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(54) IMPROVEMENTS IN RAILWAY VEHICLE
SUSPENSION

(71) We, SOUTH AFRICAN INVENTIONS DEVELOPMENT CORPORATION, Administration Building, C.S.I.R. Scientia, Pretoria, Transvaal, South Africa, a company registered according to the laws of the Republic of South Africa, do hereby declare the invention, for which we pray that a patent may be granted to us, and the method by which it is to be performed, to be particularly described in and by the following statement:—

This invention relates to railway vehicle suspensions. In particular, it is concerned with a suspension for a railway truck which simultaneously provides for good curving ability and hunting stability of the vehicle.

Railway vehicles are dynamically unstable and the various parts of a vehicle tend to oscillate laterally when it is moving. The effect of these oscillations is commonly referred to as hunting and distinction is made in the art among body, bogie frame, and wheelset hunting.

For guiding the vehicle, such as in cornering and for correcting deviations from the centre of the track it has been found to be desirable to use a wheel set arrangement in which the wheels, with conical or profiled wheel treads, are rigidly mounted on common axles. This arrangement is dynamically unstable because of the conicity of the wheels and the creep or slip forces acting between the wheels and the rails. This instability is evidenced by sinusoidal oscillations of the wheel sets, the frequency of which is dependent primarily on the speed of the vehicle. Further, the wheel sets have a natural oscillation because they are connected to the vehicle body by elastic suspension elements. At certain speeds the natural

and speed-dependent oscillations combine and the amplitude of the resulting oscillation is the factor which limits the maximum practical speed of the vehicle.

It has been found that decreased wheel tread conicity lowers, and increased longitudinal or yaw constraint on the wheelsets raises the critical speed for wheelset hunting. For these reasons, known suspensions employ relatively stiff longitudinal elements such as axle guides, radius arms, anchors and the like, and relatively small wheel tread conicities ranging from 1/20 to 1/40 the latter being used with very high-speed passenger vehicle. However, the requirements for a good curving ability are the opposite of those for good hunting stability since stiff longitudinal elements resist yawing of the wheelsets so that curving must be attained by the wheels slipping on the rails and even in moderate curves by the flange of the outside wheel of the leading wheelset contacting the inside of the rail. Further, low tread conicities do not allow for the correct or optimum difference to be attained in the rolling diameters of the inner and outer wheels. Wheel treads show very high wear tendencies because of the hunting of the wheelsets and also because of the inability of the wheels to follow the curvature of the track during cornering, i.e. they have to rely on wheel flange/rail contact. Therefore with conventional suspensions, there is a conflict between the requirements for wheelset hunting stability and steering ability.

For the above reasons, as well as other considerations such as riding quality, initial cost, etc., railway vehicle design has generally concentrated on finding a compromise between the various suspension parameters in order to

obtain an optimum solution for hunting stability and curving ability. Such compromises minimise the problems, but by no means eliminate them.

5 The above remarks can be verified mathematically using the pseudoslip theory for analysing the forces acting in the contact areas between the wheels and the rails to ascertain the equations of motion for the lateral oscillations of the vehicle, e.g. oscillations of the wheelsets, the bogie frame and the vehicle body. For example ignoring the inertia forces of the bogie frame and, vehicle body and the suspension damping elements, the analysis shows that all oscillations are stable (i.e. the amplitude of the oscillations tends to decay with time) as long as the forward speed V of the vehicle is within the limits shown by the following relationship:

$$20 \quad V < \sqrt{\frac{l r_0}{\gamma} \left(\frac{k_l}{M} + \frac{k b^2}{M l^2} \right)} \dots (1),$$

where

- 21 l = distance between wheel/rail contact points on the same axle,
- 25 b = distance between resilient elements on the same axle,
- γ = effective conicity of the wheel tread profile,
- r_0 = rolling radius of the wheel with the wheelset in its natural position on straight track,
- 30 k = longitudinal and k_r = lateral stiffness of the resilient elements between the wheelsets and bogie side frames, and
- 35 M = mass of each wheelset.

As mentioned previously the stability of a vehicle increases with increasing constraint or stiffness and decreasing wheel tread conicity γ ; this is clearly shown by the above relationship showing that theory and practice are in agreement. (k_r cannot normally be made high this would result in high feed back from the body as well as poor riding quality).

45 Theory by the inventor shows that wheel-flange/rail contact can be avoided and at the same time reasonable motion of the wheels maintained, known in the art as "self-steering", if, for normal curve radii encountered on railway lines, the following relationship holds:—

$$k < \frac{W \gamma}{R \delta_0} \dots (2),$$

where

- 55 k = longitudinal stiffness of resilient elements between the wheelsets of a vehicle and the load-bearing members supported on the wheelsets,

γ = effective conicity of profiled wheel treads,

W = maximum axle load,

R = radius of curvature of profiled wheel treads, 60

δ_0 = angle between the wheel/rail contact plane and the horizontal with the wheelset in the central position.

Relationship (2) expresses the restraint against yawing of the wheelsets in terms of "longitudinal stiffness k " which is a force per unit displacement. The restraint may also be expressed in terms of "yaw constraint K_y " which is a moment or couple per radian. K_y is equal to $2kb^2$ so that (2) can be re-stated as

$$K_y < \frac{2 W \gamma b^2}{R \delta_0} \dots (3)$$

Comparison between relationships (1) and (2) highlights the conflict mentioned previously between high hunting stability (demanding a high stiffness k and low conicity γ) and good curving ability (requiring a low stiffness k and high conicity γ). 75

The hunting stability requirements are complicated further by feed back of bogie frame or vehicle body inertia forces causing unstable oscillations at speeds where the kinematic frequency of the wheelsets coincides with the natural frequencies of the vehicle masses. This can again be described mathematically by including the inertia forces of the vehicle masses in the equations of motion. If, for example, the inertia forces resulting from the rotational motion of the bogie frame about the pivot centre connecting the vehicle body to the bogie are included then as an additional condition for stability, the following relationship must be met: 80

$$V < \sqrt{\frac{l r_0}{\gamma} \cdot \frac{4}{C} (a^2 k + b^2 k_r)} \dots (4), \quad 95$$

where

- C = is the moment of inertia of the bogie frame about its pivot centre, and
- a = half the wheel base of the bogie.

For normal vehicle parameters the critical speed given by the relation (3) is lower than that obtained from equation (1). Again the stable speed range can be increased by increasing k and/or decreasing γ ; both these variations impair the curving ability of the wheels. 100

For the purposes of this specification, a further term is defined, namely:—

f = creep coefficient, which is a function of axle load.

It is an object of this invention to provide a suspension for a railway vehicle which resolves the conflict between hunting stability and curving ability in a reasonably satisfactory manner. 110

For the purposes of this specification the term railway truck is defined to mean a basic railway unit comprising at least one load-bearing member which may be a body or a frame, supported on at least two wheelsets. A railway truck may, therefore, be a four wheeler or else it may be a bogie, on two of which a superstructure can be pivotally mounted to form a vehicle. The term "superstructure" refers specifically to a bogie vehicle situation.

According to the invention a method of minimising hunting in and improving the curving ability of a railway truck fitted with at least two wheelsets, each wheelset comprising a pair of wheels fast on an axle, includes the steps of:

(a) mounting the wheelsets to allow them to yaw relatively to the truck;

(b) limiting any yaw constraint on each wheelset relatively to the truck to allow reasonable rolling motion of the wheels during curving;

(c) profiling the wheel treads with an effective conicity greater than $1/20$; and

(d) damping any yaw and lateral movements of each wheelset relatively to the truck or to another wheelset by coupling a pair of wheelsets whereby turning movements of the wheelsets are coupled in opposite sense.

According to another aspect of the invention a railway truck having at least two wheelsets resiliently supporting at least one load-bearing member for distributing truckload forces to each wheelset, each wheelset comprising a pair of wheels fast on an axle and each wheelset being so mounted in the truck as to be capable of yawing and lateral movements relatively to the load-bearing member is characterised by:

1) each wheelset being self-steering in that:

(a) the wheels have treads that are profiled to have a high effective conicity so that steering forces are generated on the wheelset on a curved track, and

(b) any yaw constraint on each wheelset relatively to the load-bearing member is lower than the steering forces generated on the wheelset on curved track; and

2) means acting on each wheelset to counteract hunting of the wheelsets including any tendency to increased hunting and lowering of the critical hunting speed caused by the wheelsets being self-steering, without interfering with the self-steering characteristic of each wheelset, the counteracting means comprising a coupling between a pair of wheelsets to transmit any yawing movements of either wheelset in opposite sense to the other wheelset without interfering with the self-steering characteristic of each wheelset.

Features 1(a) and 1(b) mentioned above ensure that each wheelset is self-steering, and such wheelsets have an increased tendency to

hunt and to lower the critical hunting speed of the truck. This is counteracted by feature (2), the counteracting means acting between pairs of wheelsets.

Still further according to the invention a superstructure is mounted on two bogies that are trucks according to the invention.

Further according to the invention any yaw constraint on each wheelset relatively to the truck is limited to be less than

$$\frac{2 W_y b^2}{R \delta_0}$$

In a preferred form of the invention the coupling is elastic.

The invention is further described with reference to the accompanying drawings in which like parts are similarly numbered and in which:—

Figure 1 shows a side view of a bogie vehicle for employing the suspension of the invention,

Figure 2 is a schematic view of a wheelset illustrating certain dimensions associated therewith,

Figure 3 is a plan view of a bogie fitted with a longitudinal anchor,

Figure 4 is another embodiment of longitudinal anchor,

Figure 5 is a detail of Figure 4,

Figures 6 and 7 are schematic plan and side views of one embodiment of a railway truck of the invention,

Figures 8 and 9 are schematic plan and side views of a second embodiment of a railway truck of the invention,

Figures 10 and 10a shows a coupling member for the embodiments of Figures 6 to 9,

Figures 11 and 12 are schematic plan and side views of a third embodiment of a railway truck of the invention.

Figures 13 and 14 are plan and side views of a Four Wheeler employing the suspension of the invention.

Figures 15 and 16 show schematic plan and side views of a three-piece bogie fitted with articulated wishbones interconnecting a pair of wheelsets,

Figure 17 shows schematically one embodiment of a stabilizer for body-hunting,

Figures 18 and 19 show schematically two embodiments of the suspension of the invention with means for coupling three wheelsets,

Figure 20 shows a portion of a truck of the invention fitted with a resilient suspension having a negative elastic constraint.

Figure 21 shows a variation of the suspension of Figure 20,

Figure 22 shows a portion of another embodiment of a suspension having a negative elastic constraint.

Figure 1 shows a bogie 10 of a railway

(13)

vehicle having a body 100. The bogie 10 is basically a conventional three-piece bogie comprising two wheelsets 13, side frames 16 mounted on the wheelsets, and a bolster 18 located in the side frames midway between and parallel to the wheelsets. The bolster 18 rests on coil springs 20 and is located longitudinally by a known system of wedges 108 and friction plates 110, the wedges being held in position against the bolster by springs 112. This system allows the bolster to move transversely relative to the side frames, the movement being limited by appropriate stops (not shown).

The ends of the side frames indicated generally by 22 have a bridge configuration. The bases of the bridge supports are denoted 23 and 23'. Each base rests on a resilient element 24 which in this example is in the form of a sandwich comprising alternate layers of steel plates and rubber pads. The sandwich elements are used because they can be constructed to have low longitudinal and lateral spring stiffnesses. However, resilient element having these properties may be used instead, e.g. swing links (in fact, swing links are advantageous since using them the longitudinal and lateral suspension stiffnesses vary linearly with mass, but the design is more complicated and likely to be more costly). The resilient elements 24 are mounted on substantially horizontal flanges 28 provided on axle box adaptors 26. The adaptors may be of any conventional design provided with additional flanges 28. The adaptors 26 are mounted on bearings 15 fitted on axles 14 which are rigidly fixed to wheels 12. The wheels have "standard wear" profiled treads.

It should be noted (as shown in Figure 1) that the contact surfaces between the resilient elements 24 and the flanges 28 on the adaptors 26 are on the same horizontal plane passing through the axis of the axle 14. If this is inconvenient from a design aspect then the springs may be spaced away from the horizontal plane, but only if one spring is spaced at a certain distance above the plane and the other is spaced at the same distance below the plane. This placement of the contact surface is necessary to ensure that there is no movement on the adaptor 26 when the wheelset is in jaw, i.e. there must be no rotation of the adaptor 26 about the axle 14.

The resilient elements 24 (of any type) have inherent damping characteristics. In order to increase the damping as well as making it a characteristic which may be selected at will viscous or friction dampers 30 are provided longitudinally and laterally between the side frames 16 and the adaptors 26. A single damper provided angularly may also be used.

The body 100 is mounted on the bogie 10 by means of a female centre pivot 106 provided with a wear plate 104 mounted on the

bolster 18, a corresponding male pivot 102 being fixed to the body. With this arrangement the bogie is free to rotate with respect to the body.

Referring now to Figure 3 there is shown a longitudinal anchor 38 between the bolster 18 and the centre of the axle 14. The anchor 38 comprises a bearing 40 mounted over the centre of the axle 14, a ball joint 42 connecting the bearing to a rod 46, and a second ball joint 42 connecting the rod 46 to the bolster 18. It can be seen that such an anchor does not restrain the axle 14 in yaw, nor against lateral movement if sufficient play is allowed in the bearing 40. The wheel set will be restrained longitudinally.

In practice with the soft springing proposed above there would be a tendency for the wheelset to move longitudinally with respect to the bogie under high stresses such as heavy braking or high acceleration. The longitudinal anchor 38 prevents such relative movement while at the same time not interfering with the hunting stability and curving ability of the wheelsets. Where there is no or little likelihood of high stresses then the anchor may still be used as an additional safety factor.

Referring now to Figures 4 and 5 there is shown another embodiment of longitudinal anchor 50 comprising a tubular member 52 connected at one end by a flexible means 55 to a part 54 of the bolster 18 and at the other end by a similar flexible means 55 to a flange 58 supported on the bearing 40 by brackets 60. The flexible means 55 comprises a threaded element 62 engaged in the tubular member 50, steel washers 64 and 64', rubber "O"-rings or the like 66 and 66', and a nut 68. In use the threaded element 62 is engaged in the tubular member 50, the steel washer 64 is placed over the element to abut the member 50 and the O-ring is put onto the element. The element 62 is then inserted into a hole 53 formed in the flange 54 and the second O-ring and steel washer are placed in position. Finally the nut 68 is engaged with the element 62.

This arrangement is perhaps the most convenient since it performs exactly as a universal or ball joint in practice, but has the advantage in that the components can be freely adjusted or selected to suit bogie dimensions. For instance, the distance between the bolster and the axle may vary by as much as 3 cms.

While the drawings and the description indicate that the element 62 is screw engaged with the tubular member 50 it is also possible to weld or otherwise bond the element 62 and member 50. In this situation additional steel washers may be provided between the washer 64 and member 50 to adjust the length of the anchor.

The construction of Figure 1 is relatively conventional except that it is adapted to self-steering wheelsets. For example, the wheel

treads are profiled to a high effective conicity and the yaw constraints imposed by the resilient elements 24 are low. Also the adaptors 26 are made with two flanges 28 to accommodate the resilient elements 24 of low stiffness.

It is now proposed to connect directly the wheelsets to one another by a diagonal elastic anchor. In this way the elastic constraints on the wheelsets can be resolved into three components, i.e. yaw constraint and lateral constraint between each wheelset and the load-bearing member supported on it and longitudinal constraint directly between pairs of wheelsets. There is now greater freedom to select the various parameters to obtain excellent curving ability while at the same time conceding nothing to hunting stability. In other words, it is now possible to make the yaw constraint relative to the load-bearing members as low as is required for curving ability and then achieve the conditions necessary for hunting stability by selecting a suitable value for the longitudinal constraint directly between pairs of wheelsets. Furthermore, since the coupling between the wheelsets is provided diagonally, the diagonal anchor will be substantially unstressed by curving forces.

Extending equations (1) and (4) to include parameters for a longitudinal constraint directly between pairs of wheelsets in a bogie vehicle situation, it can be shown that the bogie frame rotational oscillations can thus be completely suppressed and will not be unstable, i.e. not increase in amplitude with time.

In order to obtain self-steering and to ensure that the diagonal coupling is unstressed during curving the yaw stiffness k must satisfy:—

$$k < G_r \frac{l^2}{b^2}$$

where,

$$G_r \approx \frac{W_y}{2R\delta_0} \dots (5)$$

G_r being referred to in the art as the gravitational suspension stiffness.

As previously, relationship (5) can also be expressed in terms of yaw constraint, K_y , the couple preventing rotation of the wheelset relatively to the load-bearing members, by the following relationship:—

$$K_y < 2 G_r l^2 \dots (6)$$

Relationship (6) is obtained by multiplying relationship (5) by $2b^2$ since K_y is equal to $2b^2k$. The value for the yaw stiffness and constraint respectively given by relationships (5) and (6) is approximately half that given by relationships (2) and (3) respectively.

In practice, the yaw constraint is preferably selected to be less than 750 kNm/radian yaw and the conicities to be at least 1/10.

Referring to Figures 6 and 7 of the drawings there is shown a portion of a suspension. The extremities of the axle 14 are fitted with a journal 15 having attached thereto an axle box adaptor 220. Rigidly secured to each of the adaptors 220 is one arm of a wishbone 222 which may be of a resilient material such as brass, bronze or treated steel, the other arm of which is secured to the adaptor at the other end of the axle 14. The apices of the wishbones 222 are coupled by an articulation means 225 comprising a projection 266, off-set from the centres of the apices of each of the wishbones 222, a viscous or friction damper 228, and a coil spring 230 arranged round the damper 228. This is not the only possible arrangement however and other resilient and damping elements such as leaf-springs, rubber pads or the like in a suitable configuration can be used. Outside the wheel sets and attached to the adaptors 220 are U-shaped members 224 which are provided to reinforce the wishbones 222.

In use, if one of the wheelsets 13 oscillates or yaws about a vertical axis through the centre of the axle the apex of the wishbone associated with it moves laterally. A portion of this movement is transmitted through the articulation means 225 to the other wishbone and to the other wheelset. However, the resilience of the wishbones and the elasticity of the articulation means damps the yawing motion by introducing a frequency and a phase change between the wheelsets. Thus in loose terminology, the responding wheelset also tends to yaw but at a different phase to that of the original yawing motion and, since additional creep forces come into play, the net effect is that wheelset hunting is damped.

The articulation means 225 between the wishbones 222 is such that it can only transmit very small turning moments between the wishbones. This means that during cornering the suspension imposes only a minimal rotational constraint on each wishbone, and each wheel set is free to follow the curvature of the rails. Therefore each wheelset can attain its optimum attitude for cornering and the suspension has a better steering ability than that of conventional suspensions.

Referring now to Figures 8 and 9 there is shown a portion of a suspension in which a transverse beam 232 is provided for strengthening the wishbone 222. An articulation means 235, between the wishbones is a conventional pin joint comprising a flange 234 provided at the apex of one of the members 222, a second flange or spaced flanges 236 provided on the other of the members 222, and a pin 237 passing through registering holes in both of the flanges 234 and 236, a rubber sleeve or bush 238 being arranged around the pin

237. The bush 238 provides additional lateral resilience for the wishbones.

In operation, this suspension is similar to that of the embodiment of Figures 6 and 7 except that the articulation means 235 has a definite pivot point, that is the pin 237. Thus, when the vehicle negotiates a curve the apices of the members 222 move in the same direction laterally and there are no moments in the articulation means 235 since the movement is purely rotational about the pin 237. By selection of the composition and configuration of the rubber bush 238, the suspension can be "tuned" to obtain optimum wheelset hunting stability as will be appreciated by persons skilled in the art.

An alternative embodiment of articulation means 325 which can be used between the wishbones 222 is shown in Figures 10 and 10a. The articulation means 325 comprises a small channel section 320 and a large channel section 321. Each of the sections 320 and 321 is secured to one of the wishbones 222 and provision is made for spacers 322 to be interposed between the sections 320 and 321 and the wishbones. The sections 320 and 321 are arranged to overlap longitudinally and are connected by rubber pads 323 and 324 which are vulcanised onto the inside of the larger section 321 and the outside of the smaller section 320 as shown in Figure 10a, i.e. between each of the opposing surfaces.

This articulation means is simple and inexpensive to manufacture, is durable and has the required properties of resilience and minimal moment transmission. Furthermore the means can be used as a standard item together with standard size wishbones since the provision of spacers allows for the assembled system to be adapted to variations in bogie side frame length. Of course, with any of the other arrangements spacers can be included at suitable points, e.g. at the articulation means or at the adaptors 220.

Figures 11 and 12 show an embodiment in which the wheelsets 13 are coupled by two diagonal elastic links 244. Each link 244 extends from an axle box adaptor of one wheelset diagonally to an axle box of the other wheelset.

The ends of each link 244 are coupled to the axle boxes using pin joints 246 arranged such that the links can pivot in a substantially horizontal plane. One of the links 244 has a slot 248 formed in it at approximately halfway along its length, the slot 248 being sufficiently wide to allow the other link to pass through it. An alternative to this arrangement is to crank one or both of the links near where they cross. Each of the links 244 may have resilient and/or damping means 250, the means 250 comprising a coil spring 252 in parallel with a viscous damper 254. However, any other convenient means such as

rubber pads, cranked leaf-springs or the like may be used. Further, the links have been shown as symmetrical, but this need not necessarily be so.

While not shown in any of the drawings it is also possible to form the links 244 integral with the adaptors 220, i.e. either during casting or subsequently by welding or the like. In such a situation the links need to be laterally flexible and this may be attained by suitable choice of the material used (e.g. bronze) and/or by cranking the link so that it is resilient at the bends.

In operation if one of the wheelsets pivots or oscillates then obviously one of its wheels will move towards and the other wheel away, from the centre of the suspension. The wheel which moves towards the centre causes the wheel of the other wheelset, to which it is diagonally connected, to tend to be pushed away from the centre, and conversely for the wheel which originally moves away from the centre. Because of the resilience of the diagonal links 244 a similar damping of wheel set hunting or oscillating as described previously occurs. During cornering both wheelsets follow the curvature of the rails, because there is no or little yaw constraint on the wheelsets caused by using the independent diagonal links and any constraint arises from other suspension elements.

To conclude the above descriptions on diagonal couplings the following should be noted:—

(a) for all of the embodiments which show and describe cross connected anchors it is also possible to dispense with one of the anchors, e.g. one link 244 or one arm of a wishbone, fixed to an adaptor 220 so that it cannot pivot laterally relatively to the adaptor, would be sufficient;

(b) the arms of the wishbones 222 may be formed integrally with the adaptors 220;

(c) the resilient and/or damping means 250 in the links 244 or the other resilient and damping means 228, 238, 230 can be dispensed with if there is sufficient elasticity in the materials used to form the wishbones or links. The materials also have inherent hysteresis damping. Thus, by selecting the composition of the materials used and the dimensions of the wishbones or links the required co-efficients can be obtained; and

(d) the diagonal coupling is used as a hunting stabilizer and is unstressed during curving. This is in contrast to prior art couplings which are in fact "steering arms" and are used to force the wheel sets into the correct radial position on curved track. Such steering arms as described in French Patent No. 1,006,038 Maschinenfabrik Esselen and German Patent 876,249 Dr. Ing. G. A. Gaebler are rigidly constructed as they have to withstand large forces and they in no way

serve as hunting stabilizers. Finally, because they offer no real advantage they have never been put into normal use.

Referring now to Figures 13 and 14 of the drawings which show a Four-Wheeler 260 provided with articulated wishbones. The Four-Wheeler comprises a body 261 resiliently supported by mounting means 262 on two wheelsets 13. Each mounting means 262 comprises an axle guide 264 pivotally coupled by swing links 266 to a housing 270, which in turn is resiliently supported on the adaptors 220 by coil springs 268 (rubber pad or sandwich elements may also be used).

Laterally between the housing 270 and the axle guide 264 there is a clearance so that the wheel sets can move longitudinally in the axle guides. The clearance may be of the order of 3 to 15 mm.

In operation, a number of advantages accrue from using the mounting 262. Firstly, the clearance ensures that the steering ability of the wheelsets is not interfered with by the vehicle body especially during cornering. The precise clearance is selected according to the vehicle wheelbase and the sharpest curves to be negotiated. Secondly, the use of the swing links 266 and springs 268 ensures that there is little longitudinal restraint or stiffness on the wheel sets. This can be done since suppression of wheel set hunting is no longer dependent on the stiffness of the suspension elements. The spring characteristics of the suspension can be selected to provide optimum riding quality and steering ability.

Referring now to Figures 15 and 16 there is shown a three-piece bogie 10 having two side frames 16 and a bolster 18. In contrast to some of the previous embodiments using wishbones 222 there are provided W-shaped members 286 in which the free ends of the members are bent so that they can pass around the outside of the wheels to conserve space. Furthermore (as illustrated in Figure 16) the arms of the members 286 are cranked vertically so that they can pass over the axles 14 and also so that they can pivot about a pin joint between the members 286 in substantially the same horizontal plane as the axles 14. A feature which is shown in Figure 15, but which can be applied to any of the embodiments is that the members 286 at the pin joint are each provided with a longitudinal slot to allow greater longitudinal freedom between the members 286 while still being able to provide the same properties as the aforementioned embodiments.

A resilient coupling between the wheel sets and the bogie side frames as shown in Figure 16 includes a rubber sandwich 290 having a low shear stiffness, located vertically between the side frames 16 and the adaptors 220. Again a clearance is provided between the adaptors 220 and the axle guides 283 and 283' provided at the ends of the side frames 16.

This embodiment also has a low yaw constraint or stiffness so that the optimum steering can be attained.

In association with providing a diagonal elastic coupling for limiting the hunting of the wheel sets a system incorporating levers and springs is coupled between the wheelsets and the body of the vehicle to limit body hunting; this is shown in Figure 17. A body 100 is coupled by a system of levers 302 and coil springs 316 to the side frames 16 and wheel sets 13. The system of levers 302 includes a two armed fulcrum lever 306, pivoted at its fulcrum on a bracket 310 mounted so that it is fixed laterally relative to the body, a straight lever 308 pin jointed at one end to one of the arms of the fulcrum lever 306, the other end of the straight lever 308 being pin jointed to a bracket 312 fixed to the side frame 16. The free end of the fulcrum lever 306, that is the arm remote from the straight lever 308 is secured to one end of a coil spring 316, the other end of which is attached to flanges 313 provided on the articulation between the wheelsets.

In practice, a transverse movement of the body, through the system of levers 302 and springs 316, causes each wheelset to pivot about a vertical axis through its centre of gravity. The treads of the wheels slip on the rails until sufficient reactive force is attained to rectify the undesired transverse movement of the body. Thus by selecting the spring stiffnesses and the lengths of the levers it is possible to suppress or at least minimise the body hunting.

The body hunting stabiliser just described may be referred to as a pseudo-slip damper and as the term implies it is a device which damps hunting by generating creep forces in the rail/wheel tread contact area. An essential feature of this pseudo-slip damper is that a body motion to the right (seen in the direction of travel) causes a force which tends to move the articulation of the wishbones to the left and therefore tends to cause the leading (trailing) wheelset of a bogie pair to yaw in a clockwise (anti-clockwise) sense.

Figures 18 and 19 show plan views of an elastic-diagonal interconnecting means as applied to three axled vehicles. Both the suspensions are similar to those already described and can be considered as a combination of two sets of diagonal couplings each between two wheelsets. Thus, there is a coupling between the trailing wheelset and the central wheelset and also between the central wheelset and the leading wheelset.

The relative orientation of the three-wheelset bogie during steady-state cornering is shown in outline in Figure 18. In this orientation each of the wheelsets follows the curvature of the rails and the axles lie along radial lines from the instantaneous centre of curvature.

For the purpose of this invention a "nega-

5 tive spring" may be defined as one which has a destabilising effect increasing with displacement, i.e. applies a force which tends to increase the yaw of a wheelset when it is displaced from its natural position at right angles to the longitudinal axis of the superstructure or truck. This is in contrast to a conventional spring which has a restoring force proportional to displacement, i.e. applies a force which tends to decrease the angle of yaw.

10 In order to explain a further feature of the invention more fully the equations of motion of a free running wheelset suspended to ground (as may be realised in a roller rig) may be analysed to yield a quadric equation.

15 The quadric equation is conventionally solved to give two large real roots, corresponding to lateral translation and yaw subsidence of the wheelset, and two lightly damped complex roots for yaw and lateral displacement. The damping of the subsidences is high and they are normally ignored. For the complex roots the damping increases with gravitational and elastic constraint causing creep and decreases with inertia forces which cause creep in the opposite sense. The inertia forces increase with speed so that eventually they dominate and the system is unstable. Such analysis as outlined above is well known.

20 The inventor has found that the terms of second order importance can be eliminated completely by making some of the elastic constraints on the wheelset negative (mathematically) so that the terms cancel out. In effect this results in an exponentially damped motion or a heavily overdamped motion for each wheelset, the degree of damping depending on the numerical value of the constraint. 25 In the case of exponential damping when the wheelset is disturbed it will return to its central position on the rails in an exponential manner and in the over-damped case will return to the central position, but not overshoot this position.

30 In order to obtain the required effect either k or k_r can be selected to be negative. Preferably k is selected to be negative for the following reasons:—

35 (a) a negative k allows the wheelsets to yaw freely and so attain the correct radial position on curved track;

40 (b) a negative k assisted by a longitudinal anchor connecting the centre of yaw of the wheelset to the truck frame or superstructure indirectly through the truck ensures that the wheelset remains substantially in the central position when the vehicle or truck is stationary, i.e. not "flop" over to one side of the vehicle. 45 With such a construction it is only possible for the wheelset to yaw, but this will not take place in practice as the resistance to the tread slipping on the track is greater than the maximum yaw moment that can result from a negative k ;

(c) a negative k_r will result in the truck flopping to one side or the other when at rest;

(d) profiled wheels have a natural positive restoring force, called the gravitational suspension stiffness. This supplements the positive k_r required for the case of a negative k , but has to be overcome first if a negative k_r is selected.

The maximum value of the negative k for exponential damping may be calculated from the following equation:—

$$k = f \frac{l^2}{b^2} \sqrt{\frac{\gamma}{l_{r_0}}} \dots \dots (7)$$

Equation (7) shows that k is a function of f (creep coefficient) which in turn is a function of the overall vehicle weight. This shows another important advantage of the invention is that a value for k can be calculated which will provide a hunting stabilised suspension independent of the vehicle load.

Equation (7) is of a very simple nature since it applies to a wheelset suspended to ground only and does not take into account the motions of the body and/or bogie motions. Nevertheless the concept can be extended to a whole vehicle system and though it is envisioned at this stage that it may not be possible to attain the ideal case of exponential damping, an overdamped system will indeed be possible. This unattainability of the ideal results from the fact that the equations of motion are very complex and that certain approximations will have to be made. The equations can, however, be solved empirically using a computer in which the ideal may well be realized.

Analysis to date has shown that it will be necessary to have damping laterally between the wheelsets and the superstructure and/or truck. Furthermore in a bogie mounted vehicle it is also advantageous to have damping between the bogie and the body; if the bogie is bolster mounted then conventional systems, such as wedges or friction plates, may be used advantageously, but for passenger vehicles viscous dampers may also have to be used.

Further damping is required longitudinally between the body and the wheel sets. Viscous or friction damping may be used in this situation.

Although this invention is concerned primarily with stabilising wheelset hunting as this is the factor which, *inter alia*, causes wheel tread wear and ultimately limits the maximum operating speed of the vehicle, the body hunting stabiliser disclosed previously may also be incorporated by adding suitable articulated wishbones.

Referring now to Figure 20 of the drawings there is schematically shown a bogie side frame 16, an inverted pendulum or pivotal connection 422, and a wheelset 13 coupled to

the side frame 16 by the inverted pendulum. The wheelset 13 comprises two wheels 12 having conical wheel treads with a "standard wear" profile or with a Heumann profile, rigidly mounted on a solid, common axle 14. At or near the ends of the axle 14 there are provided axle box adaptors 26 having horizontal flanges 28, one on either side of the axle. The axle box adaptors may be of any conventional design. Fixed to the upper face of each flange 28 are vertical flanges 420. These vertical flanges are provided with pins 426 so that one end of an elongated substantially rigid member 428 may be connected thereto. The members 428 are pin jointed at their other ends by pins 424 to the side frame of the bogie. Bearing means 15 are provided between the adaptors 26 and the axle 14.

Referring to Figure 21, there is shown another form of inverted pendulum rigid pivotal connection between the bogie side frame and wheelset for providing the negative longitudinal stiffness mentioned above. In this embodiment the connection comprises an eccentric member 430 which is rotatable about the axle 14 and which is pin jointed to the side frame 16 by a pin or trunnion 432.

A feature which is shown in Figure 21, but which can also be used on the embodiment of Figure 20, is that the stops 434 and 435 are fixed to the side frame 16. These serve to limit the wheelset in yaw. Any other suitable stops may also be used.

Figure 22 shows yet a further embodiment of an inverted pendulum which may be used between the wheelsets and the truck side frames 16. The connection comprises a substantially rigid element 436 which is in the form of a thick, rectangular plate, two opposing sides of which, denoted 437 are rounded and shaped complementally to shallow grooves 439 formed in two rubber pads 438. The pads 438 are fixed to the bogie side frame 16 and to the flanges 28 provided on axle box adaptors 26.

In use, this pivotal connection operates substantially in the same manner as those described previously with the exception that, because of the depth of the element 436 which can be about 4 inches or 10 cms there is an increase in the lateral suspension stiffness of the connection. Furthermore, the rubber or elastomeric pads can be selected to vary the lateral suspension stiffness as well as to provide longitudinal and lateral damping.

The above described connection can be adapted for use with either of the previously described embodiments, for instance, in place of the pin joints 432 in Figure 21 or in place of one or both of the pin joints 424 and 426 in Figure 20.

The longitudinal anchors 38 or 50 described previously are used (and, in fact, are neces-

sary) with all the embodiments using negative springs.

For driven wheels, for instance on an electric or diesel electric locomotive, the anchor may be coupled to the motor itself, the motor being rotationally mounted on the axle. This, obviously, applies to all the embodiments hereinbefore described.

In practice, when a railway vehicle employing the negative suspension of the invention is at rest the design of the pivotal elements gives them a lateral stiffness preventing relative lateral movement between the bogie frames and the wheelsets. Furthermore the longitudinal anchors restrain the centre of jaw of the wheelset. Thus, the wheelset is only free to yaw, but such yaw does not in fact occur since the frictional forces in the contact area between the wheel tread and the rail or track is greater than any couple or moment resulting from the negative stiffness of the pivotal elements and the wheelsets remain in their central position when the vehicle is at rest.

When the vehicle moves creep forces are generated in the contact area between the wheel treads and the track and these act to bring the wheel to its central position. During normal use, i.e. at operating speeds, the wheelsets act as predicted by the analysis shown previously. Thus, when the wheel is disturbed transversely or yawingly it returns to its central position either in an exponential or overdamped manner.

An advantage of this suspension is that there is only a very small jaw constraint on the wheelsets during curving, this mainly being due to friction in the pin joints. With conventional suspension there is a tendency for the wheelsets to understeer, however with the negative spring stiffness of the invention the wheelsets oversteer.

Further since wheelset hunting can be suppressed and flange free curving attained there is little or no wear on the wheel treads. This gives a considerable saving in railway operating costs. Obviously there is also less track wear.

One advantage all the embodiments of the invention provide is that "standard wear" or Heumann profiled treads may be used. Such tread profiles are those which do not change appreciably with tread wear; consequently the performance characteristics of the suspensions do not vary with tread wear.

WHAT WE CLAIM IS:—

1. A method of minimising hunting in and improving the curving ability of a railway truck fitted with at least two wheelsets, each wheelset comprising a pair of wheels fast on an axle, characterised by the steps of:—

(a) mounting the wheelsets resiliently in the truck to allow them to yaw relatively to the truck;



the side frame 16 by the inverted pendulum. The wheelset 13 comprises two wheels 12 having conical wheel treads with a "standard wear" profile or with a Heumann profile, rigidly mounted on a solid, common axle 14. At or near the ends of the axle 14 there are provided axle box adaptors 26 having horizontal flanges 28, one on either side of the axle. The axle box adaptors may be of any conventional design. Fixed to the upper face of each flange 28 are vertical flanges 420. These vertical flanges are provided with pins 426 so that one end of an elongated substantially rigid member 428 may be connected thereto. The members 428 are pin jointed at their other ends by pins 424 to the side frame of the bogie. Bearing means 15 are provided between the adaptors 26 and the axle 14.

Referring to Figure 21, there is shown another form of inverted pendulum rigid pivotal connection between the bogie side frame and wheelset for providing the negative longitudinal stiffness mentioned above. In this embodiment the connection comprises an eccentric member 430 which is rotatable about the axle 14 and which is pin jointed to the side frame 16 by a pin or trunnion 432.

A feature which is shown in Figure 21, but which can also be used on the embodiment of Figure 20, is that the stops 434 and 435 are fixed to the side frame 16. These serve to limit the wheelset in yaw. Any other suitable stops may also be used.

Figure 22 shows yet a further embodiment of an inverted pendulum which may be used between the wheelsets and the truck side frames 16. The connection comprises a substantially rigid element 436 which is in the form of a thick, rectangular plate, two opposing sides of which, denoted 437 are rounded and shaped complementally to shallow grooves 439 formed in two rubber pads 438. The pads 438 are fixed to the bogie side frame 16 and to the flanges 28 provided on axle box adaptors 26.

In use, this pivotal connection operates substantially in the same manner as those described previously with the exception that, because of the depth of the element 436 which can be about 4 inches or 10 cms there is an increase in the lateral suspension stiffness of the connection. Furthermore, the rubber or elastomeric pads can be selected to vary the lateral suspension stiffness as well as to provide longitudinal and lateral damping.

The above described connection can be adapted for use with either of the previously described embodiments, for instance, in place of the pin joints 432 in Figure 21 or in place of one or both of the pin joints 424 and 426 in Figure 20.

The longitudinal anchors 38 or 50 described previously are used (and, in fact, are neces-

sary) with all the embodiments using negative springs.

For driven wheels, for instance on an electric or diesel electric locomotive, the anchor may be coupled to the motor itself, the motor being rotationally mounted on the axle. This, obviously, applies to all the embodiments hereinbefore described.

In practice, when a railway vehicle employing the negative suspension of the invention is at rest the design of the pivotal elements gives them a lateral stiffness preventing relative lateral movement between the bogie frames and the wheelsets. Furthermore the longitudinal anchors restrain the centre of jaw of the wheelset. Thus, the wheelset is only free to yaw, but such yaw does not in fact occur since the frictional forces in the contact area between the wheel tread and the rail or track is greater than any couple or moment resulting from the negative stiffness of the pivotal elements and the wheelsets remain in their central position when the vehicle is at rest.

When the vehicle moves creep forces are generated in the contact area between the wheel treads and the track and these act to bring the wheel to its central position. During normal use, i.e. at operating speeds, the wheelsets act as predicted by the analysis shown previously. Thus, when the wheel is disturbed transversely or yawingly it returns to its central position either in an exponential or overdamped manner.

An advantage of this suspension is that there is only a very small jaw constraint on the wheelsets during curving, this mainly being due to friction in the pin joints. With conventional suspension there is a tendency for the wheelsets to understeer, however with the negative spring stiffness of the invention the wheelsets oversteer.

Further since wheelset hunting can be suppressed and flange free curving attained there is little or no wear on the wheel treads. This gives a considerable saving in railway operating costs. Obviously there is also less track wear.

One advantage all the embodiments of the invention provide is that "standard wear" or Heumann profiled treads may be used. Such tread profiles are those which do not change appreciably with tread wear; consequently the performance characteristics of the suspensions do not vary with tread wear.

WHAT WE CLAIM IS:—

1. A method of minimising hunting in and improving the curving ability of a railway truck fitted with at least two wheelsets, each wheelset comprising a pair of wheels fast on an axle, characterised by the steps of:—
 - (a) mounting the wheelsets resiliently in the truck to allow them to yaw relatively to the truck;



(b) limiting any yaw constraint on each wheelset relatively to the truck to allow reasonable rolling motion of the wheels during curving;

5 (c) profiling the wheel treads with an effective conicity greater than $1/20$; and

10 (d) damping any yaw and lateral movements of each wheelset relatively to the truck or to another wheelset by coupling a pair of wheelsets whereby turning movements of the wheelsets are coupled in opposite sense.

2. A method as claimed in claim 1 in which each wheelset is mounted in the truck by spaced resilient elements along each wheelset, the yaw constraint on each wheelset being limited to be less than

$$2 \frac{WY}{R\delta_0} b^2,$$

where:

20 b is half the distance between resilient resilient elements on each wheelset;

W is the maximum axle load;

Y is the effective conicity of the wheel tread;

25 R is the radius of curvature of the wheel tread; and

δ_0 is the angle between the wheel/rail contact plane and the horizontal with the wheelset in the central position.

3. A method as claimed in claims 1 or 2 which includes the further step of limiting any yaw constraint on each wheelset to be less than $2Grl^2$, where

$$G_r \approx \frac{WY}{2R\delta_0}$$

wherein:—

35 G_r is the gravitational suspension stiffness;

2l is the distance between wheel/rail contact points of a wheelset;

40 W is the maximum axle load;

Y is the effective conicity of the wheel tread;

R is the radius of curvature of the wheel tread; and

45 δ_0 is the angle between the wheel/rail contact plane and the horizontal with the wheel set in the central position.

4. A method as claimed in claim 3 in which the yaw constraint of each wheelset relatively to the truck is limited to be less than 750 KNm/radian yaw and the wheel treads are profiled to give an effective conicity of greater than or equal to $1/10$.

5. A method as claimed in either of claims 1 or 2 in which the yaw constraint on each wheelset relatively to the truck is made to be negative.

6. A method as claimed in any one of the previous claims including the step of anchoring the centre of yaw of each wheelset longitudinally relatively to the railway truck.

7. A railway truck having at least two wheelsets resiliently supporting at least one load-bearing member for distributing truck load forces to each wheelset, each wheelset comprising a pair of wheels fast on an axle and each wheelset being so mounted in the truck as to be capable of yawing and lateral movements relatively to the load-bearing member characterised by:

1) each wheelset being self-steering in that:

(a) the wheels have treads that are profiled to have a high effective conicity so that steering forces are generated on the wheelset on curved track, and

(b) any yaw constraint on each wheelset relatively to the load-bearing member is lower than the steering forces generated on the wheelset on curved track; and

2) means acting on each wheelset to counteract hunting of the wheelsets including any tendency to increased hunting and lowering of the critical hunting speed caused by the wheelsets being self-steering, without interfering with the self-steering characteristic of each wheelset, the counteracting means comprising a coupling between a pair of wheelsets to transmit any yawing movements of either wheelset in opposite sense to the other wheelset without interfering with the self-steering characteristic of each wheelset.

8. A railway truck as claimed in claim 7 in which each wheelset is mounted in the truck by resilient elements spaced along the side of each wheelset and in which any yaw constraint on each wheelset relatively to the truck is less than

$$2 \frac{WY}{R\delta_0} b^2$$

where:

b is half the distance between resilient elements on each wheelset;

W is the maximum axle load;

Y is the effective conicity of the profiled wheel treads;

R is the radius of curvature of the wheel tread; and

δ_0 is the angle between the wheel/rail contact plane and the horizontal with the wheelset in its central position.

9. A railway truck as claimed in claim 8 in which any yaw constraint on each wheelset relatively to the truck is made to be less than:

$$2G_r l^2$$

where

$$G_r \approx \frac{WY}{2R\delta_0}$$

wherein:

G_r is the gravitational suspension stiffness;



21 is the distance between wheel/rail contact points of a wheelset;

W is the maximum axle load;

Y is the effective conicity of the profiled wheel treads;

R is the radius of curvature of the wheel tread; and

δ_0 is the angle between the wheel/rail contact plane and the horizontal with the wheelset set in its central position.

10. A railway truck as claimed in claim 9 in which the yaw constraint on each wheelset relatively to the truck is less than 750 KNm/radian yaw and each wheel tread has an effective conicity greater than or equal to 1/10.

11. A railway truck as claimed in any one of claims 7 to 10 in which the coupling between a pair of wheelsets includes a damper.

12. A railway truck as claimed in any one of claims 7 to 11 in which the coupling between a pair of wheelsets comprises a link the ends of which are connected to diagonally opposed axle-box adaptors mounted on each of the wheelsets.

13. A railway truck as claimed in claim 12 in which the coupling comprises first and second links, which cross each other, each of the links being connected between diagonally opposed axle-box adaptors mounted on each of the wheelsets.

14. A railway truck as claimed in any one of claims 7 to 11 in which the coupling between a pair of wheelsets comprises two arms, one end of each arm being secured to an adaptor on a wheelset against lateral rotation relatively to the wheelset and with the other ends of each arm pivotally connected to each other by an articulation means.

15. A railway truck as claimed in any one of claims 7 to 11 in which the coupling between a pair of wheelsets element comprises two forked members pivotally connected to each other at their apices by an articulation means with the free ends of each forked member being connected to one of the wheelsets.

16. A railway truck as claimed in any one of claims 7 to 15 in which a resilient element is included in the coupling.

17. A railway truck as claimed in either of claims 14 or 15 in which a resilient element is included in the articulation means.

18. A railway truck as claimed in any one of claims 10 to 13 in which the coupling has ends which are integral with axle box adaptors mounted on each of a pair of coupled wheelsets.

19. A railway truck as claimed in either of claims 7 or 8 in which the yaw constraint is negative as hereinbefore defined.

20. A railway truck as claimed in either claim 7 or 8 in which means having a negative elastic yaw constraint as hereinbefore defined is provided for mounting each wheelset in the truck, the negative elastic yaw

constraint means comprising at least one stiff member pivotally connected in a vertical orientation between each wheelset and a load-bearing member of the truck.

21. A railway truck as claimed in claim 21 in which each stiff member is pivotally connected to a load-bearing member of the truck and is rotatable about the axle of a wheelset.

22. A railway truck as claimed in claim 21 in which two stiff members are provided at each end of each wheelset and are pivotally connected between each wheelset and a load-bearing member, the stiff members at each end of each wheelset being pivoted to a load-bearing member and pivoted on horizontal flanges extending on opposite sides of an axle-box adaptor rotatably mounted on the axle of the wheelset.

23. A railway truck as claimed in either of claims 21 or 22 in which each pivotal connection is a pin joint.

24. A railway truck as claimed in either of claims 21 or 22 in which each pivotal connection is formed by providing a groove into which one end of a stiff member may be inserted.

25. A railway truck as claimed in any one of claims 22 to 24 in which the means having a negative yaw constraint is made resilient in a direction transverse to the direction of movement of the truck.

26. A railway truck as claimed in claim 25 in which the resilient means includes at least one elastomeric element which supports the pivotal connection.

27. A railway truck as claimed in any one of claims 7 to 26 in which anchor means is provided to locate the centre of yaw of each wheelset longitudinally relatively to the truck.

28. A railway truck as claimed in claim 27 in which the anchor means comprises a longitudinal anchor pivotally connected to the truck and to the centre of yaw of a wheelset, bearing means being provided at the centre of yaw of the wheelset to couple the anchor to the wheelset.

29. A railway vehicle comprising a superstructure pivotally mounted on at least two bogies which are railway trucks as claimed in any one of claims 7 to 28.

30. A railway vehicle as claimed in claim 29, in which each bogie has two load-supporting side frames, and means in load-transmitting relationship between the superstructure and the side frames and in which each end of each wheelset is mounted in a side frame by two resilient elements provided between the side frame and the wheelset with each resilient element being mounted on a substantially horizontal flange provided on an axle box adaptor mounted on the axle of the wheelset, the flanges on each axle box extending on opposite sides of the axle.

31. A railway vehicle as claimed in claim 30 in which each resilient element comprises

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a sandwich of alternate layers of steel plates and rubber pads.

- 5 32. A method of minimising wheelset hunting in and improving the curving ability of a railway truck substantially as herein described with reference to any one of the accompanying drawings.

- 10 33. A railway truck when constructed by the method according to any one of claims 1 to 6 and 32.

34. A railway truck substantially as herein described with reference to and as illustrated in any one of the accompanying drawings.

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