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RAILWAY VEHICLE DYNAMICS

B V Brickle

Various aspects of the dynamic behaviour of modern high-speed rail vehicles are discussed together with an explanation of some of the physical phenómena which occur.

Dr Barrie Brickle is a Principal Lecturer in the Department of Mechanical Engineering at the South Bank Polytechnic in London. His main research interests are vehicle dynamics, vibration and noise. He is the author of several papers on railway vehicle dynamics.

Railway vehicle dynamics is a subject which received very little attention from the middle of the 19th century until the last twenty years or so. In the early 1960s British Rail were introducing diesel and electric locomotives and average operating speeds were increasing. At this time they began to encounter severe ride problems with four-wheeled freight wagons. There was, in fact worldwide interest in reducing journey times as the competition from motorways and domestic airlines intensified. It was realised that whenever rail journey times were reduced there was an increase in the number of people travelling by train.

All these problems highlighted the need for a more fundamental appreciation of railway vehicle dynamics by railway administrations all over the world, including BR. In the late 1960s the Advanced Passenger Train (APT) and the High Speed Train (HST) were proposed as the cornerstones of BR's high-speed strategy. Both trains were to run on conventional track, the APT at speeds up to 250 km h^{-1} and the HST at speeds up to 200 km h^{-1}. The APT with its higher speed and faster curving ability involved considerable technical innovation and risk while the HST was based on existing technology so that rapid progress from the prototype phase to production was achieved and the HST entered commercial service in 1976. The APT prototype encountered considerable difficulties and eventually the project in its original form was cancelled in 1982.

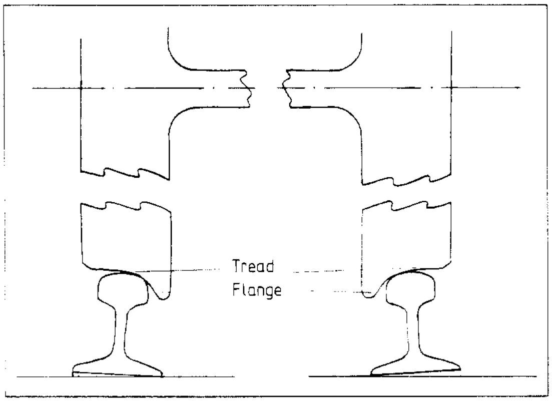


Figure 1. Wheelset on rails.

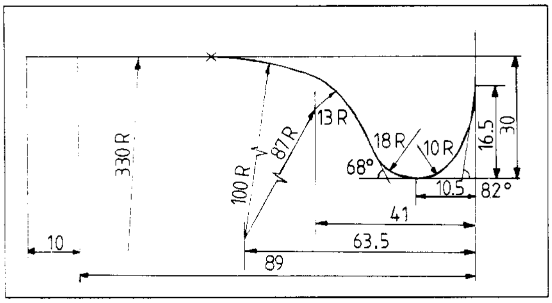


Figure 2. BR P8 tyre profile (all dimensions in mm).

It is really the Japanese with their shinkansen and the French with the TGV who have demonstrated to the world that trains running in excess of 250 km h^{-1} on purpose-built track, but using existing technology, can be successful. Generally it is agreed that speeds up to 400 km h^{-1} are possible on a conventional railway while above this value Maglev or other alternative tracked systems may be more appropriate.

The single most fundamental principle of a conventional railway is the use of a steel wheel on a steel rail to transmit all the forces including traction, braking and guidance forces. It is this interaction between wheel and rail which is likely to be the most important factor limiting the speed of the high-speed trains of the future.

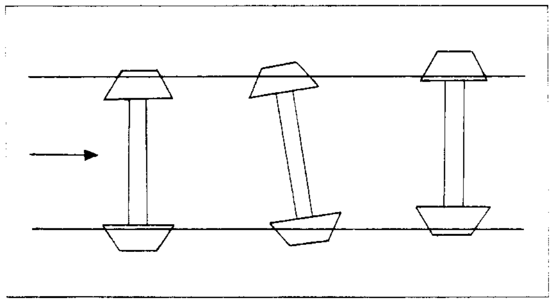
Wheel–rail interaction

Railway wheels are usually different from wheels on road vehicles in that both wheels are mounted rigidly on a common axle, the whole arrangement being known as a wheelset. This is not always the case; the Spanish high-speed train, the Talgo express, has independent wheels, as do many rail vehicles used in coal mines, but most conventional rail vehicles use wheelsets. The wheelset evolved by trial and error during the early 19th century and has changed very little to the present day. It consists of two wheels, each having a coned or profiled tread with a flange on the inside. The tread cone angle is about 2° while the flange cone angle is about 70°. A typical wheelset on rails is shown in figure 1. A wheelset runs on rails which are usually canted inwards at 1 in 20. The gap between the flange of the wheel and the rail is such that it allows about 7 mm of wheelset lateral displacement before flange contact occurs.

Recently some railway administrations have developed 'worn' tyre profiles such as the BR P8 profile shown in figure 2 which is used on the HST. The design of this profile is based on measured worn profiles. It is found that if tyres are machined to these shapes to begin with then the profile is maintained for up to 800 000 km before reprofiling is required.

The inherent guidance in a wheelset can be described by reference to figure 3 where a coned wheelset is shown rolling along straight track. If the wheelset is displaced to the right, the right-hand wheel will run on a larger radius and the left-handed wheel on a smaller radius. Consequently the right-hand wheel will speed up and the wheelset will turn or yaw towards the centre of the track, cross it at a negative angle of yaw and overshoot to a symmetrical position but displaced to the left. The motion will then repeat itself as a continuous oscillation known as the 'kinematic oscillation'. This motion of a wheelset was first described by George Stephenson in 1821 and assumes pure rolling between wheel and rail. It may be shown that the kinematic frequency is proportional to the forward speed of the wheelset. It may also be noted that a free wheelset can go around a circular curve, in pure rolling, by setting itself along the radius of the curve and displacing outwards so that a rolling radius difference exists between the two wheels (figure 4).

Figure 3. Motion of a coned wheelset on straight track.

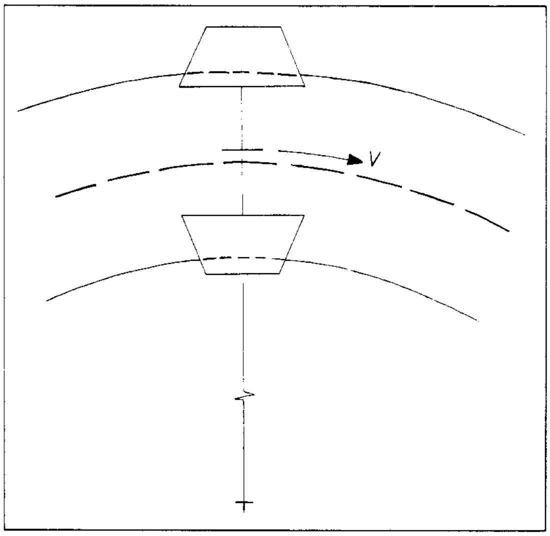


The guidance of a wheelset on straight track and its curving ability are modified when the wheelset is fitted to a vehicle through a suspension. In practice the pure rolling motion is modified by the action of forces tangential to the wheel contact plane, these forces inducing microslip or creepage which occurs in the presence of a local elastic deformation. Creepage, or creep, can be expressed in terms of the velocity difference between two bodies in contact divided by the mean velocity. The relationship between the longitudinal force and the longitudinal creep in a wheelset under traction or braking is shown in figure 5. It can be seen that if the creepage is zero the tangential force is zero; this is the condition for pure rolling. If the creepage is increased then a condition of gross sliding is soon reached where Coulomb friction may be assumed. For low creepage the relationship between tangential force and creepage is linear while for large creepages the relationship is non-linear.

For a wheelset rolling along track the contact area between rail and wheel is elliptical, according to the theory of Hertz, and the ratio of the ellipse semiaxes may be calculated from the principal radii. Creepages may be defined in both longitudinal and lateral directions and a spin creepage may also be defined as the difference in angular velocity about an axis normal to the contact area divided by the mean velocity (Love 1952).

Many research workers have investigated the relationship between the creepages, spin, forces and moments in the contact area between bodies of revolution assuming dry friction. The most complete theoretical work is that of Kalker. Various experiments have been carried out to measure forces due to creepage and these generally show that, providing sufficient care is taken in cleaning the metal surfaces, Kalker's values can be obtained in practice. Forces fall below Kalker's values because of surface contamination which is why most railway administrations multiply Kalker's values by a factor for practical use with railway wheels and rails.

Figure 4. Coned wheelset on circular track.



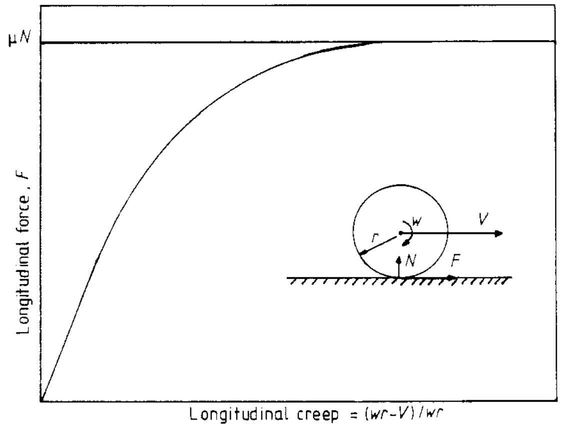


Figure 5. Longitudinal creep–force relationship.

It may be shown that if a wheelset is displaced laterally a yaw torque is produced which steers the wheelset against the restraining effect of the suspension. If a wheelset is forced to run at an angle of attack to the rails, as may happen in a curve, a lateral creepage is produced and consequently a lateral force. Since the resultant force in the contact area is limited to the sliding friction value it can be seen that the longitudinal and lateral behaviour of a wheelset are coupled and depend on the creep–force relationship as well as the wheel–rail geometry.

It has been shown that the forces between wheel and rail due to creepage are of fundamental importance to the dynamic behaviour of railway vehicles. One of the interesting research projects being investigated by German Federal Railways (DB) at the moment is the development of a creep-controlled wheelset capable of speeds up to 350 km h^{-1}. In this wheelset, the wheels rotate independently of each other on fixed axles connected via hollow shafts through a controllable magnetic powder coupling. The creep conditions at the two wheel–rail contact points can be directly influenced by adjusting the torque transmission through the coupling.

Hunting

An important aspect of railway vehicle dynamics is a sustained lateral and yawing oscillation experienced by some vehicles, known as 'hunting'. This problem has been known to railway engineers since the very early days but with very little scientific understanding of the problem. It is only in the last twenty years that an adequate theory of hunting has been available for vehicle suspension designers to use. Freedom from hunting is a prime requirement for any railway vehicle and it must exist for a range of parameters which may change over the life of the vehicle within its speed operating range.

It is well known that a mechanical system which is subject to non-conservative forces may become dynamically unstable under certain conditions. Examples of such systems are the flutter of an aircraft wing and the shimmy of a pneumatic tyre. In a railway vehicle the non-conservative forces arise at the contact point between rail and wheel and are due to creepage. The study of lateral stability or hunting involves the equations of motion for the lateral dynamics of a railway vehicle. These equations include lateral displacement, roll and yaw coordinates. Because of symmetry, the vertical dynamics involving 'bounce' and 'pitch' modes can be treated separately from the lateral dynamics. The lateral dynamics can be further divided into the motion of a vehicle on straight (or tangent) track and the motion of a vehicle on curved track. Stability involves the free motion on straight track.

For stability calculations the equations of motion assume small displacements of a wheelset from its central position and linear creep–force relationships. The equations can include a wheelset gravitational stiffness term due to the fact, that as the wheelset moves laterally, its centre of gravity rises. Solving the characteristic determinant gives the eigenvalues as a function of speed. The eigenvalues are generally complex so that a negative real part indicates stability and a positive real part instability. Associated with each eigenvalue is a corresponding eigenvector or mode shape. A special solution of the characteristic determinant occurs when the real part of the eigenvalue is zero. This gives the critical speed or hunting speed; below this value free oscillations decay and above it they grow.

It is generally accepted that railway vehicle lateral stability calculations have been proven both on roller rigs and with vehicles on real track. Determination of the vehicle and track parameters for use in a dynamic model is one of the most difficult aspects of the validation process. If wheels are coned, rails are of uniform section and suspensions are linear, as in modern vehicles, then good predictions of hunting speed can be obtained.

Ride

One of the main ride criteria in the design of railway vehicles is, of course, freedom from hunting, but assuming stability exists throughout the operating speed range, maximum vertical and lateral body accelerations can be specified for a track of a given roughness. This is usually described in terms of power spectral density and may be weighted to take account of the known effect of different vibration frequencies on human beings.

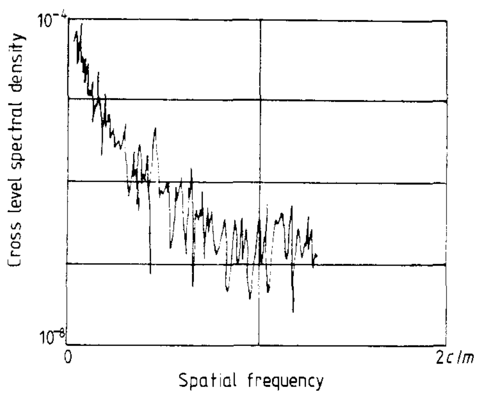


Figure 6. Cross level spectral density.

The inputs to the vehicle from the track can be defined in terms of four variables; vertical profile, cross level, lateral alignment and gauge. These variables can either be measured by surveying or by using track-monitoring vehicles. British Rail and other railway administrations have developed high-speed recording coaches for this purpose. The measured data are usually recorded on magnetic tape and then processed so that the variables are presented in the form of spectral densities describing the magnitude of each irregularity over a range of spatial frequencies (figure 6). These spectral densities can be related to temporal frequencies and used as inputs to mathematical models to calculate the vertical and lateral responses of a vehicle.

The area under an acceleration–response spectral density leads directly to the RMS value of acceleration and can be used in assessing ride quality and passenger comfort. The International Standards Organisation has produced constant-comfort curves for vibration in different directions (figure 7) and sets limits on exposure time for 'reduced comfort'. This standard is being modified in the light of new experimental work and when it is finally approved it should have much more reliable weighting functions than the original standard.

Traditionally railway vehicles have used passive suspensions, i.e. suspensions with elements whose characteristics do not change in response to measured variables. Some modern railway vehicles now have a form of active suspension in that they are fitted with air springs which automatically adjust the height of the coach as the load changes. This type of suspension does allow the designer to give the vehicle a low natural frequency which improves the

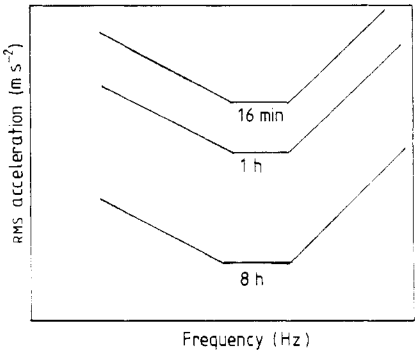


Figure 7. ISO reduced comfort boundary.

quality of the ride. It can be shown that the introduction of a proper active suspension fundamentally changes the suspension characteristics and can lead to marked improvements in ride. BR has been investigating the use of active suspensions for some time and has recently developed such a suspension for a Mark III coach. This will shortly be tested in service and the passenger reaction assessed.

One of the obvious ways of reducing the lateral force on a passenger during curving is to tilt the coach body inwards. This was the fundamental concept of the APT with its maximum speed of $250\,\mathrm{km\,h^{-1}}$ and faster curving ability achieved by tilting the coaches up to 9°. The basic aims of any tilt-control system are to achieve a fast response as the train moves in and out of curves, to remain stable at all times and to reject unwanted disturbances caused by random track irregularities.

Originally, the accelerometer on the APT to sense the lateral motion was mounted on the tilting bolster within the bogie. It was found, however, that the gain had to be reduced to such a level that the response of the system was too slow. This was eventually modified by adding a second loop and fitting a displacement transducer to the tilting mechanism as well as mounting the accelerometer on the frame of the leading bogie of the preceding vehicle. This system gave very close matching between the actual tilt angle and the ideal. One of the problems, however, was that the chance of a 'hardover' 9° tilt failure was increased and there were doubts as to whether running clearances were adequate if this rare failure mode occurred. Other technical problems became evident with the APT during its commissioning trials and authorisation for a production fleet was not given.

Within BR people have since questioned not only the effectiveness of tilting but also the basis on whch curving parameters for non-tilting trains are based. The relationships between comfort, track irregularities, curves and curve transitions are not clearly defined. Recent tests show that tilting allows higher curving speeds at acceptable comfort standards but partial tilting is almost as effective.

Curving

A significant proportion of the track on any railway system, particularly BR, is made up of curved track. It is therefore important to understand the dynamic behaviour of vehicles at curves. It can be shown that, in the absence of any constraints, a wheelset will take up a radial position as it rolls around a curve. Even with a wheelset constrained by a suspension, the possibility of guidance without flange contact still exists because of the creep forces generated in the contact area between wheel and rail. The scope of creep force guidance is, however, limited by the coefficient of friction between wheel and rail, the suspension stiffness and centrifugal forces. The introduction of these parameters usually means flange contact to restore equilibrium and this means large forces which produce excessive wear. As soon as flange contact is introduced into the equations of motion of a railway vehicle it means non-linearities associated with the wheel–rail geometry and with the creep–force relationship. This makes the equations difficult, but not impossible, to solve.

The problem of wheel flange and rail wear during curving is one that confronts all railway authorities. Several solutions are available to overcome this problem:

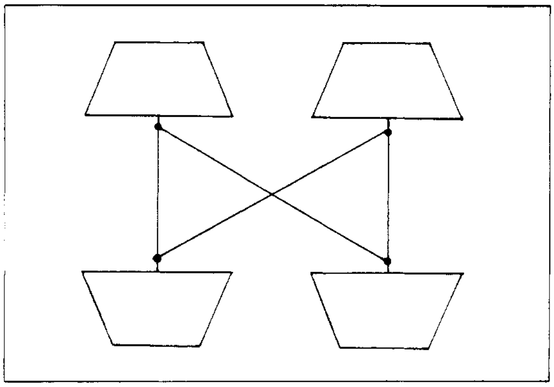
(i) to try and eliminate tight curves wherever possible;

(ii) to lubricate either the rail in the curve or the flange;

(iii) to modify the bogie so that curving is improved.

Solution (iii) may be achieved by designing a bogie with sufficient yaw flexibility to allow the axles to

Figure 8. Cross-braced bogie.



steer towards a radial line. This does, however, introduce another problem in that softening the yaw suspension usually means a greater tendency for the bogie to hunt. Various designs of steering bogies have been developed, such as the cross-braced bogie shown in figure 8. Another form of steered bogie is the linkage-steered bogie: here a steering link is provided which couples the body to the cross bracing and forces the axles into radial alignment.

Steering bogies are not always the best solution for any flange–rail wear problems, but for a railway system with a lot of tight curves, such as a rapid transit system, it may be an alternative to fitting lubricators on all the curves.

Derailment

The ultimate ability of a flanged wheel to sustain a lateral force is fundamental to railway engineering. Flange climbing occurs when a laterally loaded wheel flange climbs up the rail as the wheelset rolls forward. Under certain conditions the flange can support the equilibrium of the wheel but any increase in lateral force will cause the wheel to derail.

The classical treatment of derailment (Nadal 1896) calculates the minimum lateral force for a given vertical force that will cause the flange to start climbing. The ratio of these two forces is called the 'derailment ratio'.

Later work which included the creep forces showed that Nadal's formula is a conservative estimate of the derailment condition and should be used for practical decision-making even today.

Future work and conclusions

Railway vehicle dynamics has now reached a state where most of the problems have been solved (Wickens and Gilchrist 1977). However there is one area where more work is needed and that is the rail corrugation problem. Many theories have been put forward to explain the origin of rail corrugations but no fully satisfactory theory has so far emerged. Significant damage is caused to the track by vibrations set up when vehicles run over corrugated rails and the noise which is generated constitutes an environmental nuisance. Grinding the surface of the rail represents the only treatment available. The problem of rail corrugations seems to get continuously worse and until the mechanism of corrugation is fully understood it will remain an expensive problem for all railway administrations.

Europe's extensive rail network was built in the 19th century; its motorway network was built in the 20th century and with the decision to build a rail link through the Channel Tunnel connecting London to a European high-speed rail network, perhaps the 21st century will once again belong to rail travel. It would appear that, now most of the problems in railway vehicle dynamics are understood, there is nothing to stop future trains running at speeds up to $400\,\mathrm{km\,h^{-1}}$ on conventional track between European cities.

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degree of coarse-grained control-flow parallelism is possible on the dyadic (2-processor) and quad (4-processor) configurations where offered. However, for symbolic processing the debate concerning the most appropriate organisation – control flow, data flow or reduction – and topology – mesh network, hierarchical network, cube network or switched – is by no means over.

Assuming that the technical problems are solved, in part at least, there is still a barrier to widespread use of parallel symbolic processing. For control-flow systems employing conventional 'imperative' languages, the programmers need training in explicit restructuring of code into concurrent tasks. For reduction and data-flow systems using 'declarative' functional and logic programming languages, the change in programming style requires education and experience – both of which will take time.

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