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H. SCHEFFEL

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Unconventional Bogie Designs – Their Practical Basis and Historical Background

H. SCHEFFEL*

SUMMARY

This paper deals with the design concepts for steerable bogies. A brief historical background is given and the modern design basis generated by the creep theory is summarised with regard to curving performance and dynamic stability of two- and three-axle bogies. The basic structural elements used for trailing and motorised steerable bogies are illustrated. Experience gained with some recent designs of self-steering and forced-steering bogies is discussed and achievable stability and curving performances are quoted.

1. INTRODUCTION

In recent years there has been a considerable interest in bogie designs which improve the curving ability of railway vehicles. This interest stems from a variety of operating conditions. For example, heavy haul lines often include sharp curves in the escarpment regions which these lines have to traverse to reach the harbours, and in view of the high axle loads used on such lines, wheel and rail wear on curved track can be excessive. Flange and rail wear can also adversely effect the maintenance cost of suburban, rapid transit and under-ground railways where noise generation in curves is often an additional cause for concern. Furthermore the modern high speed services which are restricted to new track built in an almost straight line with trains stopping at larger cities only are generating an interest in increased curve and straight line speeds on existing lines in an effort to provide an attractive feeder service to the stations of the high speed railways [1].

In view of this demand a number of unconventional bogie designs have been developed in recent years which aim to improve the curving ability of railway vehicles. The designs of so-called steerable bogies which will be discussed in this paper are bogies which use conventional wheelsets with coned wheels firmly mounted on a common axle. Such di-cone like wheelsets have the ability to align themselves radially on curved track if they are in yaw and free to move laterally.

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* Railway Dynamic Systems, 83a van Wouw Str., Groenkloof, 0181, Pretoria, Republic of South Africa.

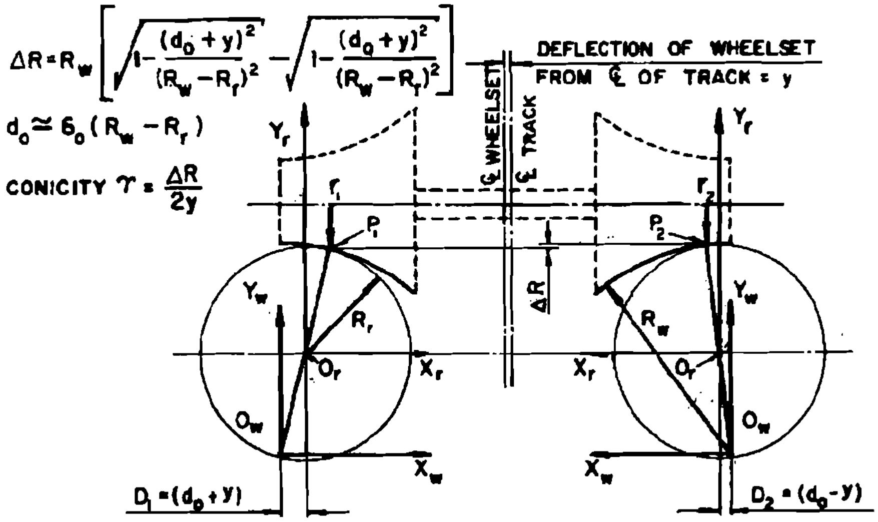


Fig. 1. Effective conicity of profiled wheels.

As the lateral motion of the wheelsets is limited by the wheel flanges, the radius of the tightest curve in which an unconstrained wheelset can align itself radially is inversely proportional to the product of wheel tread conicity times gauge clearance. For conventional coned wheels which have a wheel tread conicity of 0.05 only, the natural steering ability of the wheelset is insignificant. However, the use of profiled wheel treads which have a higher effective conicity (figure 1) makes the exploitation of the steering ability of a wheelset a practical proposition.

Steerable bogie designs which take advantage of the steering ability of wheelsets having profiled wheels are called self-steering bogies. As long as the steady-state lateral excursions of the wheelsets do not exceed the available gauge clearance, such bogies will curve in the off-flange curving mode. However, in very tight curves and turnouts flange contact cannot be avoided. For this reason the on-flange curving capability of self-steering bogies also requires attention.

Steerable bogies which include linkages connecting the wheelsets via the bogie frames to the vehicle body aim for a radial alignment of the axles on curved track through the application of a steering moment on the wheelsets. Such bogies are, therefore, referred to as forced-steering bogies. However, latest designs of such bogies also use wheels with profiled wheel treads and will, therefore, also curve in the on-flange and off-flange curving modes depending on the curvature of the track.

2. CHRONOLOGY

The kinematic conditions for pure rolling on curved track were known before mechanically hauled railways started operating. This is clear from the

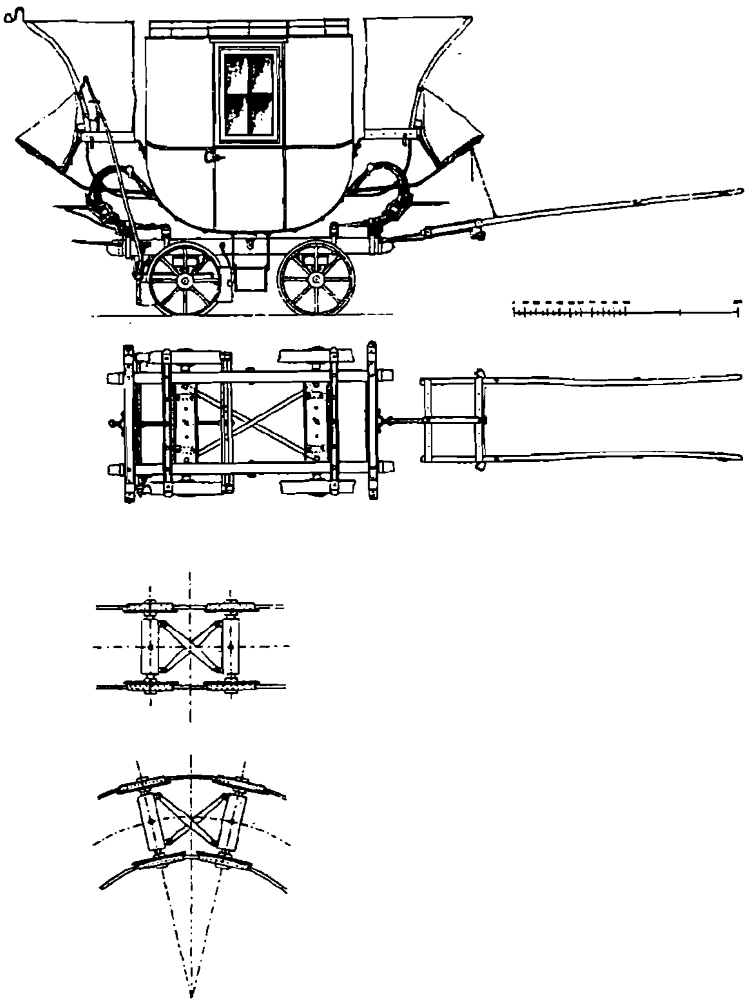


Fig. 2. Horse drawn coach with cross-linked wheelsets (1928).

construction of the horse drawn vehicles (figure 2) designed for the Budweis-Linz-Gmunden Railways in 1828. The beam which contained the journal bearings was pivotally connected to the chassis. This allowed the axles to rotate about their centre of yaw constrained only by the frictional resistance between the beam and the chassis. Relative to each other the axles were coupled by diagonal links. The sketch showing the radial alignment of the axles on curved track is an indication that the effect was understood which such diagonal links have on radial alignment of the axles when the flange of the outer leading wheel touches the rail.

Once bogie vehicles had come into use on locomotive hauled railways the diagonal links fitted to the horse drawn vehicles were also used for steerable bogies [2]. As an alternative design, yokes pivoted together at their apices [3] were proposed for use as inter-axle shear connections. However, both types of inter-axle connections were usually combined with structures connecting the wheelsets to the bogie frame and vehicle body in order to obtain a forced-steering action under on-flange curving conditions.

For steam locomotives it was recognised that the flange force on the leading driven axle could be reduced by the provision of leading and trailing non-driven wheelsets held in yokes which were pivoted at their apices to the locomotive frame. On curved track the longitudinal creep forces acting on the wheels of these pivoting wheelsets would be reacted by transverse forces at the pivots. This had the effect of reducing the angles of attack of the pivoting wheelsets and of exerting a moment on the coupled driven wheelsets of the locomotive which assisted in turning the driven axles into the curve. However, it was found that in the leading direction, pivoting wheelsets had a tendency to run up against one rail on straight track. For this reason leading pivoting wheelsets were either coupled to the leading driving wheels by a steering mechanism or replaced by two-axle bogies.

Similar steering forces were later employed to improve the curving performance of two- and three-axle electric and diesel locomotives. In this case the

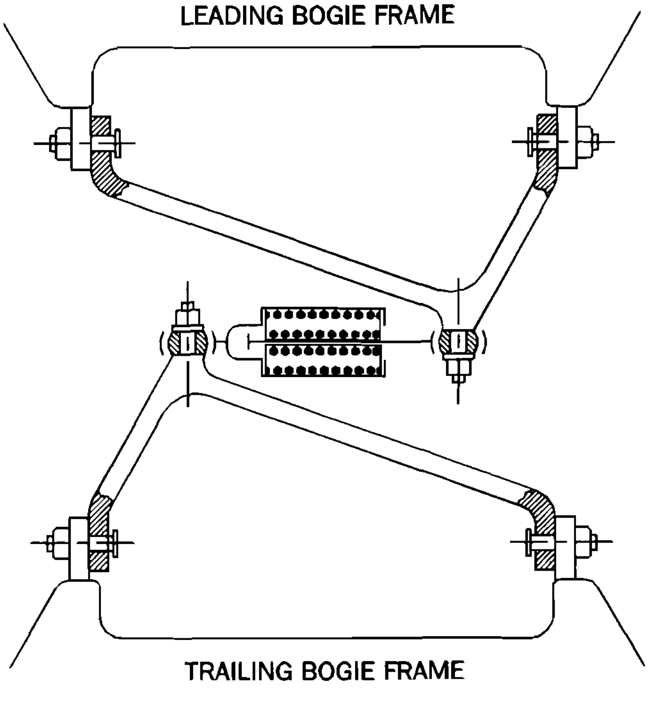


Fig. 3. Schematic view of inter-bogie control gear.

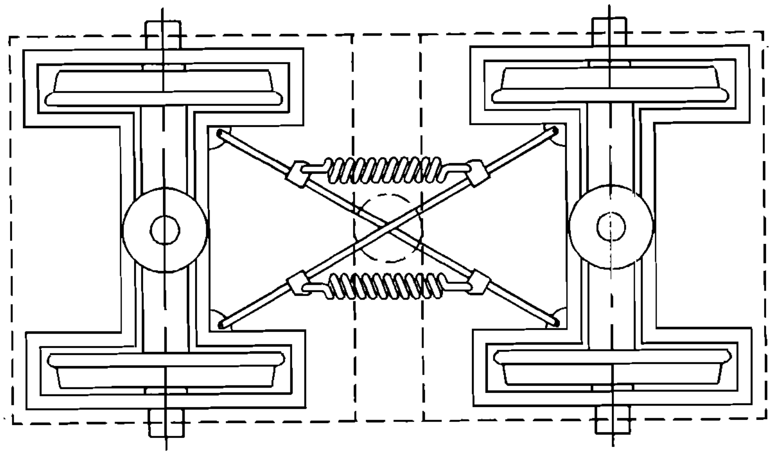


Fig. 4. Plan view of C.A. Lincoln's 'cross-tied truck' (1912).

bogie frames were coupled in shear by a flexible transverse coupling (figure 3). This arrangement, usually referred to as inter-bogie control gear. is still being used widely in South Africa to reduce flange forces on Bo-Bo and Co-Co locomotives.

In 1911 C.A. Lincoln realised that an inter-axle shear connection would have a similar effect on the on-flange curving performance of a two-axle bogie and obtained a US patent for a bogie having 'crossed tie rods' which diagonally connected subframes mounted on the journal boxes. Recognising that such an inter-axle shear connection could not restore the axles to their parallel position on straight track Lincoln included longitudinal 'resilient members to maintain the parallelity of the axles' (figure 4), which in to-day's terminology would be referred to as inter-axle bending stiffness.

In the 1930s further experiments were carried out in Switzerland [4] and Germany with forced steered bogie designs. However, the steerable bogie designs proposed during more than a century of railway operation appear to have gained little practical importance. One reason for the low rate of acceptance is probably the lack of sophistication in material technology and manufacturing technique at the time, another reason the fact that the designers did not know how to deal effectively with the dynamic response of the vehicle resulting from the periodic motion of coned railway wheelsets on straight track. In 1887 Klingel analysed the kinematics of the wheelset motion and in 1928 Carter first used creep forces to describe the behaviour of locomotive wheelsets. However, only the extensive research which started in the 1960s at the beginning of the high speed era led to the formulation of a 'practical theory' for vehicle dynamics [7] which, with the assistance of modern computers, provided the railway suspension designers with the means to predict the dynamic behaviour and curving performance of complete railway vehicles.

3. SUSPENSION REQUIREMENTS FOR DYNAMIC STABILITY AND CURVING ABILITY

A. Two-Axle Bogies

I. Stability

During the last three decades the dynamic and steering behaviour of single wheelsets and simplified multi-axle vehicles have been analysed extensively on the basis of the creep theory [8,9,10,11,12]. The conclusions drawn from these investigations can be summarised as follows:

1. The oscillations in the lateral plane of an unconstrained wheelset moving along straight track at constant forward speed can be adequately described by two degrees of freedom, namely the lateral motion at right angles to the track and the rotational motion about the vertical axis of the wheelset (yawing).
2. At slow speed the wheelset oscillations are sinusoidal and characterised by the kinematic wavelength:

$$L = 2\Pi\sqrt{\frac{r_0 l}{\gamma}}$$

and the kinematic frequency equals

$$\omega = \frac{2\Pi V}{L} = V\sqrt{\frac{\gamma}{r_0 el}}$$

where

r_o is the wheel radius when the wheelset is in the central position,
l is the half-distance between contact points,
γ is the effective conicity of the wheel tread and
V is the constant forward speed of the wheelset.

The lateral motion as a function of time is

$$y = -y_0 \times \cos(\omega t)$$

and the yawing oscillation of the wheelset, which lags 90 degrees behind the lateral oscillation, equals

$$\phi = y_0\omega \times \sin(\omega t)$$

3. As the forward speed increases the unconstrained wheelset becomes

unstable as result of the inertia forces generated by the acceleration and deceleration of the sinusoidal motion.

4. The wheelset oscillations can be stabilised by elastically constraining the wheelset to ground either laterally or in yaw. The elastic constraint generates creep in the wheel/rail contact areas which provides damping to the wheelset oscillations up to the speed where the elastic modal frequency equals about half the kinematic frequency. This means that for a constant elastic constraint and a given wheelset mass the critical speed is proportional to the inverse of the square root of wheel tread conicity.
5. In order to analyse the influence of the elasticities of the structures which connect the wheelsets of a two-axle bogie the connecting structures are considered to have zero mass. Such a simplified two-axle model has four degrees of freedom (figure 5). The analysis shows that in this case for stability each wheelset has to be constrained to the other wheelset by two elastic structures. Therefore, the two wheelsets have to be coupled in shear as well as in bending. The bending constraint requirement means that the wheelsets of a two-axle bogie which depends solely on elastic constraints for stability cannot align themselves perfectly radially on curved track.
6. In generalised co-ordinates (such as lateral and yawing motions of the two wheelsets in equal and opposite senses) the shear and bending structures will elastically constrain only two, i.e. half of the four degrees of freedom, and the remaining two motions, namely the lateral motion of the wheelsets

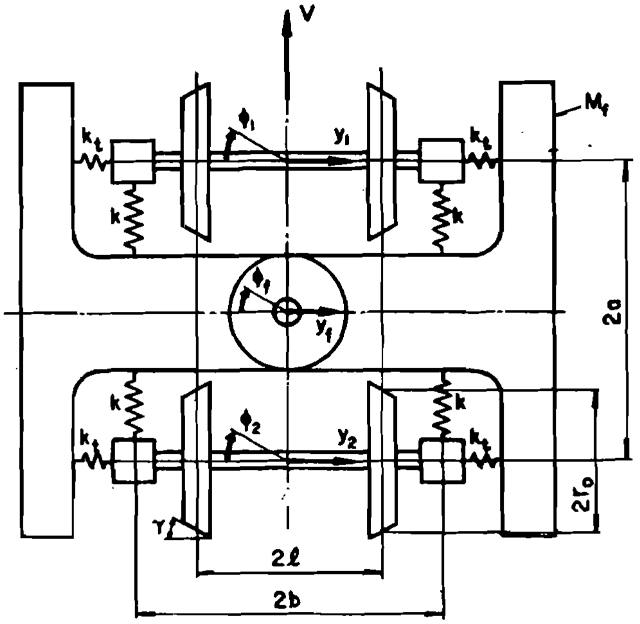


Fig. 5. Two wheelsets constrained by 'massless' bogie frame.

in equal senses and rotational motion about the bogie centre are elastically unconstrained. This can be extended to vehicles having more than two wheelsets where again in generalised co-ordinates only half the number of degrees of freedom require an elastic constraint for dynamic stability.

7. For stability, the elasticities of the bending and shear connections of the wheelsets act in series. Therefore, the stabilising effect of the elasticity of one of the structures is best utilised by making the other structure as stiff as practicable.
8. The stabilising effect that can be obtained from elastic inter-wheelset connections is limited by the adhesion between the wheels and the rails. For this reason the critical speed as a function of the in series inter-wheelset structural constraint reaches a maximum, i.e. the critical speed will go towards zero when both the shear and bending stiffnesses approach rigidity.
9. The two-wheelset arrangement can be stabilised without the provision of an elastic bending stiffness by the combination of inter-axle shear stiffness and longitudinal damping.
10. As mentioned above for the simplified model the structures connecting the wheelsets are assumed to have zero mass. However, in practice the load carrying masses of the vehicle (bogie frame, vehicle body) are often used to effect the structural connection between the wheelsets. In that case the assumption that the structural connections of the wheelsets are massless is no longer justified and the de-stabilising effect of the mass of the connecting structure has to be considered. The de-stabilising influence of the motions in the lateral plane of a mass suspended on the wheelsets is more severe if the motions of the mass are coupled to relative yawing motions of the wheelsets in opposite senses.

II. Curving Ability

1. Off-Flange Curving

As mentioned above, two-axle bogies require inter-axle connections which constrain the two wheelsets in shear as well as in bending if stability is to be obtained through elastic couplings of the wheelsets. For perfect curving on the other hand the inter-axle bending stiffness has to be zero. This means that theoretically the elastic suspension requirements for stability and perfect curving are in conflict with each other. However, from a practical point of view this has to be seen in perspective as there are a number of other factors mentioned below which do not allow the wheels of a two-axle bogie to follow a pure rolling motion on curved track. Therefore, the bending stiffness is but one parameter that requires attention in the optimisation of the suspension of a self-steering bogie.

It was mentioned earlier that for self-steering to be of practical significance, profiled wheels have to be used. Due to gravity and spin creep such profiled wheels are subjected to lateral forces when deflected laterally and the resultant

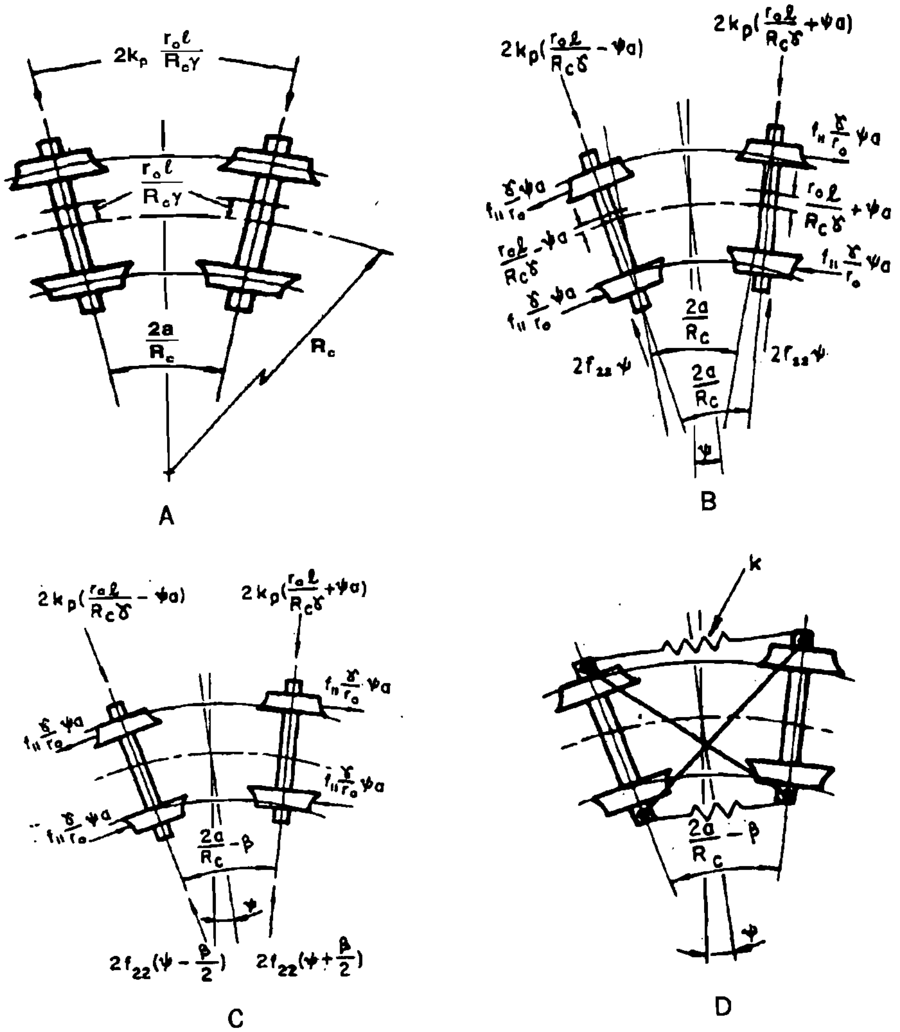


Fig. 6. Off-flange curving position of wheelsets of optimised two-axle self-steering bogie.

so-called profile stiffness cannot be ignored in an analysis of the curving performance of self-steering bogies as it is of the same order as the bending stiffness used for optimised self-steering bogies. This is one reason why even at zero bending stiffness self-steering bogies cannot curve perfectly. However, an analysis of the steady state deviations of the wheels from the pure rolling position on curved track shows that the detrimental effects of the profile and bending stiffnesses combined can be minimised if the two stiffnesses are related to each other. Figure 6 shows that for the assumption of an infinitely high shear stiffness the lateral forces resulting from the profile stiffness cause the two wheelsets to rotate about the bogie centre. As a result, longitudinal creep forces are generated which can be held in equilibrium by a corresponding bending stiffness, leaving the inter-axle shear structure unconstrained in the off-flange curving mode. In this manner wear at the joints of the inter-axle shear coupling is kept to a minimum and a relatively high shear stiffness of the coupling can be used. This best suits the requirements for stability and on-flange curving.

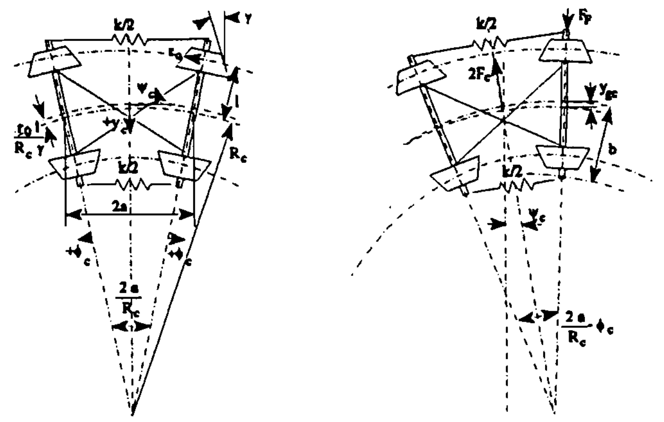
There is also a practical reason for retaining a certain inter-axle bending stiffness. The springs of the primary suspension, whether they are coil springs or rubber elements, invariably have a longitudinal stiffness which generates a yaw constraint between each wheelset and the bogie frame and this constitutes a constraint to inter-axle bending. Obviously it is not very practicable to provide a suspension with a zero longitudinal stiffness. Furthermore, such a primary suspension would be incapable of transmitting longitudinal forces due to braking or traction and special linkages would be required to transmit such forces at the centre of yaw of the wheelsets. For many applications of self-steering bogies (particularly freight car bogies) the expense of such additional linkages would not be warranted as the further improvement in curving performance which could be gained from using zero bending stiffness is of little practical significance.

In addition perfect curving is possible only at a speed where the centrifugal force is in equilibrium with the gravitational component of the axle load due to track cant. In practice track cant is selected to suit the curve speeds of goods trains and passenger trains operate at up to 10% cant deficiency. Under such conditions of cant deficiency the inter-axle shear structure limits the range of curves which can be negotiated in the off-flange curving mode by self-steering bogies.

Furthermore, perfect curving also requires zero rotational constraint between bogie frame and vehicle body. However, in recent years the so-called sill support of the body on the bogie frame via air springs, coil springs or rubber shear pads has been widely accepted as this simplifies the design of the bogie frame. Such sill support elastically constrains the rotational motion of the bogie frame relative to the vehicle body and thus has an adverse effect on curving performance.

2. *On-Flange Curving*

In curves where the gauge clearance is insufficient to allow for the rolling radius difference required for off-flange curving to be developed, so called on-flange curving will occur. In this case the longitudinal creep forces will change direction and exert a couple on the wheelsets which acts to rotate both wheelsets into an angle of attack position. As the simplistic curving model of figure 7, which assumes infinite shear stiffness, shows, theoretically on-flange curving at zero flange force is possible for the case of zero bending and profile stiffness. In this case the axles will oversteer and a creep force pattern will develop which is similar to the off-flange curving mode for rigid bogies [13] with the direction of the longitudinal and lateral creep forces reversed. However, with profiled wheels a gravitational force (which is the equivalent of a flange force) will act on the outer



$$\Psi_c = \frac{kb^2\left[\frac{a}{R_c} + \frac{l\gamma}{r_0}\left(y_{gc} + \frac{r_0 l}{R_c\gamma}\right) - \frac{F_c}{2f}\right]}{a\left(f\frac{l\gamma}{r_0}\right) + kb^2\left(1 - \frac{l\gamma}{r_0}\right)}$$

$$\Phi_c = \frac{f\frac{l\gamma}{r_0}\left(y_{gc} + \frac{r_0 l}{R_c\gamma}\right) + kb^2\frac{a}{R_c} - \frac{F_c}{2}a}{af - kb^2} - \frac{af}{af - kb^2}\Psi_c$$

$$y_c = y_{gc} + \frac{r_0 l}{R_c\gamma} + a\Psi_c \qquad F_p = 4\Psi_c f + 2F_c$$

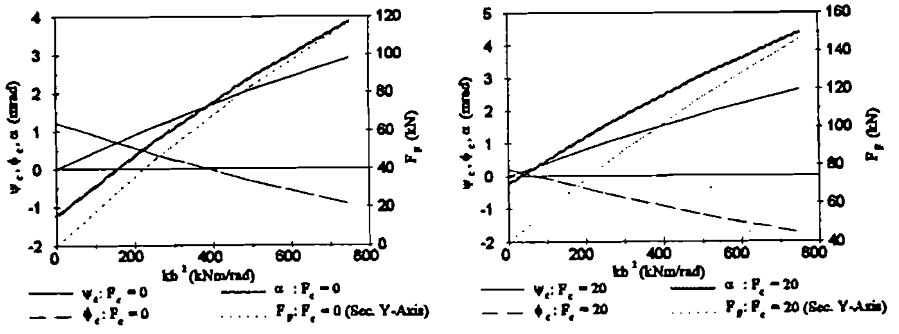


Fig. 7. On-flange curving of two-axle self-steering bogies.

leading wheel when the gauge clearance has been taken up in the on-flange curving mode.

The equations and graphs given in figure 7 show the position of the wheelsets in the on-flange curving mode for the range of bending stiffness used for self-steering bogies. The effect of a centrifugal force on the position of the wheels in the on-flange curving mode is also shown. For the lower range of bending

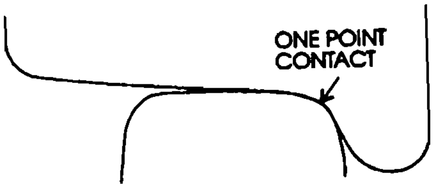


Fig. 8. Curved track: one point wheel/rail contact.

stiffness the rotational motion about the bogie centre which results in an angle of attack for both wheelsets is partially off-set by the increase in the angle between the axles, which reduces the angle of attack of the leading wheelset. Tests conducted with self-steering bogies in 90 m curves have shown that for the lower range of bending stiffness the angle between the axles is greater than the radial angle. This shows that valid conclusions can be drawn from the algebraic equations obtained from the simplistic linear on-flange curving model with regard to the influence of the suspension elements on the on-flange curving performance of self-steering bogies.

3. *Wheel Profile*

The simplistic curving model of figure 7 assumes one point contact (figure 8) between the outer wheel and the rail, and linear effective conicity and creep. In practice the wheel/rail geometry and the creep forces will be non-linear and two point contact (figure 9) may occur frequently. In very tight curves creep saturation will occur and the creep forces will reach the maximum value of vertical force times coefficient of friction. All these factors are taken into consideration by non-linear on-flange curving models which allow for the

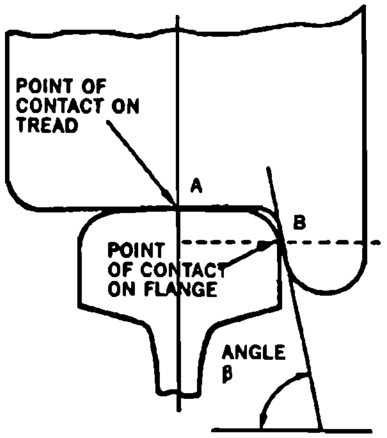


Fig. 9. Curved track: two point wheel/rail contact.

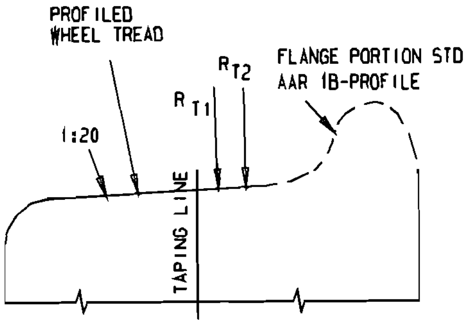


Fig. 10. 'Standard wear profile' of throat of wheel.

position of the wheels and the flange force to be numerically determined for any given wheel/rail geometry situation and suspension parameter combination.

Most railways specify the flange angle and throat region of the wheel profile (figure 10) to comply with the so-called "standard wear" profile. For self-steering bogies it is important to blend this throat profile smoothly into the tread profile which starts at the taping line of the wheel tangentially to the conventional 1/20 wheel tread taper (figure 11).

Both for stability and curving performance it is important that the rolling radius difference Δr increases smoothly with lateral deflection without discontinuities. (figure 12). As some new rail profiles have a "knife edge" like shape (figure 13) which changes with wear, worn rail head profiles must be taken into consideration for the design of the wheel tread profile. On lines which have "tight gauge" track the gauge clearance can be increased to a nominal value of 10 to 12 mm by a reduction in the flange thickness. This is permissible for self-steering bogies where the flange thickness and gauge clearance remain relatively constant between wheel re-profiling periods due to the virtual absence of flange wear. A minimum gauge clearance of 10 mm is desirable for self-steering bogies if the

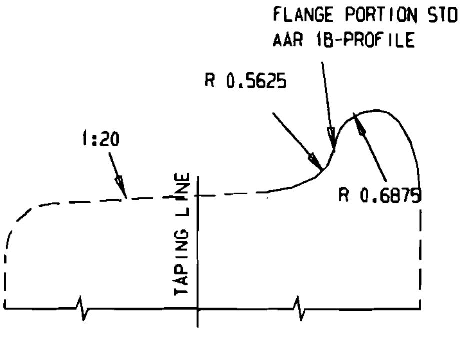


Fig. 11. Profiled wheel tread.

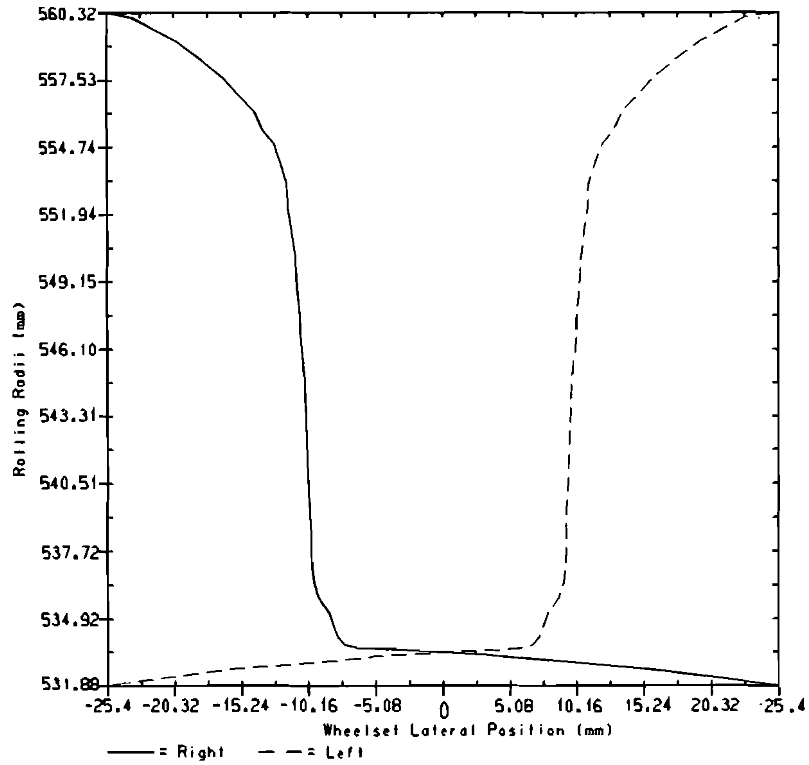


Fig. 12. Rolling radius difference as function of lateral wheelset deflection.

widest practical off-flange curving range is to be obtained and the amount of creep in the on-flange curving mode is to be kept to a minimum. The equations in figure 7 show that in the on-flange curving mode the longitudinal creep is a function of the difference between gauge clearance and the lateral deflection required to reach the pure rolling line. Thus a gauge clearance of 10 to 12 mm will ensure that creep and consequently wear will remain minimal even in 100 m curves. Generally, experience has shown that the wheel life of self-steering bogies can be more than doubled if the wheel profile is designed to ensure optimal conformity with the rail head profile [14].

An adequate gauge clearance and well conforming wheel profile also ensure that stresses in the inter-axle linkages remain low when the bogie enters a turn-out. For this condition dynamic forces in the inter-axle shear structure are at their highest as the inter-axle shear structure resists the motion of the leading axles towards the radial position in the transition to a curve. In view of the relatively short wheel base of two-axle bogies this is not of great consequence for the overall curving performance but does require attention in the structural design of the inter-axle shear structure [15].

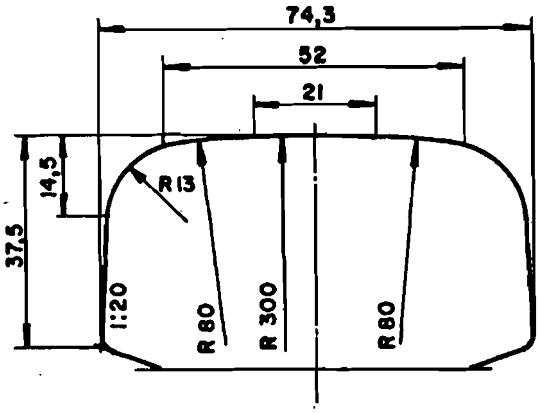


Fig. 13. UIC-60 rail head profile.

B. Three-Axle Bogies

1. Stability

An important application for three-axle bogies are Co-Co locomotives. Conventional designs of such bogies are known to have poor curving performance. This has generated interest in the development of steerable bogies for Co-Co locomotives [16]. It was mentioned above that in generalised co-ordinates only half the number of degrees of freedom have to be elastically constrained for dynamic stability. As the simplified model of a three-axle bogie has six degrees of freedom, three degrees only have to be constrained. In order to achieve this, each wheelset requires two inter-connecting structures. However, as there are now three wheelsets each wheelset can be coupled to its adjacent and non-adjacent wheelset by one structure each. This means that connecting structures can be used which do not constrain the three wheelsets in bending. Therefore, the pure rolling position of the axles and the two rigid body motions of the bogie (lateral motion of all three wheelsets in equal sense and rotational motion about the bogie centre) are elastically unconstrained. On the assumption of zero profile stiffness three-axle bogies which have such inter-axle connecting structures are, therefore, capable of perfect curving. However, the combined effect of such inter-axle connections can result in instability at low and high conicities [17,18]. This means that such inter-connecting structures can have a similar effect on the motion of the leading wheelset as the yoke arrangement of the pivoting wheelsets used on steam locomotives mentioned in the introduction. In the case of a leading pivoting wheelset having an infinitely stiff lateral connection to the frame, divergence will occur if the product of half the distance between contact points times conicity divided by wheel radius is smaller than one. For a three-axle bogie having an infinitely high shear stiffness between the outer axles, divergence of the leading wheelset will occur at conicities lower than half this value. In practice low conicity instability for steerable three-axle bogies can be avoided by a correct selection of the type and stiffness of the inter-axle connecting structures.

Steerable three-axle bogies also use profiled wheel treads with an appropriate conicity in order to obtain a good off- and on-flange curving performance. For Co-Co locomotives having axle-hung motors the resulting combination of high wheelset mass and high effective conicity may cause the dynamic stability obtainable from the elasticities of the inter-axle connections to be inadequate for the higher range of operating speeds. However, the inclusion of yaw dampers will ensure that modern operating speed requirements for such locomotives can be fully met.

II. Curving

As there are six simultaneous algebraic equations which determine the steady-state curving positions of the wheels of a three-axle bogie it is difficult to obtain algebraic expressions for the wheelset positions. The steady-state deviations from the pure rolling position of self-steering three-axle bogies must, therefore, be determined numerically for both the off- and on-flange curving modes. Such an analysis shows that a Co-Co locomotive having self-steering bogies can negotiate all curves with radii greater than 200 m in the off-flange curving mode. In the on-flange curving mode, flange contact will initially occur at the leading wheelset. As the curvature increases the outer flange of the centre wheelset will also make contact with the rail. For an 80 m curve the angle of attack will be about 0.2 and 0.4 degrees for the outer and centre axles, respectively.

4. DESIGN DETAILS

I. Flexible Bogies

In conventional two-axle bogies the inter-axle shear and bending stiffness required for stability is obtained from the lateral and longitudinal stiffness of the primary suspension which acts between the axles via the bogie frame. Therefore, in shear the lateral and longitudinal suspension stiffnesses act in series which means that a reduction in bending stiffness will also reduce the shear stiffness. This limits the scope for improving the curving performance of conventional bogies Nevertheless, bogies having an optimised flexible primary suspension have been developed and improved curving performance is being claimed without undue loss in dynamic stability[19]. The curving performance of flexible bogies can be further improved by using a primary suspension having a hydraulically adjustable longitudinal stiffness. The adjustment can be controlled by the vehicle speed or as a function of the frequency of the lateral oscillation of the wheelset (Hydrobuchse) (figure 14) Bogies having such primary suspensions have found acceptance as high speed passenger coach bogies [20].

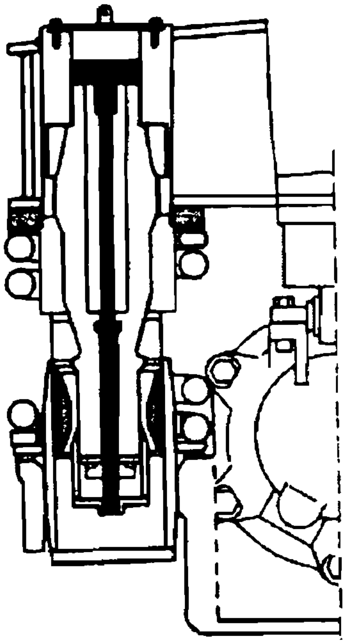


Fig. 14. Spring having hydraulically variable transverse stiffness.

II. Self-Steering Bogies Having Inter-Linked Axles

For optimised curving performance, yaw constraints lower than acceptable to flexible suspensions are required. This necessitates the inclusion of direct linkages between the wheelsets in order that inter-axle shear stiffness which is independent of the inter-axle bending stiffness can be provided. This means that both the bending stiffness (yaw constraint) and (what is often equally important) the lateral stiffness of the primary suspension can be selected independently of the inter-axle shear stiffness.

Basically three types of inter-axle connections can be used for the purpose of providing a direct shear stiffness between the axles. They are, triangular yokes mounted on the journal boxes and pin-jointed together at their apices (figure 15a), diagonal links pin-jointed to the journal boxes or subframes (figure 15b) and Watt's linkages (figure 15c). If the centre lever of the Watt's linkage is pivotally connected to the bogie frame the inter-axle shear stiffness is again dependent on the lateral stiffness of the primary suspension. This can be overcome by attaching the Watt's linkages to a separate frame which connects to the centres of yaw of the axles (figure 15d).

In most instances the space available for inter-axle linkages is very limited and for motorised bogies in particular it is often not possible to fit linkages in the plane of the axles. To address this space problem the inter-wheelset connection consisting of a combination of Watt's linkages shown in figure 16 was designed for a self-steering locomotive bogie.

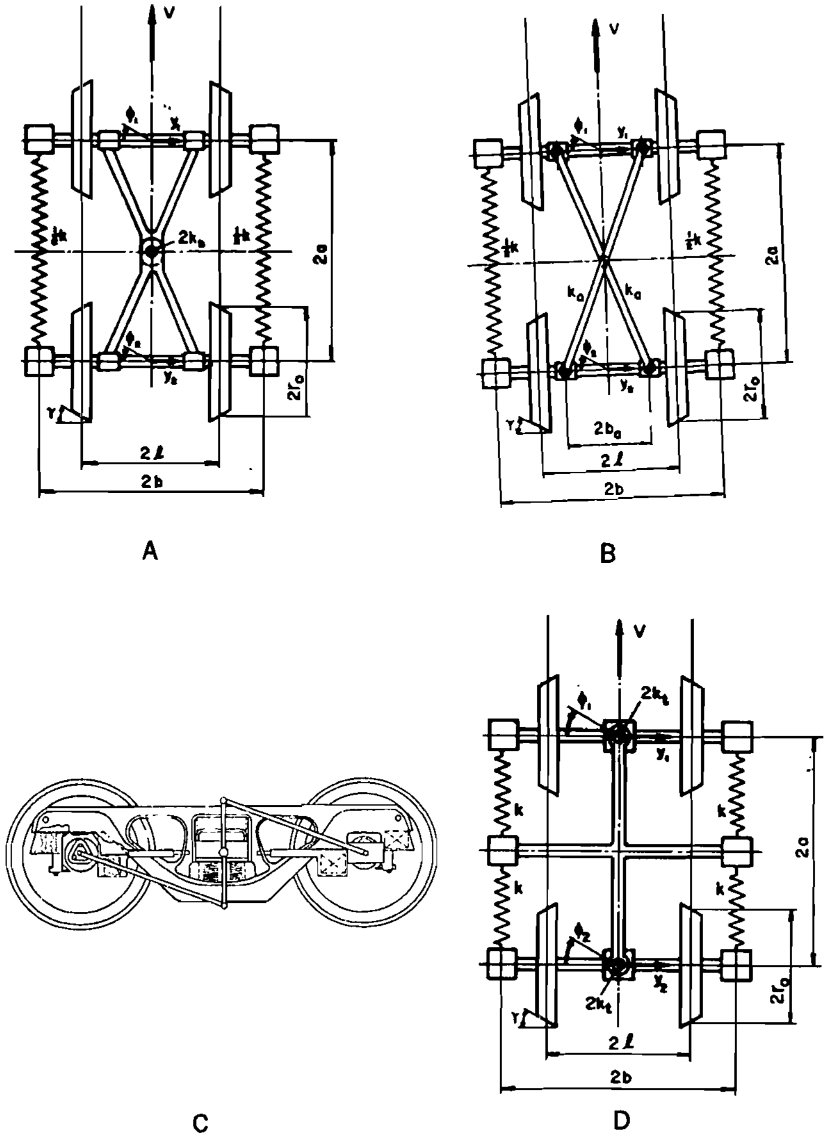


Fig. 15. Basic types of inter-axles shear structures.

Furthermore, for high speed and motorised bogies the low longitudinal stiffness of the primary suspension required for the low bending stiffness of self-steering bogies is insufficient for the effective transmission of the braking and traction forces from the wheelsets to the bogie frame. Therefore, additional connections are required. Such connections can again include Watt's linkages in combination with bell cranks or cross-beams like the so-called rotatable

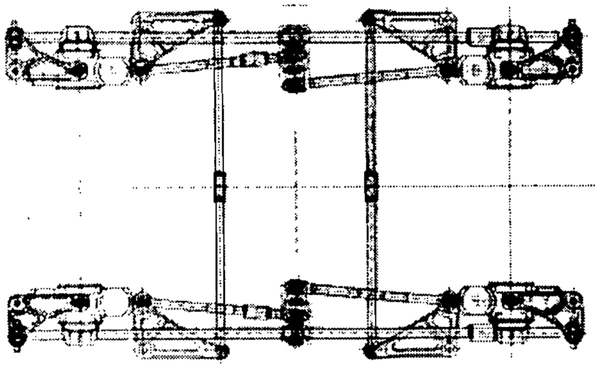


Fig. 16. Wheelset shear connection of locomotive bogie consisting of combination of Watt's linkages.

lemniscate suspension (Fig 17 a, b) which transmits longitudinal forces only, or a frame mounted inter-wheelset shear coupling mechanism (Fig. 18) which combines the traction links and inter-axle shear connections.

5. EXAMPLES OF SELF-STEERING BOGIES.

Steerable bogies using triangular yokes are the radial axle freight car trucks used in the USA and Canada (figure 19) and the cross-braced freight car bogies developed in Britain (figure 20). Linkages which diagonally connect subframes mounted on the journal boxes are used in the cross-anchor freight car bogies developed in South Africa (figure 21). Experimentally, cross-anchor bogies have

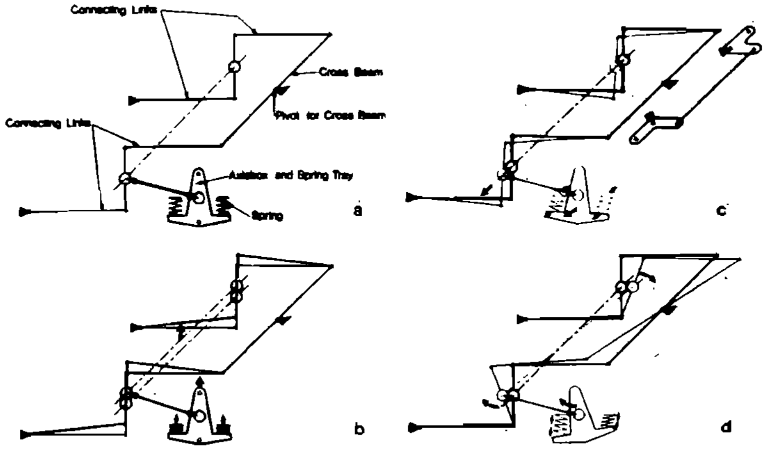


Fig. 17a. Rotatatable lemniscate linkage for transmission of traction forces having transverse beam.

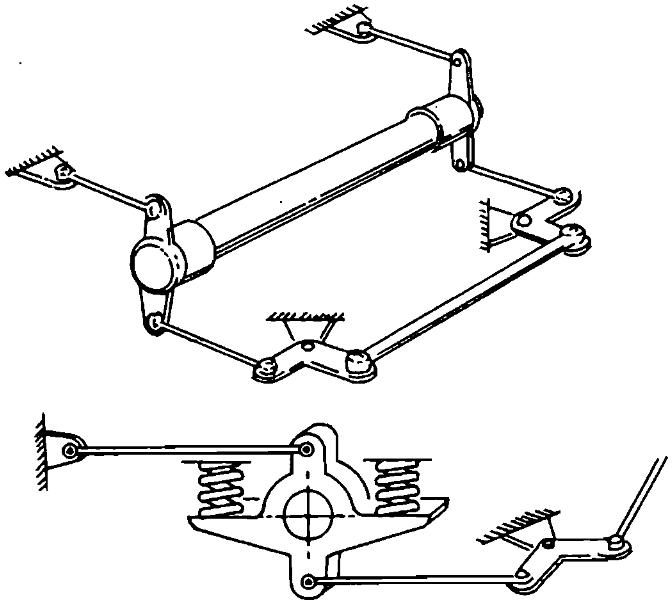


Fig. 17b. Rotatatable lemniscate linkage for transmission of traction forces having bell cranks.

been equipped with a variable yaw constraint suspension system (figure 22) and fitted under container cars operating at maximum speeds of 140 km/h. The variable yaw constraint suspension system is a spring mechanism which is activated by the longitudinal creep forces (figure 22) [21] and has a similar effect on stability and curving as the hydraulically adjustable primary spring

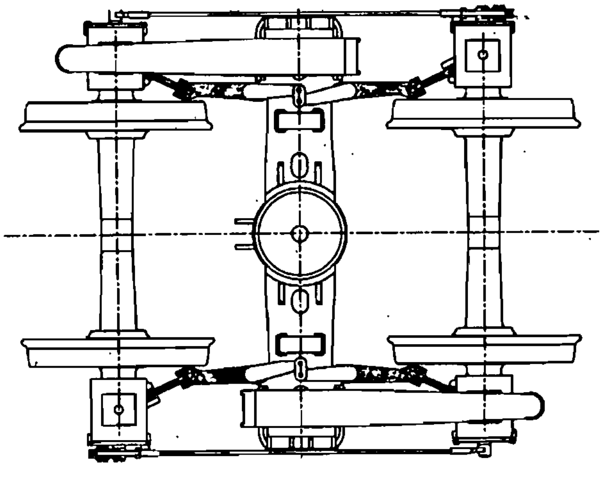


Fig. 18. Frame mounted inter-wheelset shear coupling.

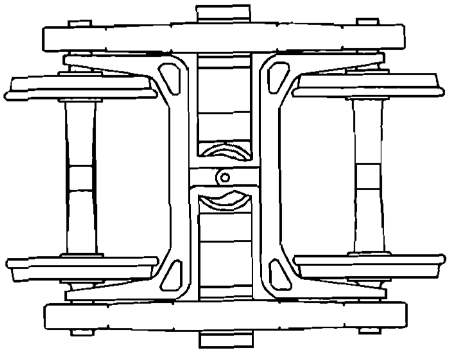


Fig. 19. AR-1 freight car truck.

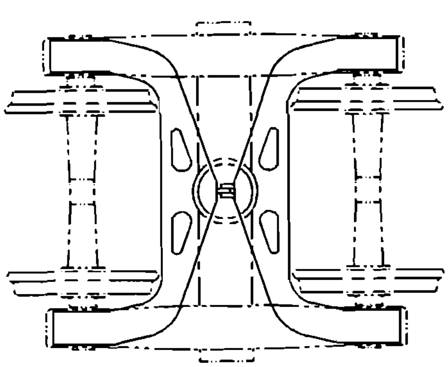


Fig. 20. Cross-braced freight car bogie.

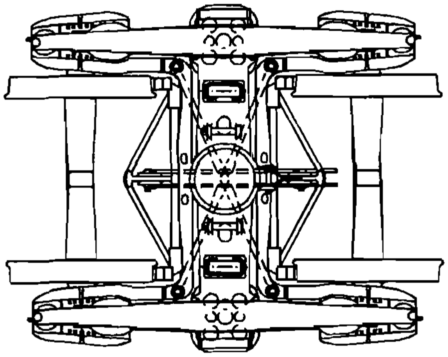


Fig. 21. SAR self-steering cross-anchor freight car bogie.

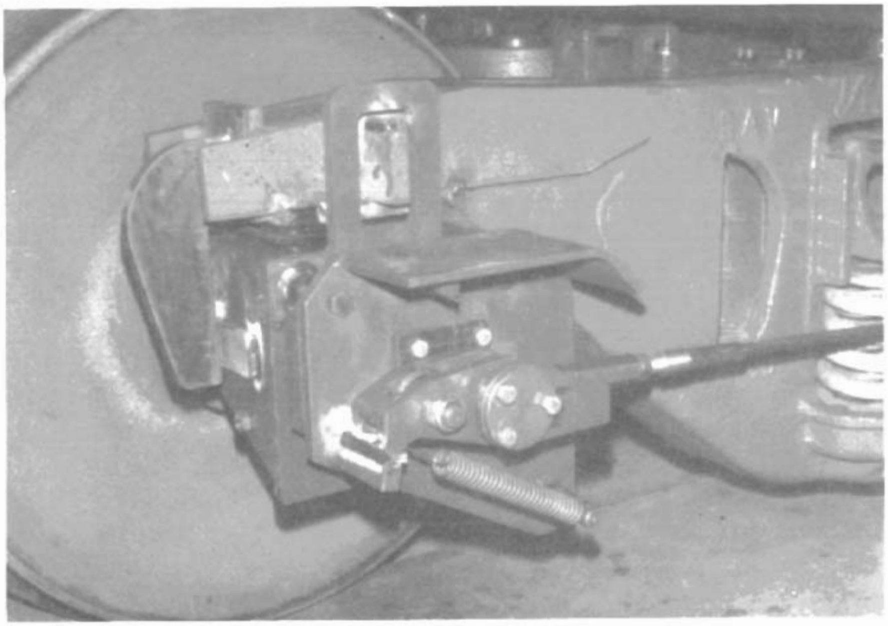


Fig. 22. Self-steering bogie having variable yaw constraint suspension mechanism.

mentioned above. The mechanism raises the stable operating speed of the cross-anchor freight car bogies from 120 to 160 km/h without impairing their curving performance.

A passenger bogie built in South Africa for an operating speed of 160 km/h incorporates cross-anchors which directly inter-connect the journal boxes and Watt's linkages for the transmission of braking forces (figure 23). In this case axle box yaw dampers are fitted to ensure stability at high speed. These 3–6" gauge bogies were tested at a maximum speed of 245 km/h.

Bogies developed for the Vienna Underground use cross-anchors in combination with a rotatable lemniscate suspension incorporating cross-beams for the transmission of traction forces (figure 24). These bogies operate at a maximum speed of 80 km/h. The tightest open line curve has a radius of 100 m.

The four megawatt dual voltage Bo-Bo electric locomotives built for South African Railways' 3'-6" gauge have self-steering bogies which use a combination of Watt's linkages as inter-axle shear connection and a rotatable lemniscate incorporating bell cranks for the transmission of the traction forces (figure 25). The maximum operating speed is 160 km/h.

Steerable bogies developed for the Netherlands Railways in motor and trailer versions have a specially developed cross-bracing mechanism which is situated below the bogie frame to overcome the space restrictions in the plane of the axles [22].

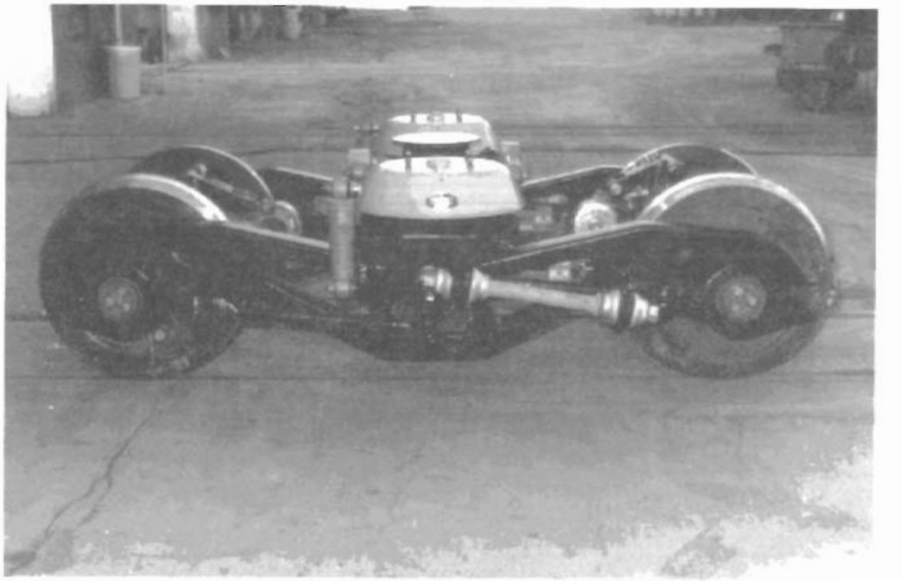


Fig. 23. Self-steering passenger coach bogie.

6. FORCED-STEERING

The most common railway vehicle is the two-bogie four-axle vehicle. As was mentioned in the Chronology the first proposals to passively force-steer the axles of such vehicles in the on flange curving mode by means of linkages connecting the wheelsets having conical wheels to the bogie frame and the vehicle body were made more than hundred years ago. However, modern designs of forced-steering bogies will use profiled wheels and can thus curve in the off-flange curving mode in most main line curves. For this reason, it is important that the steering linkages serve a stabilising as well as a steering function. As the simplest dynamic model of a four-axle vehicle has eight degrees of freedom of which, in generalised co-ordinates, four degrees only, have to be constrained for stability, wheelset interconnecting structures which do not elastically constrain the wheelsets in bending can be applied. Therefore, as is the case for three- axle bogies, four-axle vehicles having inter-axle shear connections and zero bending stiffness are capable of perfect curving if the effect of the profile stiffness is ignored. Furthermore, since four degrees of freedom can be left elastically unconstrained, theoretically, perfect steering in transition curves can also be achieved.

It has been shown analytically that inter-axle structures which constrain in shear, the adjacent wheelsets and the wheelsets separated by two bays, meet the requirements for stability and perfect curving [23]. However, in view of the long distance between axles separated by two bays, it is more practicable to arrange

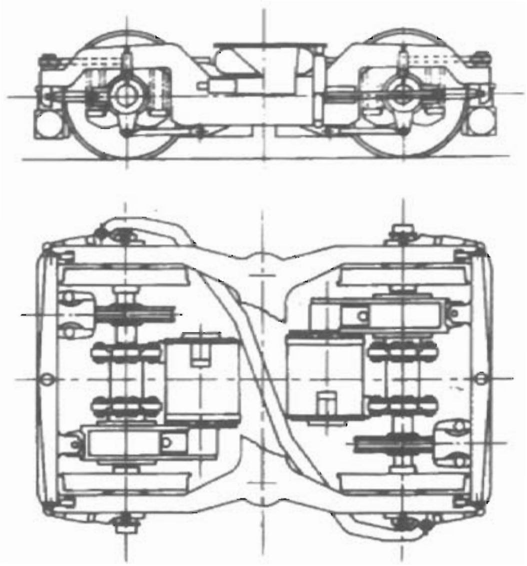


Fig. 24. Self-steering bogie for underground railway.

the inter-axle connections via the bogie frame and vehicle body. Thus actual designs of bogie vehicles which have all four axles elastically inter-connected still use traditional steering' links. Furthermore, for practical reasons a primary suspension having a longitudinal stiffness greater than zero is used.

Experience gained with such forced-steering bogies has confirmed the predicted stability and curving performance. However, it has also been found

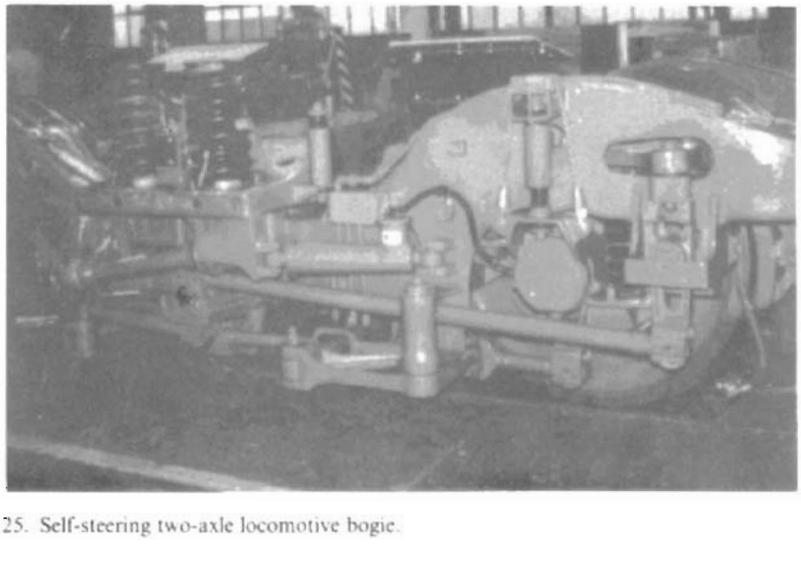


Fig. 25. Self-steering two-axle locomotive bogie.

that such designs are prone to instability at low conicities. The low conicity instability resembles the primary instabilities which can be experienced with vehicles having conventional or self-steering bogies [24, 25]. However, the destabilising inertia forces transmitted to the wheelsets via the steering linkages are generally more severe than the forces transmitted in a primary instability mode due to the fact that the steering linkages dynamically couple the body yaw oscillation to the yawing motion of the wheelsets in opposite senses. To control the low conicity instability, the stiffness of the steering linkages has to be reduced. This may lower the high conicity stabilising capability of the linkages and effect the on-flange steering ability. However, in spite of this compromise, curving requirements which limit the angle of attack to 0,1 and 0,5 degrees in 100 m and 35 m curves, respectively, can be met. Forced-steering bogies are, therefore, particularly suited for trams and street cars which operate on lines where 35 m radius curves are not uncommon.

Forced steering bogies usually have the outer and/or inner wheelset connected to the bogie frame and vehicle body by a vertical steering lever (figure 26a, b). If one axle only is linked to the body a Watt's linkage (figure 15c) is fitted between the axles for increased inter-axle shear stiffness. Alternatively the vertical lever of the Watt's linkage connecting the axles of each bogie may be extended and elastically linked to the vehicle body. In either case the inter-axle shear stiffness is dependent on the lateral stiffness of the primary suspension.

Examples of forced-steering bogies which were placed in service in recent years are the Navigator bogies developed for the Swiss Federal Railways [26], the steered bogies developed for the London Regional Transport [27] and the bogies built for the Skytrain System of Vancouver [28].

7. PROFITABILITY OF STEERABLE BOGIES.

As was shown above, self- and forced-steering bogies use inter-axle linkages for wheelset guidance in combination with the conventional suspension elements which couple the wheelsets to the bogie frame. To-day, computational techniques based on the creep theory are available to optimise the suspension parameters of complete vehicles with respect to stability and curving performance in relation to the operational requirements for any particular application. In order to realise the desired performance in practice the wheelset guidance structures have to be carefully designed and integrated into the bogie suspension arrangement. Accurate manufacture of the structures is a further essential requirement as good alignment of the wheelsets is as important for improved performance as are the stiffness characteristics of the suspension elements [29]. In addition, close attention has to be paid to structural strength and adequate size of joints if trouble free operation of the suspension system is to be ensured between normal maintenance cycles. In this respect modern elastomer and bearing technology as well as finite element methods for stress calculations offer invaluable assistance.

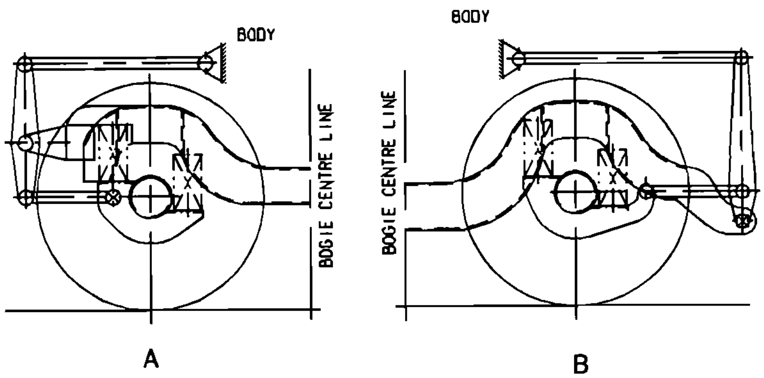


Fig. 26. Forced-steering linkage: schematic view of vertical lever connecting outer (a) or inner (b) wheelset to bogie frame and vehicle body.

Obviously the additional components and accuracy requirements result in higher initial cost which range from about 10% in the case of freight car bogies to as much as 25% for motorised bogies. Although it is to-day generally accepted that steerable bogies can reduce wheel and rail wear considerably, save energy as a result of the lower curve resistance and reduce the risk of derailments in curves, the higher initial cost is still a deterrent to the acceptance of steerable bogies for general use. There is also a perception that additional components and particularly additional joints impair the service reliability. Further objections are that the inter-axle structures increase the tare mass and make normal maintenance operations such as changing brake blocks or attending to commutator brushes more difficult. For these reasons railways generally adopt a conservative approach when assessing savings that will accrue from the use of steerable bogies and the amortisation of the increased cost is often based on reduced wheel wear only. For these reasons utilisation is at this stage limited to applications which are known to have stringent curving requirements or where operating experience has shown that the performance of conventional designs is inadequate or even problematic. By the same token, on lines which have curving problems conventional designs will no longer be considered once steerable bogies have been tried. On the whole,, in spite of the cautious approach of railway operators to innovation, interest in steerable bogies is steadily increasing particularly for locomotives where improved utilisation in curves of available tractive effort is considered an additional advantage.

8. CONCLUSIONS

Efforts to improve the curving performance of railway vehicles can be traced back to the very beginning of railway transportation. Early designs of steerable vehicles aimed to improve the on-flange curving performance. Features of such early designs still find their reflection in modern forced steered bogies. The exploitation of the self-steering capability of wheelsets is relatively new and received its impetus from the creep theory and the acceptance of profiled wheel treads in favour of the traditional 1/20 coned wheels. Considerable progress has been made with the development of steerable bogies during the last two decades and to-day reliable, service proven designs are available for a variety of applications. Provided the suspension parameters are carefully selected steerable bogies will have adequate stability to meet modern operating speed requirements. The need for steering and stabilising structures results in increased initial costs which have to be amortised by the savings accruing from reduced wear and energy consumption, and operational advantages. Projected reductions in wheel and rail wear differ from line to line and operating conditions Space limitations tend to increase the complexity and cost of the steering and stabilising structures particularly for motorised bogies. In spite of this the interest in steerable bogies for locomotives is increasing as the improved utilisation of available tractive effort in curves is perceived as an additional advantage.

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