Development of the railway vehicles axle assemble

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1 Introduction

Considering the historic development of railway vehicles one can see that the first vehicles were double-axle (Figure 1a). The need to increase the loading capacity of the vehicles created a need to increase its length. This also meant an increase of the wheel base. Double-axle vehicles with a greater wheel base had problems in negotiating curves because of the greater angle of contact of the wheels on the outer track. A partial solution for increasing the length of the vehicle meant an increase of the vehicle superstructure overhang compared to the axles (Figure 1b). This, however, increased the moments acting as a load on the box.

Apart from problems in negotiating curves, double-axle vehicles drove in an unsteady manner along straight lines and at higher speeds, due to the excitation caused by the winding movement of the wheel and axle sets.

The invention of the bogie was a perfect solution. Vehicles with bogies showed a steady movement along straight lines and a significantly easier driving round the curves. Vehicles with bogies could be even longer and could have greater loading capacity. (Figure 1c). Thus, the bogies have up to the present remained the basic form of axle assemble (driving unit) of all railway vehicles.

If this work analyses only passenger railway cars, it is obvious that the cars with bogies have become very long, narrow and with a great proper mass. It should be noted that a significant portion in the overall vehicle mass have the bogies. This portion is between 25 and 35%.

Considering that apart from the resistance to air, all other resistance to the motion of the train depend on its mass, it is important for the reduction in energy consumption in railway traction to make the vehicles as light as possible. The lightness in construction has therefore become the imperative of the modern vehicles. In order to reduce the proper mass of the vehicles, there are significant possibilities in the variation of the driving unit, i.e. reduction of its mass. One of these possibilities is the double-axle vehicle design.

2 Analysis of the possible axle assemble solutions

Today’s vehicles are very long and with bogies (Figure 2a). By increasing the length, the width of the vehicle has to be reduced so as to maintain the vehicle, when negotiating a curve, within the structure gauge (Figure 2b). Therefore long vehicles do not utilise the structure gauge in a satisfactory way, since narrow vehicles carry fewer seats in a single row compared to shorter but wider vehicles.

The underframe with the vehicle body presents a beam continuously subjected to the bending load with supports at the swivelling units of the bogies (Figure 2c). The deflection $f$ of such a beam depends on the length to the power of four ($f=\text{const} \cdot q^4/EI$). In order to keep the deflection within allowed limits the moment of inertia $I$ has to increase along with the increase of the vehicle length, which also means the increase in the vehicle weight. Therefore, long vehicles are at the same time heavy vehicles.

Looking at the ends of two connected four-axle cars with bogies, one has to notice that a small space accommodates as many as four axles, i.e. two bogies (Figure 2d). This means insufficiently utilised axles, heavy weight and an expensive solution.
The introduction of only one bogie between the two vehicles is a noticeable improvement (Figure 3a). This is a well-known solution of articulated vehicles. Here, one bogie supports the ends of both connected vehicles (e.g. TGV France). This practically means that one bogie per vehicle is reduced. For the same distance between the bogies like in four-axle vehicles, this solution means shorter vehicles. Here, the vehicles do not have overhangs behind the bogie supports.

Considering e.g. a passenger car 25.5 m in length including buffers, and the body 24.2 m in length, with the distance between the main bogie bolts of 17.2 m (Beelt car TZV Zagreb), it would in a one-bogie-between-cars design have the body length of 17.2 m. This means a 7 meters shorter car body (Figure 3b - the criss-crossed section). This would reduce the number of seat rows in the car, but the width, i.e. the number of seats in a single row could not be increased. In negotiating curves, the distances between the main bogie bolts remain the same, and thus also the width limit regarding passing the structure gauge (Figure 3b).

Since there are no overhangs of the car body, which had partly acted as the counterweight to the central loading section, the deflection $f$ of the body increases compared to the conventional four-axle car. To maintain the same, i.e. allowed deflection of the body, the moment of inertia has to be increased, which also means increase in the weight of the body. Thus the weight of the vehicle in articulated railcars with one bogie between cars is reduced because of the reduced number of bogies, but the weight of the body per unit of length is increased due to the need for a greater moment of inertia.

In order to avoid the increase in weight necessary for the increase of the moment of inertia, the deflection is efficiently reduced by the reduction of the body length, i.e. of the distance between the body supports. As
already mentioned, the length affects the deflection $f$ to the power of four (Figure 4a). The additional shortening of the car body, its weight can be noticeably reduced. Shortening of the body, i.e., a shorter distance between the body supports, also provides the possibility to widen the body, up to the limits allowed by the structure gauge when negotiating the curves (Figure 4b). Thus, in the mentioned example of a car with a 2883 mm wide body, the width could be theoretically increased to 3200 mm by reducing the length to 12 m. Such widening provides the possibility of adding one more seat per row, resulting in better utilisation of the structure gauge. Thus the first class cars could accommodate instead of three, four seats per row, increasing the capacity by 33%, and the second-class cars could have five instead of four seats per row, increasing the capacity by 25%. Shorter and less heavy car bodies do not need then bogies. The driving unit can be designed with one axle between the cars (Figure 4c). This further reduces the car weight, especially since the one-axle driving unit does not need a frame like a bogie.

With the same vehicle width and the same distance between body supports, the body could be lengthened by adding overhangs behind the axles, which means that the vehicle should be double-axle (Figure 5a). Thus the structure gauge in negotiating curves would be fully utilised (Figure 5b), and the vehicle could be fitted with one additional row of seats. With the same distance between supports, a body with overhangs has a lower deflection $f$ due to the moment of overhang (Figure 5c). This means that a body with a lower moment of inertia, i.e., less weight, can be built with the same allowed deflection.

Car body with two axles and their distance of 12 m, can be lengthened in overhangs at each end by 3.5 m, so that it could be 19 m long. That would mean, by connecting of two cars, a distance of over 7 meters between axles of two adjacent cars, which is a distance that may accept a new axle (Figure 5d). Further advantages of double-axle cars are a lower axle load, more suitable contact, easier connecting and disconnecting of trains etc.

So, from the long, narrow and heavy four-axle bogie vehicle, the described transformation is to a shorter, wider and less heavy double-axle vehicle with a greater number of seats per unit of length. The mentioned advantages speak in favour of using the two-axle vehicles in the future.

### 3 Some designs and projects

With the double-axle vehicle design the problems arise of the more difficult negotiating of curves and of the stability in driving along straight line and at higher running speeds. Modern double-axle vehicles have to have a specially designed driving unit, which means the design of steering axles in the radial position when going round curves, and high-quality suspension by elastic and shock-absorbing elements. This significantly alleviates guiding round curves and provides steady driving along the straight line.

Some of the possible designs of axle steering mechanisms in double-axle driving unit are shown in Figure 6 [1]. In case of the ideal position of the driving unit in the centre of the gauge, the mechanisms swivel the axles into the radial position of the passing curve. All the solutions can include wheel and axle sets or pairs of trailing wheels.

Figure 6a shows the version of two short double-axle cars whose mechanism for steering axles, i.e., wheels, is controlled by the central coupling between the cars (coupling controlled axle assembly for two cars - CCAA2). The angle of coupling in relation to the vehicle is the control value.

Figure 6b shows the version of two short double-axle cars whose mechanism for steering axles, i.e., wheels, has been designed as a follow-up of the previous version. The steering mechanism control does not depend on the angle of coupling, but on the angle between the two adjacent heads of the cars, which is the control value (adjacent car controlled axle assembly for two cars - ACCAA2). The advantage of this solution compared to the previous one, is that lateral shift of one car body in relation to the other does not affect the control of the axles. However, this mechanism is more complex and more expensive.

Figure 6c shows the version with three cars, two end cars and a central one, which is a follow-up of the previous versions and has the same number of axles, i.e., pairs of wheels. Mechanism connecting adjacent cars provides steering of the axles by half the angle compared to the angle between the adjacent heads of the railcars, meaning the radial position when passing a curve. This is then, the control of the steering mechanism.
using the bodies of the adjacent railcars (adjacent car controlled axle assembly for three cars - ACCAA3). Figure 7 shows the portion of the driving unit mass in the overall mass of the unit with two or three railcars with the axle steering mechanisms (CCAA2, ACCAA2 and ACCAA3), compared to two conventional old railcars (2 Byg 514) of the German Railway [1]. The portion of 12.3 and 10.6% is less than the half of the portion compared to conventional bogie railcars. Such significant reduction of the driving unit mass contributes to the overall reduction in the vehicle mass, which is what this type of construction tries to achieve. For assessment of the ease in negotiating curves and stability in driving along a straight line, the calculation results have been provided in Figures 8 and 9 [1].

The wear characteristics of wheels and tracks expressed in specific work of sliding forces wk show very low values for all the three driving unit versions with axle steering mechanisms (Figure 8). The values are especially low for the driving unit version with trailing wheels that are not on a common axle, but rotate independently. The wear is three to four times greater in versions of the same steering mechanisms, when the driving unit is designed as wheel sets, i.e., wheels fixed to the axle. However, these values are still below half of the values obtained for driving units with conventional bogies (MD 522).

The driving stability along the straight line expressed in characteristics of side swaying is best in driving units with trailing wheels, somewhat worse for driving units with wheel sets, and the worst in the conventional driving unit with bogie (MD 522).

According to both criteria by far the most suitable results are obtained by the mechanism in which the driving unit is controlled by the adjacent railcars (CCAA2) and when the wheels are free. Comparison in practice can be made between two trains meant for suburban transportation, and of completely different concepts.
One is modern - articulated with one-axle driving unit which has a mechanism for steering the wheel sets into radial position in negotiating curves (Figure 10) [2]. The train was ordered by the Danish Railway (DSB) for suburban transportation in Copenhagen from the German consortium Linke-Hofmann-Busch (LHB) and Siemens. At first, eight trains were ordered with an optional further order of 112 trains. It is an articulated train consisting of eight cars of 83720 mm total length over the coupling, one car being 9400 mm long, i.e. 11665 mm (head cars), 3600 mm wide, with the wheel base of 9850 mm, i.e. 7500 mm (head cars). Proper mass of the train is 123.7 tons, and the highest driving power 1720 kW.

The other train is for suburban transportation in Berlin ET 480, consisting of two cars with two conventional bogies per car [3]. The total length is 36800 over the coupling, with a body 17800 mm long and 3120 mm wide. The proper mass of the train is 60 tons, and the highest driving power 720 kW.

For assessing the lightness of construction, a suitable parameter is the mass of the train expressed by the unit of useful passenger area. So, the modern train for suburban transportation in Copenhagen has 456 kg/m², and the train for suburban transportation in Berlin has 604 kg/m². This means that the modern articulated train with a single-axle driving unit is by about one third lighter per unit of useful area, than the conventional train with two double-axle bogies per car. Here the biggest portion in this difference is due to the driving unit (168:80), and very little to the car bodies (405:350).

The power expressed per units of mass is 13.9 kW/t for the Copenhagen train, and 12 kW/t for the Berlin train. If we wanted to increase the specific power of the Berlin train to the level of the other one, then the mass per useful area in a conventional train would increase even more.

The comparison of characteristics can be done even for high-velocity trains. So e.g., the high-velocity train of the German railway InterCityExpress (ICE) consisting of 14 cars and two motor cars at each end of total power of 9600 kW has 883 seats and proper mass of 896 tons [4]. The seating comfort is 1.38 m²/seat. The specific power for the measurement of driving dynamics amounts to 10.7 kW/t, and the highest running speed is 280 km/h.

The other train is a project of a high-velocity suburban train with double-axle driving unit for the year 2000, symbolically marked S22L (2xS and 2xL for schnell, sparsam, leicht, leise = fast, economical, light, quiet) [5]. With 18 short and wide cars it has 808 seats and providing approximately the same comfort of 1.26 m²/seat like ICE. With a light double-axle driving unit, light car body and therefore less powerful and lighter driving device it would have proper mass of 462.5 t. With the driving power of 7355 kW it would run at the highest speed of 300 km/h, which would still leave a reserve of specific power of 2.94 kW/t.

Compared to the ICE train, which has the specific power of 10.7 kW/t, the S22L train has specific power
of 15.9 kW/t which improves its driving dynamics significantly. With the approximately same comfort per seat, and same number of seats, the S22L train has a significantly lower mass per unit of useful area. If it amounts to 793 kg/m² for ICE, in S22L it is reduced to remarkable 420 kg/m².

Projects, calculations, and tests give quantitative values which prove that the proper mass per unit of useful area in trains has to and can be significantly reduced in the future. Light construction is becoming a must, and great possibilities in this field are provided by the application of double-axle driving unit.

4 Conclusion

Light construction of railway vehicles is becoming an important requirement. The main part of the resistance to motion depends on the mass of the train. Therefore, by reducing its mass, also the required driving energy is reduced, as well as the amount of material used in construction, the price, and finally, at the end of its operating life, there is less waste, i.e. recycling material. In reducing the proper mass of railway vehicles, the replacement of driving unit offers significant possibilities. Namely, in passenger cars with conventional driving unit with two double-axle bogies, the portion of the driving unit mass in relation to the proper mass of the whole car is between 25 an 35%. When a modern double-axle driving unit is applied, the portion of its mass in relation to the whole car is reduced to remarkable 11 to 15%.

The problem of difficult negotiating of curves by the double-axle vehicles can be solved by the mechanism for steering the axles into the radial position. Further improvement of driving unit suspension brings also improvement in the running performance along straight line at higher speeds. Calculations, experiments and exploitation have shown that the best results regarding the ease of negotiating curves and stability of driving along straight line are shown by the double-axle driving unit with trailing wheels whose axes can swivel into the radial position in going round curves.

By reducing the mass of the driving unit and by constructing lighter car bodies, the vehicle mass per unit of useful passenger area is significantly reduced, which is a very reliable parameter of light construction, i.e. a measurement used for comparison of single cars. Compared to trains with conventional four-axle cars, the introduction of light construction, primarily using modern double-axle driving unit means a reduction of mass per unit of useful area by 30 and even by unbelievable 89%.

Double-axle vehicles are designed with a shorter body compared to the four-axle vehicles, which makes it possible to widen the body and thus make better use of the passenger area.

LITERATURE


