinal friction forces are “used”, which are prone to cause wear. The axle movement of the wheel set is transferred to the entire vehicle and thus affects the ride comfort. In addition, the stability of the hunting oscillation depends on the running speed. For each design there is a “critical speed” above which the running becomes unstable and the vehicle inevitably derails. This speed can be influenced by a variety of design parameters, so that it does not pose a hazard in practice. The effect, however, forces compromises to be made in the design to the disadvantage of ride quality and wheel-rail wear.

### 3.2.2 The independently rotating wheel

The guidance of IRWs is based on completely different modes of action in which the wheel profile geometry plays a decisive role. Whereas a conical profile is sufficient for the wheel set hunting oscillation, the geometry in the case of independently rotating wheels must exhibit an increasing gradient from the wheel tread to the wheel flange. Fig 5 shows that a lateral offset of the pair of wheels results in unequally large  $S_y$  forces on the left and right wheels, so that a centering effect is created. The magnitude of the centering force is a function of the lateral offset. The diagram represents the centering factor “delta tan(gamma)”. This, multiplied by the mean wheel load, produces the centering force acting on the pair of wheels. On railways using IRWs the centering force is responsible for the release not only from a lateral offset, but also from a misalignment of the bogie (see Fig. 6). The geometrical profile forces  $S_y$  act vertically to the running direction and are therefore practically free from wear.

The hollow profile geometry necessary for the guidance of IRWs offers further advantages over conical profiles. As far back as the early 1970s, the UIC-ORE Standardized Profile S1002 [4] was developed for mainline railways. The aim of this development was to guarantee a profile form that would remain as constant as possible over the service life, despite the unavoidable wear. Although nobody thought of IRWs during the development, the S1002 would have been quite suitable for achieving reasonable guidance with IRWs.

Due to the lack of a rigid rotational speed coupling between the IRWs, there is in practice no hunting oscillation and thus no resulting "critical speed" or negative impact on ride comfort. Interestingly, Prof. Dellmann and Dr. Abdelfattah demonstrate in [1] and [2] that a pair of independently rotating wheels also performs hunting oscillation similar to that of a wheel set. The examinations relate however to an individual pair of independently rotating wheels without a carbody supported on them. If one adds to the model a connection to the running gear and the mass and mass inertia of a car body, the effect is lost – as is to be observed in practice.

It should be remembered that the centering effect exclusively from the geometrical profile forces is less than that of a wheel set. When designing the running gear, therefore, great importance must be attached to the exact parallelism of the "axles" as well as of the wheels. If this is successful, the unwanted single-sided wheel flange contact of IRWs does not arise either.

### 3.2.3 The comparison

Wheel sets represent a functioning guidance concept that has been known for almost 200 years which, however, on the basis of the hunting oscillation, induces unwanted vibrations into the vehicle. IRWs are not subject to this effect and thus allow very calm running with low wear on straight tracks. A low level of wear, however, presupposes particular attention being paid to axle and wheel parallelism and a suitable wheel profile in the design of the IRW running gear.

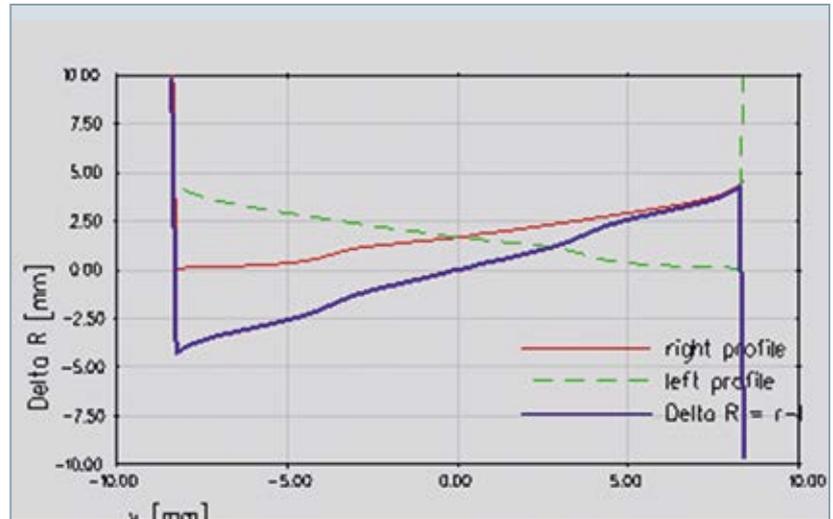


Fig. 7: Wheel radius difference between left and right wheel with lateral offset in track  $\gamma$ : Lateral offset in track  
Delta R: Difference in radius of the wheels

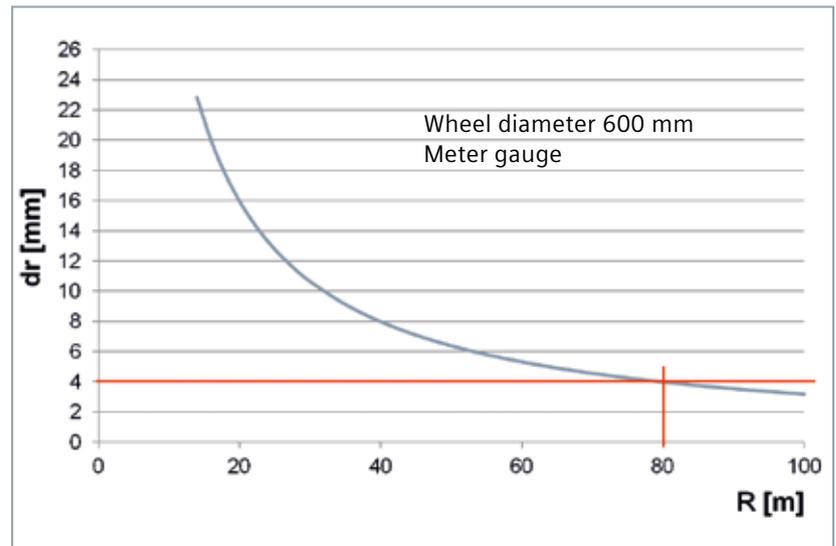


Fig. 8: Wheel radius difference that is necessary for rolling free from longitudinal slip, in relation to curve radius.  
dr: Difference in wheel radius  
R: Curve radius

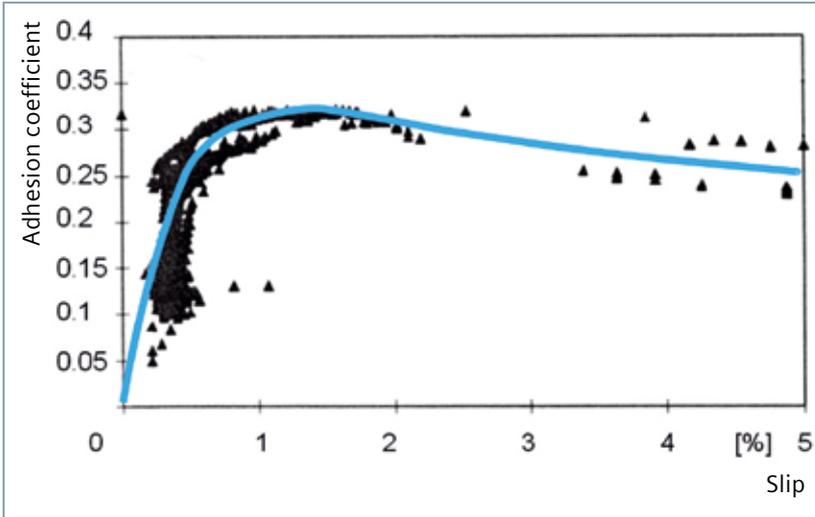


Fig. 9: Friction force slip function for the longitudinal direction according to a measurement determined by Deutsche Bahn (Source [5])

### 3.3 Running in a curve

#### 3.3.1 The wheel set

Despite the rigid rotational speed coupling between the rotation of inner and outer curve wheels, wheel sets can roll without slip on large radii curves. This is possible because the lateral offset towards the outer rail of the curve causes a wheel radius difference  $\Delta R$  to build up (see Fig. 7), which means that the circumferential speed at the contact point for the outer wheel is greater than that of the inner wheel. This property – the automatic steering in curves

– makes the wheel set the (almost) undisputed guidance element for main-line railways. One way in which tram networks differ from main-line railways, however, are in their significantly tighter curve radii. Radii of 20 m are frequently encountered and even 15 m radii are to be found. The mechanism of the wheel sets, however, no longer functions with these small curve radii. Fig. 8 specifies for a typical tram system which wheel radius difference is necessary in order to enable the wheels to roll without longitudinal slip. By adopting a reasonable wheel/rail pairing the maximum possible difference is 4 mm. At this point, contact occurs between the wheel flange and the rail. These 4 mm, however, only permit slip-free running on a 80 m radius curve. Even the “popular” 25 m radius curve requires a 14 mm difference. It is clear that longitudinal slip is the rule rather than exception when negotiating tramway curves with wheels sets – longitudinal slip that inevitably leads to wear. This can be quantified by means of an example:

Running on a curve with  $R = 30$  m under the conditions shown in Fig. 8 geometrically produces a longitudinal slip of 1%. According to Fig. 9 on a dry rail, this results in a friction force coefficient of 0.3. With a wheel load of 40 kN (VDV 2/3 loading) a frictional force of 12 kN is acting on every wheel!

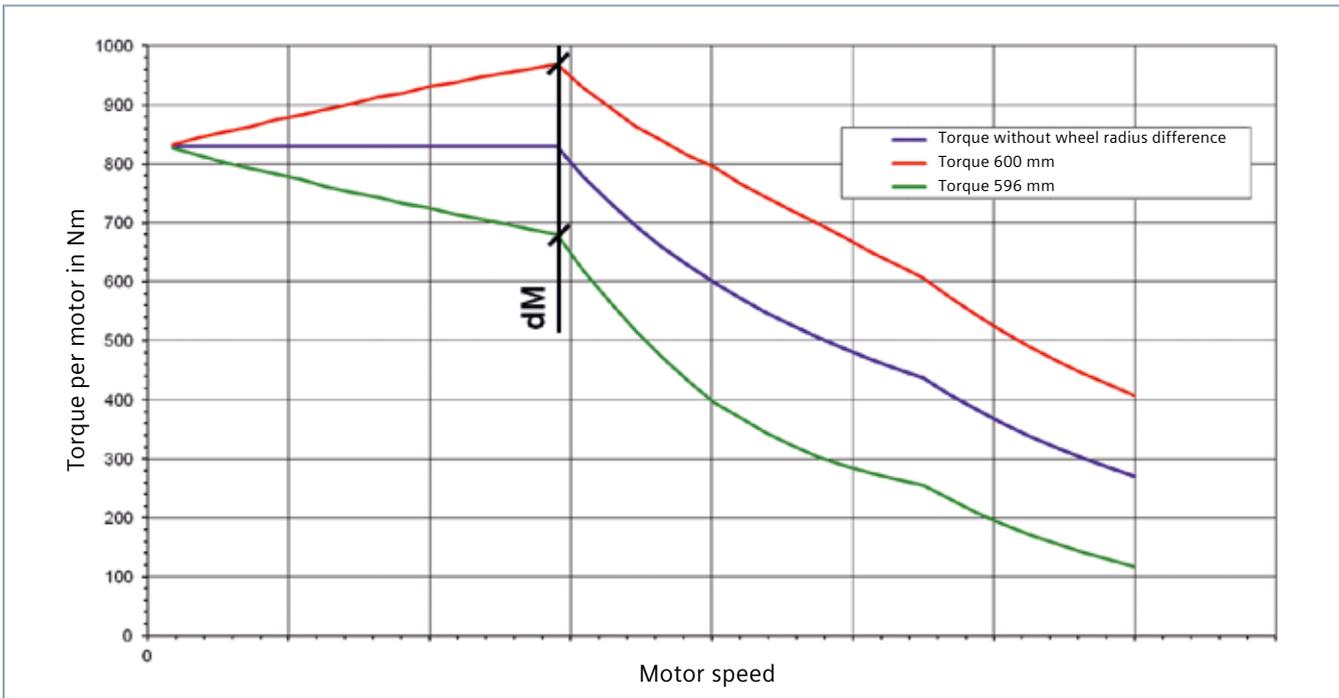


Fig. 10: Torque-speed characteristic of the Avenio motors when controlled via a common traction converter with or without wheel radius differences at the contact points  
dM: Differential torque between right and left motor

### 3.3.2 The independently rotating wheel

The mechanism that allows IRWs to steer automatically in curves is the same that releases them from misalignment on a straight track (see Fig. 6). Whether the running gear is misaligned relative to the track, or the track turns under the running gear (entry to curve), is unimportant. IRWs have no rigid mechanical rotational speed coupling and are therefore in principle not affected by the longitudinal slip that occurs in tight curves – provided they are not connected by means of an “electrical shaft”. The right and left wheels on IRWs are frequently controlled by the same traction converter and therefore receive a stator phase sequence with an identical rotational speed. If the rotational speed of the wheel were linked rigidly to the phase sequence, this would produce the same conditions as in the mechanical coupling. With the asynchronous machines normally used, this rigid coupling does not exist, but instead it behaves more like a rotational damper between the left and right wheel. The effect of this “rotational damper” should now be quantified.

In the following IRWs with longitudinal drive coupling from Siemens are considered. Longitudinally coupled IRWs were developed for the Combino fleet of vehicles and adopted virtually unchanged for the Avenio M platform (Ulm, Germany). The running gear of the Avenio platform (Munich, The Hague, Qatar) has also adopted this tried and tested system, the connection of the running gear to the carbody being adapted to the different requirements of a single-articulated vehicle as opposed to those of a multi-articulated vehicle. For the sake of simplicity, the running gear of all three families of vehicles are referred to below as “Avenio running gear”. If the specific vehicle type is relevant to the consideration, this is referred to in the text.

The tram is run on a curve with  $R = 30$  m with the lateral acceleration specified in the BOStrab alignment guidelines of  $a_q = 0.65$  m/s<sup>2</sup> and thus with a running speed of 16 km/h. As shown in Fig. 8, a wheel radius difference of  $dr_{nec} = 10$  mm is necessary in order to pass through the curve with the same rotational speeds at the left and right wheels. For the wheel/rail pairing under consideration here, however, only a maximum difference of  $dr_{poss} = 4$  mm is possible. Six millimeters are therefore missing ( $dr_{miss} = 6$  mm), which leads to a load torque between the wheels. Fig. 10 shows the magnitude of this torque for a radius difference of 2 mm at the maximum motor

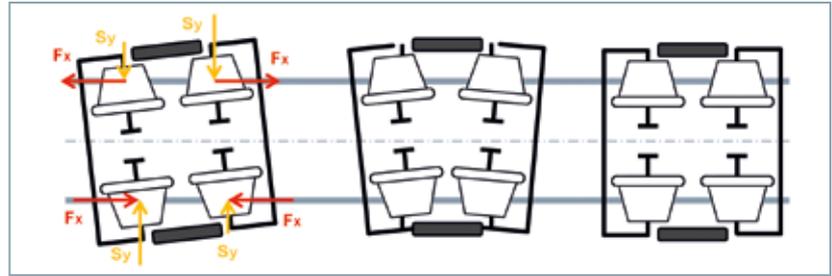


Fig. 11: Operating principle of the longitudinal drive when bogie is misaligned in the track  
 $S_y$ : Geometrical profile forces in y direction  
 $F_x$ : Longitudinal geometrical profile forces

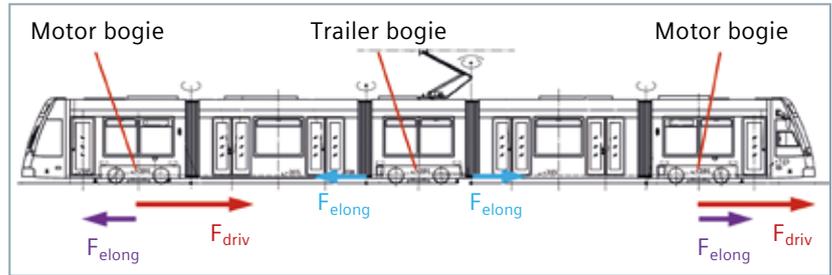


Fig. 12: Principle of “vehicle stretching” to support the centering of the trailer bogie, using the example of the Avenio M  
 $F_{drive}$ : Average driving force of the motor bogies  
 $F_{elong}$ : Superimposed stretching force

torque. Taking into account the gear ratio, the wheel diameter and the fact that two wheels are driven by one motor (longitudinal drive of the Avenio), this gives a longitudinal force at the wheel/rail contact point of  $F_{x,max,2} = 1.8$  kN per wheel. In our example, the effective radius difference is 6 mm, so that the value for 2 mm is extrapolated to three times the value on a simplified linear basis. At the maximum motor torque this would produce a longitudinal force of  $F_{x,max,6} = 5.4$  kN per wheel. Level running on the curve with  $R = 30$  m, however, does not demand the maximum motor torque, but only about 20% of it. The majority of the tractive resistance is generated by the curve resistance. This arises mainly from the lateral slip of the wheels due to the crab position of the running gear in tight curves. This is a phenomenon that affects all running gear in which the wheels cannot position themselves completely radially in curves – regardless of whether they are wheel sets or IRWs. On obtaining 20% of the maximum torque, the longitudinal force is reduced – again interpolated on a simplified linear basis – likewise to one fifth and thus to  $F_x = 1.1$  kN. Running in tight curves without longitudinal slip is not generally possible, even with driven or braked IRWs.

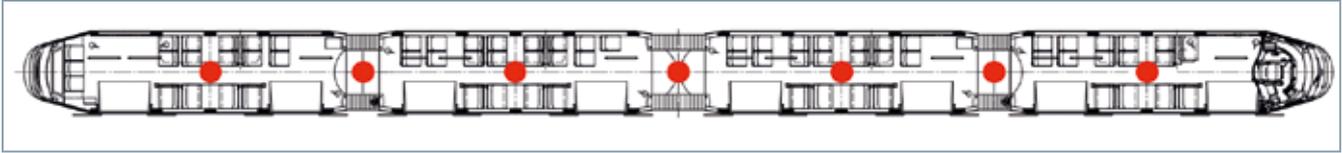


Fig. 13: Measuring points (red dots) for the ride comfort of the Avenio Munich

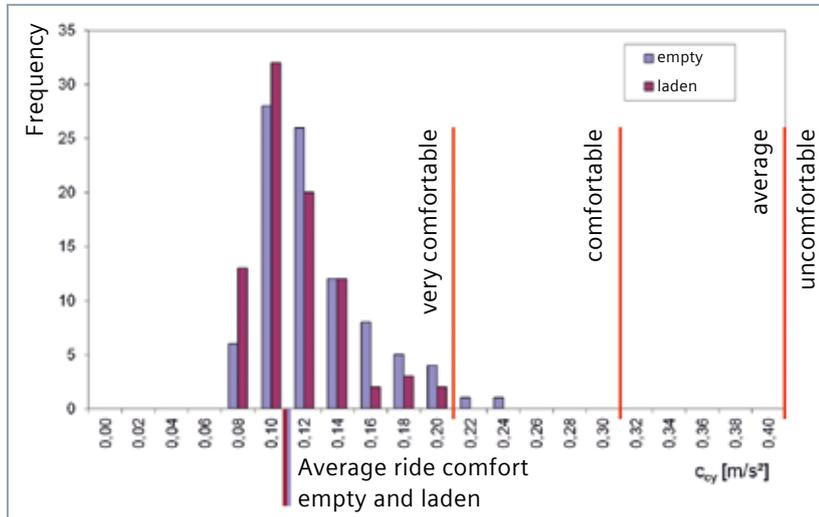


Fig. 14: Frequency distribution of the  $C_{cy}$  characteristics according to EN 12299 in the ride comfort measurements of the Avenio Munich

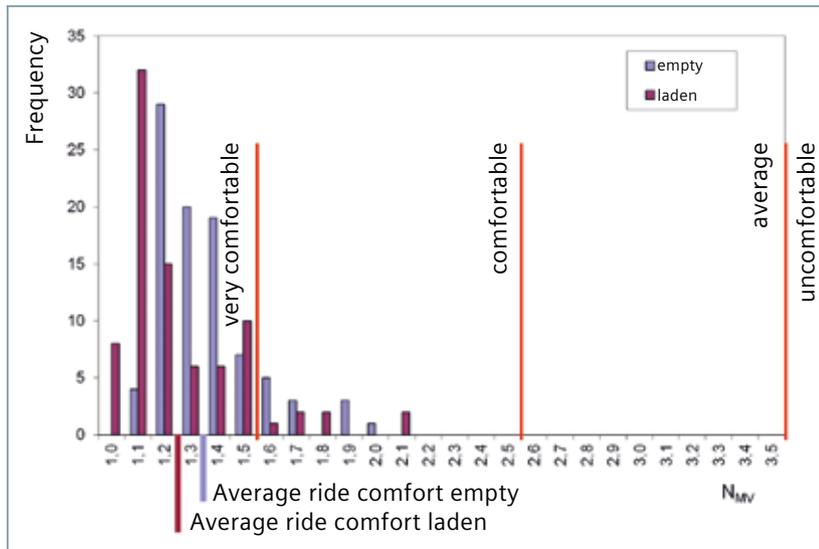


Fig. 15: Frequency distribution of the  $N_{MV}$  characteristics according to EN 12299 in the ride comfort measurements of the Avenio Munich

### 3.3.3 The comparison

The wheel set principle fails in the case of tight curve radii that are typical of tram networks. The possible wheel radius difference is insufficient by a long way to prevent rolling of the wheels without longitudinal slip. Even taking into consideration an “electric shaft”, a significantly reduced longitudinal slip occurs in the case of IRWs. In a curve with radius  $R = 30$  m the longitudinal slip force for the wheel set is 12 kN and therefore greater by a factor of 10 than for the IRWs at 1.1 kN!

### 4. Measures for centering the running gear

IRWs exhibit a smaller centering effect than wheel sets. This fact must be considered in the design of the vehicle and running gear, if the above-mentioned advantages in terms of wear behavior are not to be negated. Three different measures are described below which are used on Siemens tram vehicles.

#### 4.1 Omission of articulation dampers

Articulation dampers, which are used to attenuate the yaw movement between two car sections, are frequently encountered on tramway vehicles. These dampers, however, also slow down the tangential positioning of the car bodies after entering or leaving a curve and thus also – especially in the case of multi-articulated vehicles – the tangential positioning of the running gear. The unavoidable dry friction component of the dampers can even result in a persistently incorrect orientation and thus a rail one-sided flange contact by the running gear. Especially in the case of vehicles with IRWs, therefore, articulation dampers are to be avoided. The absence of “hunting motion” with this running gear – assuming there is a well attuned running gear connection – makes this easily possible. Siemens trams show no tendency toward yaw vibrations, even without articulation dampers.

Operator	Vehicle type	Number of vehicles	MD/BD	Gauge [mm]	Tire service life [km]	Reprofiling interval [km]
Bernmobil	Combino	36	MD	1000	MB: 280,000 TB: 260,000	MB: 40,000 TB: 40,000
MPK Poznan	Combino	14	MD	1435	MB: 217,135 TB: 209,630	MB: 25,500 TB: 38,500
VAG Freiburg	Combino	18	BD	1000	MB: 450,000 TB: 450,000	MB: 60,000 TB: 60,000
Rheinbahn Düsseldorf	NFU NF8 NF10	127	MD/BD	1435	MB: 260,000 TB: 260,000	MB: 35,000 TB: 35,000
GVB Amsterdam	Combino	155	MD/BD	1435	MB: 225,000 TB: 250,000	MB: 32,000 TB: 32,000
AVG Augsburg	Combino	41	MD	1000	MB: 207,500 TB: 207,500	MB: 45,000 TB: 45,000

Table 1: Tire service life periods of the Combino bogies of various operators

MD – Monodirectional vehicle    MB – Motor bogie  
BD – Bidirectional vehicle      TB – Trailer bogie

#### 4.2 The longitudinal drive

One particular feature supports the centering of the motor bogies on Siemens trams: the longitudinal drive. With longitudinal drive, both wheels on one side of the bogie are driven by just one motor and are thus – with the exception of an elastic coupling – coupled with a fixed rotational speed. Fig. 11 shows the effect on the guidance. If this bogie is misaligned within the track, the wheels on one side are running on different diameters. Due to the rotational speed coupling, one wheel thus becomes the driving wheel and the other becomes the braking wheel. It can be seen from Fig. 11 that this results in a V-orientation of the axle supports, provided the longitudinal rigidity of the primary suspension permits this. This V-orientation causes the bogie to “steer” back to the tangential positions. The geometrical profile forces are supported in their centering action. The longitudinal drive thus represents an effective element in the guidance of IRWs.

#### 4.3 Vehicle stretching

The described effect of the longitudinal drive is, of course, not present in trailer bogies. The expense of an “artificial” rotational speed coupling is not economical and also not necessary. A centering effect can also be achieved, simply by extending the drive control: the “stretching software”. In this procedure, a slightly higher torque is applied to the forward-mounted drives than to those at the rear (see Fig. 12). In the equilibrium of forces this produces a force  $F_{\text{elong}}$ , which stretches the train and thus favors a tangential orientation of the trailer bogie. The optimum ratio of stretching force to drive force is obtained from the compromise between increased drive slip at the motor bogies and reduced lateral slip due to the improved tangential orientation of the trailing bogie. The principle is used not only for drives, but also for brakes, but in this case with the opposite prefixes.

## 5. Practical experiences

The theoretical considerations set out above paint a picture that represents IRWs as “better” in every respect for tramway systems, not only in terms of ride comfort (vibration comfort), but also in terms of wear behavior. Theoretical considerations, however, are compelled to reduce reality to the (hopefully correctly identified) dominant influencing factors. In practice, these are overlaid by countless other influences, the impact of which is often difficult to estimate. It is therefore always necessary to offset the theoretically achieved findings against reality.

In the following sections, the practical values for ride comfort and wheel wear are highlighted for the Avenio and Combino. Both series of vehicles are equipped with identical running gear in terms of the guidance principle. Both have independent wheels with longitudinal drive.

### 5.1 Ride comfort

The Avenio vehicles have been in passenger service in Munich since September 2014. During commissioning, exhaustive test runs were carried out to determine the level of ride comfort. On 13 track sections in the Munich network, specified jointly with the acceptance authority, a total of 13 test runs were performed with an empty vehicle and 12 runs with a fully laden vehicle. Seven positions in the vehicle were equipped with accelerometers (see Fig. 13), enabling 175 measurements to be recorded ( $13 \cdot 7 + 12 \cdot 7 = 175$ ). These measurements were analyzed according to EN 12299 [6] and in each case the continuous comfort level  $C_{cy}$  and the mean comfort level  $N_{MV}$  were determined.  $C_{cy}$  represents the vibration comfort exclusively in the lateral direction and  $N_{MV}$  combines the comfort values of all three spatial directions.  $C_{cy}$  is particularly meaningful in the assessment of the guidance concept, as it mainly has effects on the lateral movements of the vehicle. In EN 12299 the identifiers  $C_{cy}$  and  $N_{MV}$  are characterized by the evaluations “very comfortable”, “comfortable”, “average” and “slightly uncomfortable” and “uncomfortable”. The frequencies of the values determined for the Avenio Munich are shown in the histograms below (Figs. 14 and 15).

The  $C_{cy}$  value determined across all measurements is less than  $0.12 \text{ m/s}^2$  – well within the limit for “very comfortable” which stands at  $0.2 \text{ m/s}^2$ . The distribution of the measured values is astonishingly narrow. Only two of the 175 measurements lie just outside the top mark. The  $N_{MV}$  that were determined are also clearly within the limit for “very comfortable”. As the vibrations in a vertical direction are also included in these key characteristics, the results reflect the familiar effect that a vehicle with a full payload offers better vertical vibration comfort than an empty one.

The designation of the ride quality of the Avenio Munich as “very comfortable” as defined by EN 12299 was impressively proven by the measurements. The “independently rotating wheels with longitudinal drive” running gear concept is not the only parameter influencing the vibration comfort, but certainly contributes toward it.

### 5.2 Wheel wear

The achievable service life of wheels for a vehicle fleet is a good indicator of the wear behavior of the running gear. As the routing of the network and the operator’s maintenance strategy also have a considerable influence, only a statistic that covers the largest possible number of networks is meaningful. For this statistic (see Table 1) the vehicles of the Combino fleet are considered, as these are operated in a sufficient number of networks. The figures given were not compiled by Siemens AG, but were submitted by the operators. The vehicles of types NF8U, NF8 and NF10 use the unmodified bogies of the Combino in the running gear modules; the end modules are equipped with small wheel bogies.

From the compiled data it is clear to see that IRWs facilitate a long service life for the wheels. The direct comparison with conventional wheel set vehicles is left to the reader. As Siemens AG does not operate any low-floor trams with conventional wheel sets, no such information is possible on our part. Those familiar with the service lives of other vehicles will however notice that the values for the Siemens running gear are excellent.

## 6. Summary

This paper opened with the question: “[Wheel set] axle, or no [wheel set] axle?”. Even the subsequent observations cannot provide a definitive answer. But what can be shown is the following:

- In theory, both wheel sets and IRWs exhibit strengths and weaknesses conditional upon the different principles when they are exposed to the particular design criteria of tram networks.
- There are structural and design options to compensate for the weaknesses of both IRWs and wheel sets.
- Practice shows that the Siemens vehicles with IRWs offer levels of ride comfort and wear behavior that set the standards.

In conclusion it may be said that the guidance concept alone is not the deciding factor for the quality of running gear, but the technical design – either with or without an axle.

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