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Curving and stability optimisation of locomotive bogies using interconnected wheelsets

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SUMMARY

The paper demonstrates the application of an equivalent axle guidance stiffness in the design of self-steering bogies, as well as the potential of the modular wheelset guidance with optional application of wheelset coupling, in order to optimise the trade-off between curving and stability of locomotive bogies. The sensitivity analysis illustrates the influence of the operating conditions on the self-steering ability.

1 INTRODUCTION

The conflict between curving and stability is a well known challenge concerning railway vehicle dynamics. Bogies with longitudinally soft axle guidance are suitable for curved track, whereas good stability performance can be achieved with stiff axle guidance. Independent of the form of the wheelset guidance and suspension design in the horizontal plane, the stability and curving performance can be described by two stiffness parameters: the shear stiffness and the bending stiffness [1, 2]. In order to achieve optimal curving properties, the bending should be low. However, the vehicle then lacks stability. To achieve the required stability the wheelsets have to be restrained by an increase in shear stiffness. For conventional bogies a limit exists to the shear stiffness that can be provided in relation to the bending stiffness. The trade-off stability/curving in which the bending stiffness must be minimised is restricted.

This limitation can be improved if the wheelsets are connected to each other directly or by a mechanism fitted on the bogie frame. An overview of design options and realised examples can be found in [3, 4]. The application of a cross anchor on the three-piece bogies and the service experience gained is described in [1, 5]. In order to design self steering interconnected wheelsets for locomotives, the transfer of tractive forces between the wheelsets and bogie frame should not influence the

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axle guidance. A solution with a wheelset cross coupling with a mechanism fitted on the bogie frame realised on the Locomotive 2000 series [6] was developed by the erstwhile SLM Swiss Locomotive and Machine Works in Winterthur, now a part of Bombardier Transportation. This design solution is in service in Switzerland (SBB Re 460, BLS Re 465), Norway (NSB El 18) and Finland (VR Sr2).

The paper deals with the application of this coupling mechanism in order to optimise curving and stability of newly developed locomotive bogies. A modular wheelset guidance design is presented, which enables utilisation of the bogie performance depending on the service conditions, and the sensitivity of the self-steering to the service conditions is illustrated.

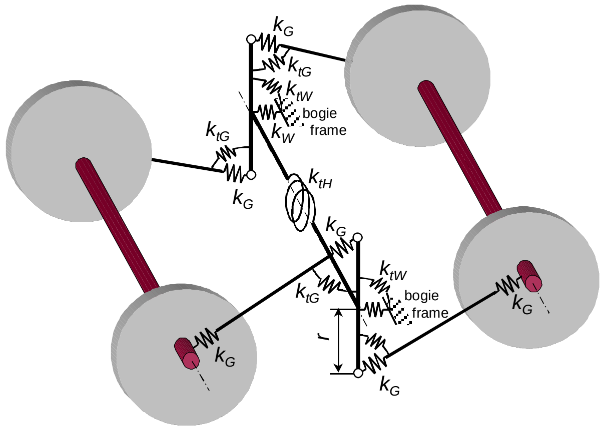

Fig. 1. Scheme of coupling mechanism between the wheelsets.

2 DESIGN ASSESSMENT USING EQUIVALENT AXLE GUIDANCE STIFFNESS

The mechanical scheme of the wheelset coupling analysed in the paper is shown in Fig. 1. The design uses frictionless rubber elements with finite stiffness. The main parameters apply, as follows:

- k_G - radial stiffness of the longitudinal linkage bushing
- k_W - radial stiffness of the bushings between the shaft and bogie frame
- k_{tG} - torsional stiffness of the longitudinal linkage bushing
- k_{tW} - torsional stiffness of the bushings between the shaft and bogie frame
- k_{tH} - torsional stiffness of the coupling shaft
- r - swing arm of coupling shaft.

The longitudinal stiffness of the linkage rod itself is very high, and the body is assumed as being rigid. The bending stiffness of the coupling shaft is not considered in our analysis due to the symmetrical fitting of the bearings (bushings).

The wheelsets, coupled by the mechanism according to Fig. 1, are able to move in the horizontal plane in four eigenmodes, see Fig. 2:

- Shear (lozenging) mode (S)
- Bending (steering) mode (B)
- Tractive (longitudinal in-phase) mode (T)
- Longitudinal anti-phase mode (L).

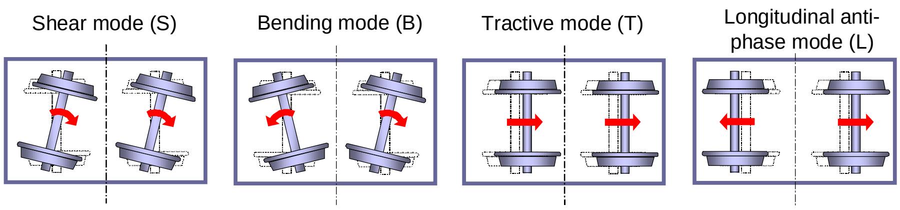

Fig. 2. Wheelset eigenmodes of a two-axle bogie.

When analysing only one eigenmode, the stiffness of the coupling between the wheelsets can be expressed as an equivalent longitudinal stiffness k_{eI} between the axle box and bogie frame. Index I indicates the mode, e.g. k_{eB} for bending mode.

The total equivalent axle guidance stiffness includes the longitudinal stiffness k_{Px} and lateral stiffness k_{Py} of primary suspension. The total longitudinal equivalent axle guidance stiffness then comprises

$$k_{xI} = k_{Px} + k_{eI} \qquad (1)$$

with k_{Px} - longitudinal axle guidance (primary suspension) stiffness.

The equivalent stiffness can be expressed by serial and parallel combinations of the single stiffness parameters shown in Fig. 1. The equivalent stiffness for bending is

$$k_{xB} = k_{Px} + \cfrac{1}{\cfrac{2}{k_G} + \cfrac{1}{\cfrac{k_{tW}}{2 \cdot r^2} + \cfrac{k_{tG}}{r^2}}} \qquad (2)$$

The same equivalent stiffness is achieved both for shear and the tractive mode

$$k_{xS} = k_{xT} = k_{Px} + \cfrac{1}{\cfrac{2}{k_G} + \cfrac{2}{k_W}} \qquad (3)$$

For the longitudinal anti-phase mode we get

$$k_{xL} = k_{Px} + \frac{1}{\frac{2}{k_G} + \frac{1}{\frac{k_{tW}}{2 \cdot r^2} + \frac{k_{tG}}{r^2} + \frac{k_{tH}}{r^2}}} \qquad (4)$$

To achieve best possible curving performance paired with stable running at high speed independent of the transmission of high tractive forces between the wheelset and bogie frame, the equivalent longitudinal stiffness of the coupling mechanism must be low for bending mode, but high for other eigenmodes. The torsional stiffnesses of the coupling elements k_{tG} and k_{tW} should be as small as possible, and the radial stiffnesses k_G and k_W as large as possible. Friction bearings would fulfil these requirements best, but have proven unsuitable in respect to maintenance during operation. For this reason rubber elements, which provide the closest correspondence with the given requirements, are utilised.

From equation (4) the necessity for high torsional stiffness of the coupling shaft ensues, in order that a greater equivalent stiffness for longitudinal anti-phase mode can be achieved. This requirement must be taken into consideration in the dimensioning of the coupling shaft.

The equivalent stiffness is suitable for parameter analysis during the wheelset guidance design, e.g. see analysis of three-axle steering bogies in [7]. During the remainder of this study the bending stiffness k_{xB} will be applied in order to analyse curving and stability performance of the investigated locomotive bogie. The steering ability and curving properties are related to bending stiffness and can therefore be easily assessed using this equivalent parameter.

3 LOCOMOTIVE BOGIE WITH MODULAR AXLE GUIDANCE

With the development of a new locomotive bogie, the Flexifloat Bogie Family of Bombardier Transportation [8] has been complemented with the proven wheelset coupling mechanism with separation of axle guidance and tractive force transfer as demonstrated by the Locomotive 2000 series. The newly developed modular axle guidance system allows the construction of four axle guidance versions based on specified service conditions:

- longitudinal stiff axle guidance (ST)
- longitudinal soft axle guidance (SO)
- longitudinal very soft axle guidance combined with wheelset coupling shaft (CW)
- longitudinal very soft axle guidance combined with wheelset coupling shaft and dampers of coupling shaft (CWD).

Using the coupling shaft mechanism, the following improvements can be achieved:

- self steering ability and radial adjustment in curves, together with reduction of wheel-rail guiding force and wear

- transfer of tractive force without influencing the axle guidance parameters
- increase of the critical speed to the same range as bogies with stiff axle guidance.

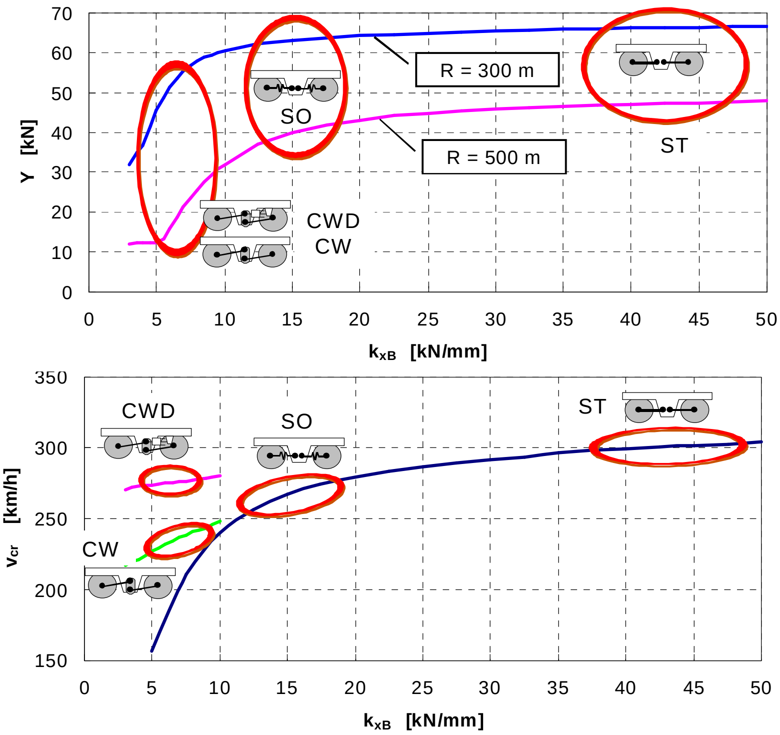

Fig. 3. Guiding force in curve (top diagram) and critical speed (bottom diagram) as function of equivalent longitudinal axle guidance stiffness. Marked areas display recommended equivalent stiffness for the proposed versions of modular axle guidance.

Based on the equivalent longitudinal axle guidance stiffness for the bending mode k_{xB}, the influence on the stability and curving performance of the locomotive with four different axle guidance versions was evaluated using the locomotive model built in to SIMPACK programme. Fig. 3 illustrates the critical speed dependent on the equivalent longitudinal stiffness k_{xB} of the axle guidance. The stability declines with lessening stiffness of the axle guidance. In the case of soft axle guidance with interconnected wheelsets and damping of the coupling shaft, stability is comparable with the stiff axle guidance. The advantage of the soft axle guidance and the coupling of the wheelsets becomes apparent during curve negotiation, see top diagram in Fig. 3. Both the guiding force of the leading wheel and the wear index decrease with sinking stiffness k_{xB}. The version with the coupling shaft mechanism (possibly supplemented with coupling shaft damping) deals excellently with the conflict in objectives between stability and curve negotiation.

4 SENSITIVITY ANALYSIS OF SELF-STEERING

As the radial adjustment of the wheelsets in curves is achieved through creep forces in the contact between wheel and rail, the running characteristic is influenced by the conditions in the wheel-rail contact. The influence of curve radius, cant deficiency, wheel-rail contact geometry, tractive effort and flange lubrication on the self-steering ability of presented locomotive bogie was analysed and a comparison was made between:

- self-steering bogie with longitudinal very soft axle guidance, coupling shaft and dampers of coupling shaft (CWD)
- conventional bogie design with longitudinal stiff axle guidance (ST).

The results presented were calculated using a full non-linear locomotive model in the simulation tool SIMPACK. In order to assess the curving performance, values on the outer wheel of the leading wheelset are presented for

- guiding force Y [kN]
- wear index A_R [Nm/m], given as the sum of products (creep force × creep) in longitudinal and lateral direction.

The **influence of curve radius and cant deficiency** is presented in Fig. 4. As can be seen, with decreasing curve radius R the guiding force Y and the wear index A_R increase significantly. The self-steering of the wheelsets demonstrates a good efficiency up to a certain minimum radius. The design presented here for the standard gauge locomotive significantly reduces the guiding force in large, medium and small curve radii. In very small curve radii approx. below 250 m, the creep forces cannot overcome the reaction of the axle guidance, and the guidance force is practically the same for both versions. For self-steering bogies, wear is significantly lower throughout the whole range of the curve radii. With increasing uncompensated lateral acceleration a_{lat} the guiding force and wear index increases. However, the influence of same is significantly smaller than for the curve radius. In the results presented in the following chapters, curve radii $R = 300$ and 500 m and uncompensated lateral acceleration a_{lat} = 0.98 m/s^2 are applied as characteristic parameters to assess curving performance.

The **rail profile and inclination** also has an influence on the self-steering ability. Fig. 5 demonstrates the guiding forces between the wheel profile S 1002 and the rail UIC 60. In the case of rail profile S 1002, which is optimised for the rail inclination 1:40, the guiding forces are somewhat higher at a rail inclination of 1:20. However, when the versions with the stiff and very soft axle guidance are compared, the advantages of the self-steering bogie are clearly apparent.

In order to estimate the **influence of rail wear** on self-steering, calculations were carried out on rail profiles which were identified from measurements as characteristic worn rail profiles in curves [9], see Fig. 7. The heavily worn outer rail and small rolling radii difference lead to a reduction in the self-steering ability, see Fig. 6. Even though the effectiveness of the self-steering is significantly lower, the self-steering bogie is still more favourable, particularly with regard to wear.

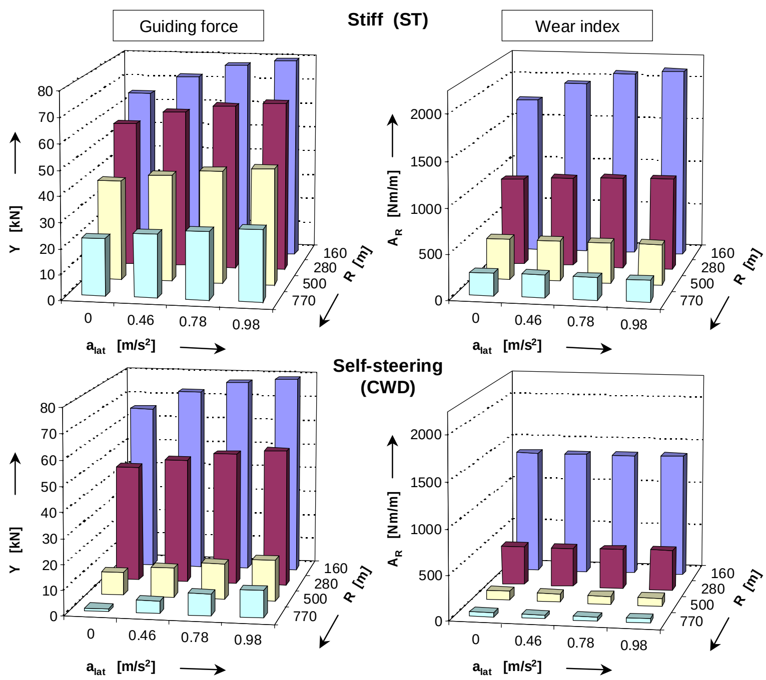

Fig. 4. Comparison of stiff (top) and self-steering (bottom) axle guidance: Guiding force and wear index of the outer leading wheel in a curve in function of lateral acceleration and curve radius.

Fig. 8 illustrates the **influence of tractive effort** on the examined values *Y* and A_R. With increasing tractive effort the creep forces between wheel and rail reach the saturation point. The longitudinal creep forces incurred by the varying rolling radii difference reach lower values and self-steering is reduced. Nevertheless, the self-steering bogie demonstrates a more favourable curving performance. Wear at full tractive force is mainly caused by tractive creep and is therefore hardly influenced by self-steering. As calculated, the results assume dry rails and favourable adhesion conditions. Should the run be viewed with tractive effort under critical adhesion conditions, the creep force control must be taken into consideration [2, 10], and the calculation methods concerning the creep forces extended, as described in [11, 12].

The radial adjustment of the wheelsets will be slightly reduced by the **influence of the wheel flange lubrication**, so that the guiding force achieves a higher value than without lubrication. However, the wheel flange lubrication definitely has a positive effect on wear. As can be seen in Fig. 9, the wear index demonstrates values which are approx. 5 times lower than without lubrication. It is therefore clear that the utilisation of flange lubrication on self-steering bogies can lead to a further reduction in flange wear if a slight increase in the guiding force can be accepted.

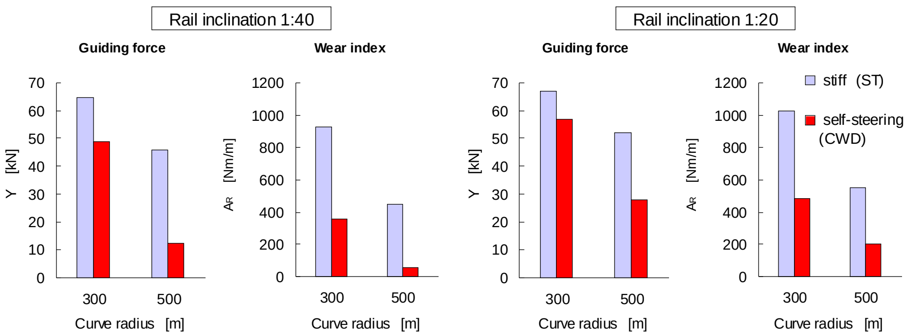

Fig. 5. Influence of rail inclination on the guiding force and wear index.

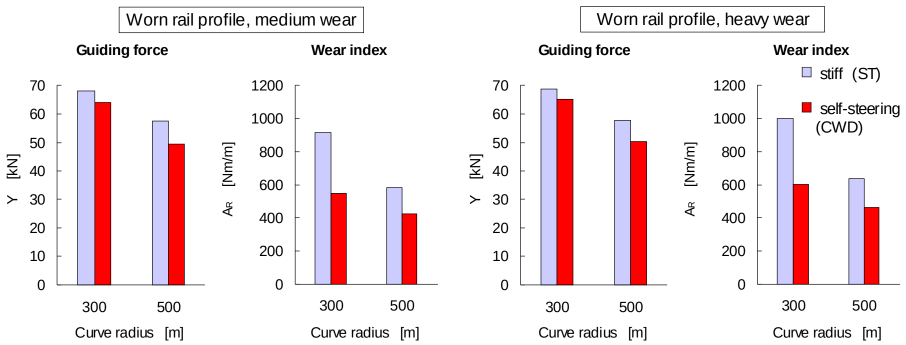

Fig. 6. Influence of worn profile, as shown in Fig. 7, on the guiding force and wear index. Results for new wheel profile – see Fig. 5 (left diagram).

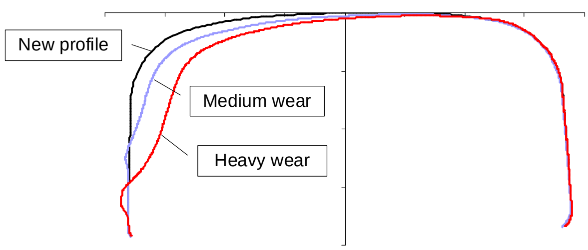

Fig. 7. Worn rail profiles of high rail in curve from [9] as used in the sensitivity analysis.

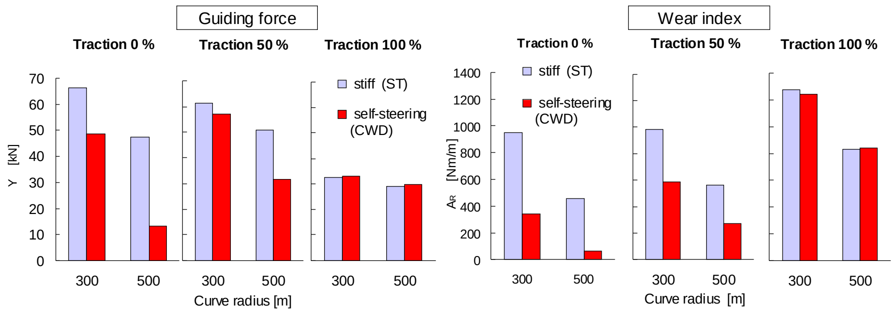

Fig. 8. Influence of tractive effort on curving performance (a_{lat} = 1.1 m/s^2).

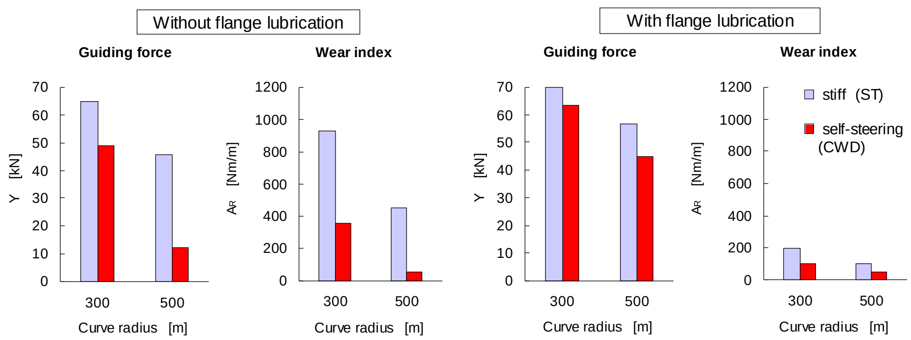

Fig. 9. Influence of flange lubrication on curving performance (wheel-rail friction coefficient: tread 0.4, flange 0.1).

The sensitivity analysis demonstrated that the radial adjustment of the self-steering wheelsets in curves is influenced by various factors. In spite of this, a self-steering bogie with interconnected wheelsets always achieves better running characteristics on curved tracks than a conventional bogie construction with stiff axle guidance. The requirements of the track infrastructure management concerning modern rail vehicles [13] confirm the necessity of radial steering wheelsets. According to Veit [14], a locomotive with coupled self-steering wheelsets only incurs approximately 60% of the annual expenses of the track maintenance in curves having radii between 250 m and 400 m in comparison to other locomotives with stiff axle guidance.

In the case of the design considered here - radial steering design by way of coupling of the wheelsets with a coupling shaft - the reduction of wheel wear has already been proven during service of the locomotives SBB Re 460 and BLS 465 on tracks with a high number of curves. On the Gotthard route in Switzerland, the locomotive SBB Re 460 achieves 3 to 4 times longer running performances between re-profiling of the wheelsets than previous locomotive versions [15].

5 CONCLUSION

The paper demonstrates the application of the equivalent axle guidance stiffness in the design of the radial steering bogies, as well as the potential of the modular axle guidance with optional application of wheelset coupling, in order to optimise the trade-off between curving and stability. The sensitivity analysis demonstrates the influence of operating conditions such as curve radius, rail inclination, rail wear, tractive force and wheel flange lubrication on the self-steering of the wheelsets. Despite a certain dependency on the relative improvement of effective operating conditions, the self-steering bogie generally achieves better characteristics and provides significant potential for savings in connection with maintenance of vehicle and infrastructure when compared with bogies with stiff axle guidance.

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