7 Gauging Issues

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I. PHILOSOPHY AND HISTORY OF GAUGING

Gauging is the name given to the techniques used to ensure that rail vehicles fit through the infrastructure and pass by each other in safety. Increasingly, there is emphasis on maximising the capacity of the railway corridor through a more thorough understanding of the gauging system, and reducing conservatism in the processes that ensured adequate space was available when the railways were first built.[1]

This chapter is intended to provide readers with an insight into the techniques used in Britain, where an infrastructure of up to 200 years old is now required to deliver the capability of running large, intermodal freight trains and passenger trains of increased capacity and comfort for which they were not designed. Internationally, capacity constraints are also real, but invariably infrastructure that has been built later requires less incremental change to cope with the near standardised loads being transported. Virtually every country has its own methodologies through which loading gauge is managed, and it is beyond the scope of this chapter to provide anything but a look at gauging principles and approaches that form the basis of most of these gauging practices. Beyond Britain, western Europe has adopted a near-standard UIC (Union Internationale des Chemins de Fer) approach, which is described briefly for information.

Railways were originally built to *gauges* — vehicles to a maximum vehicle (or load) gauge and infrastructure (structures) to a minimum structure gauge. A *clearance* was included between the vehicle gauge and the structure gauge to allow for unknowns, or those items that were known but had not been included in the gauge.

At the turn of the last century, the U.K. Board of Trade (whose job it was to monitor rail traffic) had registered 127 different load gauges from (private) railway companies. No load gauge was universal — except, perhaps, the smallest. Many railway administrations still work by these simple gauging methods, indeed the methodology used in most of Europe is a derivative of the earlier fixed gauge approach. Much of the original railway infrastructure built to accommodate these load gauges still exists, but the trend is to increase vehicle size. The challenge is to develop new gauging methodologies that enable this to happen. The original methods provide a good starting point.

British engineers, forced to make increasingly better use of small, Victorian (predominantly arched) infrastructure, have been at the forefront of developing gauging systems that analyse the vehicle-infrastructure interaction on a case-by-case basis to minimise the cost of upgrade works needed to run these larger passenger coaches and bigger freight loads.

New developments also introduced additional factors that had to be taken into account. Early railways used short wagons, and their swept envelopes were not significantly different to their static size. The introduction of long coaches rather than short carriages generated a new vehicle-infrastructure interaction. Overthrow complicated the basic interface between mechanical engineer and civil engineer as it related to both the curve geometry and the arrangement of the vehicle. Railways that had worked well with short vehicles now exhibited weaknesses in certain situations, having restricted clearances on curves. The first significant development in the trend towards gauging analysis was the adjustment of gauges to include vehicle overthrows associated with curvature of the track.

Increasingly, the understanding of vehicle dynamics has led to techniques that predict suspension movements (and hence the local swept envelope) in response to curvature and speed. Those techniques, largely developed by British Rail Research, became invaluable in the acceptance processes for air-suspension rolling stock (with implicitly softer suspension) in the 1980s. However, although it became increasingly possible to calculate vehicle movements with precision, gauging standards were slow to react to these improved methodologies and for a while failed to allow all of the benefits that the techniques could offer.

Significant advances in vehicle dynamics and the introduction of computerised techniques have allowed tolerances, clearances, and "unknowns" to be defined in a more robust manner. Tolerances may now be calculated accurately, and clearances provided for the fewer remaining unknown or incalculable effects. An important factor is that as unknowns are understood, they may be removed from mandated clearances and analysed as appropriate tolerances. Conservatism is thus being progressively removed from the system.

Modern gauging technology is far removed from the simple pen and paper solutions of 100 years ago. This chapter aims to give an insight into the factors considered and the calculations performed in modern gauging methods.

In simple terms, gauging has moved on from being the technique for simply deciding whether something will fit to what can be done to enable something to fit.

A. GAUGES

1. Static Gauges

In what may be described as "simple gauging" the mechanical engineer built vehicles to a "vehicle gauge," being the maximum cross section of the train, and the civil engineer ensured that structures were always larger than the "structure gauge." A separation between the two, known as clearance, allowed for any variations of track position (track being anything but the "permanent way" that it is traditionally called) and the suspension movements of the vehicle. These are known as static gauges.

2. Geometric or Swept Gauges

Geometric or swept gauges represented a development of the above, where the vehicle was substantially affected by the geometry of the track. On curves, vehicles sweep a larger path than on straight track, a phenomenon known as "overthrow." The amount depends on the tightness of the curve, the vehicle bogie (or axle) centres and the overall length. In the immediate postnationalisation period in Britain (approximately 1951 onwards) "national gauges" for rail passenger vehicles (known as C1) and freight vehicles (W5) were defined, based upon the vehicle gauges used by the majority of component railway companies absorbed into British Railways (BR). C1 and W5 gauges are geometric gauges, requiring knowledge of both vehicle parameters and curve geometry in order to calculate the clearance to a structure. A clearance of 150 mm (6 in.) was usually allowed, comprising 100 mm potential vehicle movement on its suspension and 50 mm for potential track positional and geometric errors.

In Great Britain, details of current and historic gauges, together with other useful information on current gauging practice may be found in a guidance note published by the Rail Safety and Standards Board.[10]

B. SWEPT ENVELOPES

1. Kinematic Envelopes

In the late 1970s and 1980s cost engineering became prevalent in Britain, particularly in the area of track maintenance. A given ride quality can be achieved by maintaining high-quality track geometry or by providing softer vehicle suspensions. The former solution is particularly expensive since as track quality is raised the cost of providing this increases exponentially. The new generation of rolling stock then being commissioned could readily be given suspension capable of providing adequate ride comfort on poorer track. Air suspension provided this mechanism, but at the expense of having greater kinematic movement (movement associated with the speed of the vehicle). The methodologies described would have meant that the infrastructure would have required enlargement to maintain clearance. However, it was recognised that by relating kinematic movement to operating environment, the locations where enlarged infrastructure was required could be minimised. A publication known as "Design Guide BaSS 501"[3] provided a methodology whereby the kinematic envelope of a vehicle (the space required by a given vehicle, moving at speed) at a specific location could be manually calculated from a number of input parameters. The techniques used are quasistatic, equating dynamic conditions to stationary forces, and are generally conservative. Nevertheless, the techniques have been very successful in allowing larger trains to operate on restrictive infrastructure at minimal cost. In particular, a derivation of the technique has allowed tilting trains to be designed for Britain that would otherwise have been of a nonviable cross section if traditional gauging rules were applied.

2. Dynamic Envelopes

Increasingly, the conservatism of quasistatic gauging has challenged the development of larger vehicles. Furthermore, certain basic assumptions about vehicle behaviour are oversimplifications that are necessary to create a technique capable of manual calculation. With the advent of computerised gauging software (ClearRoute™) and vehicle dynamics simulation software (VAMPIRE™), the millions of calculations necessary for the calculation of the dynamic gauging performance of vehicles can be undertaken in a practical timescale. (ClearRoute is the registered trademark of Laser Rail Ltd. and VAMPIRE is the registered trademark of AEA Technology Rail.)

C. HYBRID GAUGES

1. Pseudokinematic Gauges

A pseudokinematic gauge is where maximum kinematic movements are included in the gauge. It is common for light rail and metro systems to use a vehicle gauge that includes all suspension movement for particular vehicles (this is sometimes known as a *red-line* kinematic gauge). The system used across Europe is a further development of this, using a reference profile to define a notional boundary between train and infrastructure under certain, prescribed limits, beyond which both vehicle builder and infrastructure controller must make adjustment. Pseudokinematic gauges work well for new infrastructure, but lead to the restriction of vehicle size as softer suspension is introduced.

2. Kinematic Gauges

It should be noted that the swept envelope of a vehicle is really a series of swept envelopes, since some parts of a vehicle move more than others (depending on where the section of the vehicle is in relation to bogie or axle centres), and some sections may have projections. In particular, the cross section of a vehicle at the bogie/axle positions will exhibit zero throw, whereas the section located in the centre of the vehicle will have maximum throw towards the inside of a curve. Similarly, the ends of a vehicle will have maximum throw towards the outside of a curve. A kinematic gauge (examples being those which define the GB/SNCF/SNCB Eurostar[9] vehicle and the new W12 freight gauge) is a union of different kinematic vehicle dimensions defining the largest envelope under given operating conditions. W12, for instance, consists of many thousands of gauge diagrams appropriate to curve radius, installed cant, and speed. The Eurostar gauge is computer generated from the same set of parameters.

Gauges refer not only to a cross-sectional profile, but also to a set of rules that must be applied. A basic understanding of the gauge definitions will show that the clearance required for safe operation is intrinsically linked to the derivation of the gauge and the parameters considered.

D. INTERNATIONAL METHODS

1. UIC

UIC gauging methods are defined in the 505 series of leaflets, and use reference gauges as the basis for gauging[4–6] (Figure 7.1). The method dates back to 1913 and has been developed as a hand-calculated technique that contains a number of simplifications. To ensure safety it is very conservative. No clearance is required — the conservatism ensures that contact is not physically possible. From a vehicle perspective, this reference profile defines a base gauge into which the vehicle must fit under certain defined conditions.

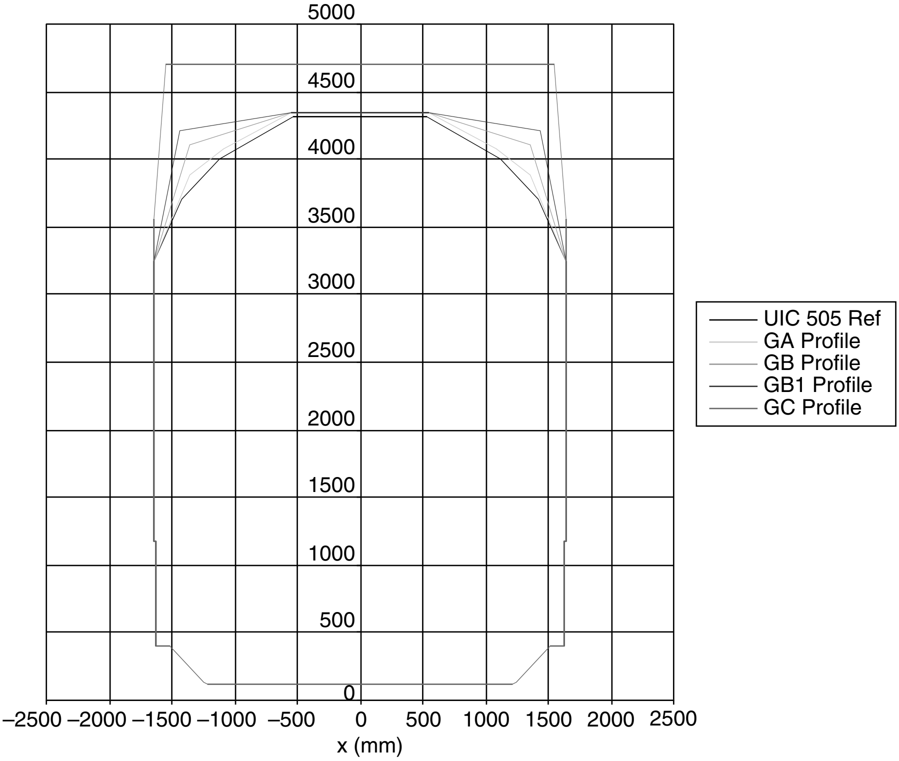

FIGURE 7.1 Basic UIC reference profiles.

The conditions under which vehicles must be contained within the reference dimensions are (inclusively):

- Horizontally, on a 250 m radius curve
- Under 50 mm of installed cant and 50 mm of developed cant deficiency
- With full horizontal suspension travel
- Stationary

Note that this is not a vehicle gauge in the British sense. It represents a vehicle snapshot, which requires further analysis in applying this to the infrastructure. In particular, the following effects (known as infrastructure additions) must be taken into account:

- Authorised projections on curves and throws on curves between 150 and 250 m radius (note that UIC vehicles are not designed to run through curves of less than 150 m radius)
- The effect of track quality associated with speed
- Gauge widening
- Roll from cant excess or deficiency above 50 mm
- Track alignment tolerances
- Static and dynamic cross level error
- Possible vehicle loading asymmetry
- Vertical curvature

Figure 7.2 shows a developed vehicle gauge for a specific condition (1000 m horizontal curve, 150 mm installed cant, 160 kph developing a cant deficiency of 150 mm, good track, 1000 m

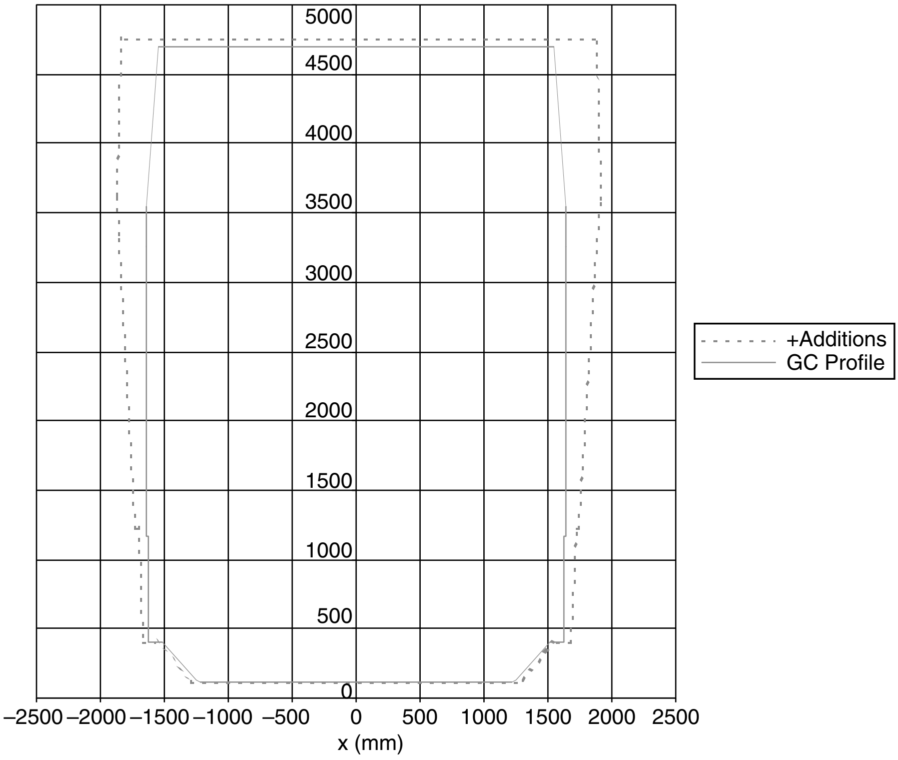

FIGURE 7.2 UIC GC reference profile with infrastructure additions.

vertical curve). Under strict UIC rules, it is not necessary to provide any clearance to this envelope, there is sufficient conservatism in the calculation process to ensure that vehicle-structure contact can never occur. However, the UIC process by this very conservatism makes poor use of the space envelope that would normally be used in Britain.

II. COMPONENTS OF GAUGING

A full gauging model requires the interactions between structure, track, and vehicle to be understood. Before examining these interactions an understanding of the behaviour of the individual components is required.

A. STRUCTURE

1. Shape

In Britain, clearance issues mainly relate to arch bridges and tunnels. Containers, particularly, provide an obvious "square peg in a round hole" challenge when trying to run the former through the latter. Overbridges generate height restrictions and platforms generate width restrictions. All obstacles in the vicinity of the train must be measured.[11,12]

2. Accuracy of Measurement

Accuracy of structure measurement is becoming increasingly significant. As analysis methodologies improve, conservatism in infrastructure measurement that results from inaccurate measurement becomes less acceptable. In particular, while it may be possible to define the swept envelope of a vehicle to within a few millimetres, the accuracy of many structure measuring techniques may be poorer than 50 mm. In order to maximise infrastructure capacity, it is important that an opportunity is not lost through poor measurement accuracy.

Figure 7.3 shows various structure measuring systems on a graph of measurement accuracy (bottom axis) and relative cost (vertical axis).

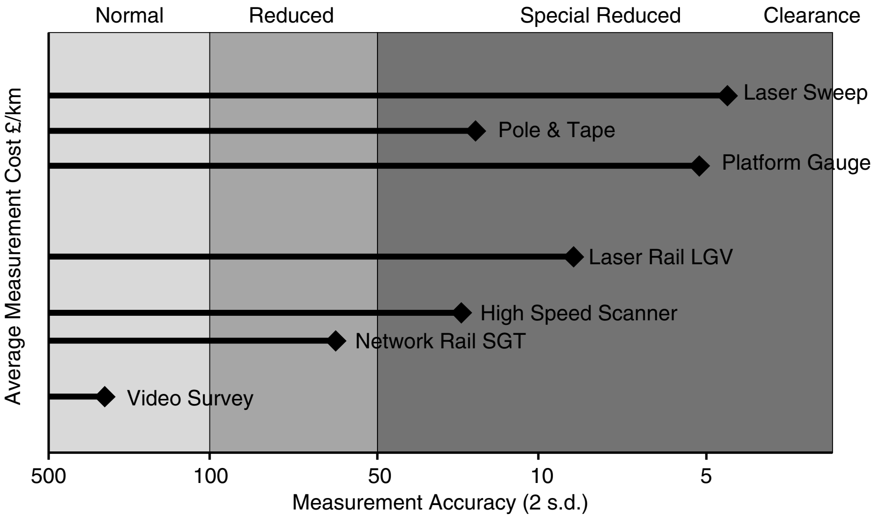

FIGURE 7.3 Structure survey systems showing relative accuracy and running cost.

The top axis shows bands relating to clearance regimes used on the British infrastructure. Normal clearances require minimal control measures, reduced clearances require better management of track position, and special reduced clearances require stringent controls.

Measurement cost relates to a cost per kilometre, assuming that the system is fully utilised for a measuring shift. Costs arise from a variety of sources, and include the following components:

- Capital cost
- Maintenance cost
- Operating cost
- Possession/protection cost
- Train path cost
- Data processing cost
- Effective working shift length

Measurement accuracy is the sum of inaccuracies in the measuring system. Quoted accuracies provide only an indication of this. How the measuring system relates measurement of the structure to the rails is just as important as its ability to measure the structure, but is often overlooked. Although a measuring system may be quoted as having a particular accuracy, the statistical accuracy should be considered in defining what accuracy of measurement *may be expected*. Quoted accuracies are often misleading, and if incorrectly used may result in unsafe calculations. Generally, an accuracy of two standard deviations would be used, representing a 95% confidence limit, based upon a normal distribution. System calibration over the full range of measurement provides the only reliable method of defining measuring system accuracy, particularly for more accurate systems.

From Figure 7.3, it can be seen that some methods of measurement are more appropriate than others in terms of accuracy, cost, and the clearance regime that is being monitored. Video assessment, while cheapest, is a method of safely determining which structures are sufficiently far from the track to present no risk. It cannot be used to identify locations that may operate under

FIGURE 7.4 The LaserSweep profiler.

FIGURE 7.5 Road–Rail laser gauging vehicle, operated by Laser Rail Ltd.

special reduced clearances. LaserSweep™ (Figure 7.4) would not be economic to use for screening purposes, and is best restricted to locations where clearances may be tight. In considering an appropriate measuring method, it must be remembered that traffic type and future change of use may indicate that a more accurate measuring method should be used (Figure 7.5), if this proposed traffic were likely to reduce available clearance (for example, a tilting train). A structure gauged for containerised freight would require more accurate measurements in the area of the top corner of the container.

B. TRACK

1. Track Position

Knowledge of the position of the track, and the amount by which it may move, is vital in accurate gauging calculations. Track position controls vehicle position. Track position may vary as a result of traffic loading, effects of weather, and most importantly, the movement that is allowed for maintenance and alignment purposes. Some track is better restrained than others. Slab track is generally very stable. Ballast glueing can reduce lateral movement (although it would not affect vertical movement significantly). Strutting sleepers against platforms will generally reduce lateral movement towards the platform. Track fixity is discussed later in this chapter.

2. Track Geometry

As we try to model vehicle behaviour more accurately, irregularities of track geometry become increasingly important. In basic gauging, the only geometric input comes from the curve radius used in the calculation of throws. In the more complex models, the full spectrum of track geometry must be considered.

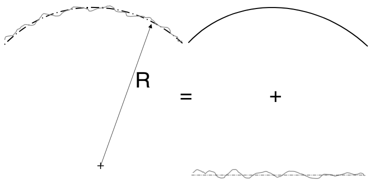

FIGURE 7.6 Superposition of track design alignment and irregularity.

Track geometry is essentially the variation of lateral and vertical track position in relation to the longitudinal position. On perfect, straight track, there is no track geometry. However, track is neither constantly straight nor perfect, and consists of straights, curves, and track irregularities. This is generally referred to as design geometry and roughness. These parameters are handled separately, in that they have different effects on vehicles. However, in practice, the boundary between geometry and defect is impossible to define. The key issue is one of wavelength. Generally, design geometry is of long wavelength and defects are of short wavelength. However, it is possible for deviations to be longer than design alignments. In particular, some transition curves are very short, and would, in other circumstances, be considered to be irregularities.

In Figure 7.6, the shape on the left would be considered to be normal curved track. It is a summation of the true curvature (shown top right) and irregularity (shown bottom right). If the exact (design) curvature is known, then the irregularity can easily be calculated. In practice, it is unusual (in Britain) to know the exact design curvature, and thus approximations must be performed to extract the two shapes. This process is known as filtering. The use of a high-pass filter (one which lets high frequency, short wavelength through) would produce the roughness from the measured, compound profile. This process is used to extract track roughness from track topography in order to determine when to maintain the track. The curvature of the track can be calculated by using a low pass filter. This process is sometimes referred to as regression, the regressed alignment being the underlying geometric shape of the track.

The filter used makes a significant difference in the separation of track roughness and track geometry. A commonly used filter is the Butterworth filter, originally developed for medical instrument technology in removing 50 Hz mains "hum" from body electrode signals. However, this filter, on its own, creates a spacial phase shift (where there is a longitudinal movement of peaks and troughs), which may be corrected by performing a reverse pass of the same filter.

It is important to understand how to use track geometry data in gauging calculations. It will become clear that the curvature data and the roughness data are used for different purposes. However, measuring track provides a single curvature reading, the nature of which is dependent on how it is measured and processed.

High-speed systems tend to use inertial geometry measurement, sampling at frequent intervals. Such systems are principally used for track quality recording, but have been adapted for use on gauging systems. Inertial systems are best at measuring high rates of change of curvature. Since sharper curves provide the greatest input to gauging calculations, these systems may be used provided the roughness (which they can also measure well) is removed. If unfiltered geometry is used, there is a risk of under- or overcalculating throws, and double-counting dynamic effects.

Manual systems tend to sample infrequently, usually every 10 to 20 m. As such they tend to pick up more general curvature without significant effect from track geometry errors. However, it should be noted that track faults will have an effect on the measured curvature. The true "design" curvature may need to be extracted using methods such as "Hallade," a filtering technique using a combination of mathematics and human skill that is used to determine optimal lateral track alignment.

C. VEHICLE

1. Geometric Considerations — Overthrow on Curves

The axles of a railway vehicle form the end points of a chord placed on curved track. The body represents an extension of this chord. As the vehicle traverses the chord the centre of the vehicle is thrown towards the inside of the curve, and the end of the vehicle is thrown towards the outside of the curve. The overthrow effect increases with vehicle length and tighter curvature. A bogie is simply a vehicle with centre throw only. Vertical curvature is not generally an issue on main line railways, but is often considered on metro and light rail systems.

The equations for calculating throw are shown below. The simplified equations ignore some small angle effects leading to marginal inaccuracy, but are useful for quick calculations.

If we consider Figure 7.7, the overthrow at a point on a vehicle body is the difference between the radial distance from the track centreline to the point, and the lateral distance from the vehicle centreline to the point (W_o or W_i). This is calculated with the vehicle stationary.

Consider a vehicle with bogie centres L, and a bogie axle semispacing of a_0 (the actual axle spacing is $2a_0$).

The inner overthrow of a point U_i from the centre of a the vehicle is:

$$R - W_i - \sqrt{[U_i^2 + (J - W_i)^2]}$$

The outer overthrow of a point U_o from the centre of the vehicle is:

$$\sqrt{[U_o^2 + (J + W_o)^2]} - R - W_o$$

where $J = \sqrt{[R^2 - a_o^2 - L^2/4]}$

The simplified equations are:

$$\text{Inner throw} = 125(L^2 - (L - 2x)^2)/R[\text{body}] + 500(a_o^2/R)[\text{bogie}]$$

$$\text{Outer throw} = 125((L + 2x)^2 - L^2)/R[\text{body}] - 500(a_o^2/R)[\text{bogie}]$$

where $x = L/2 - U_o$.

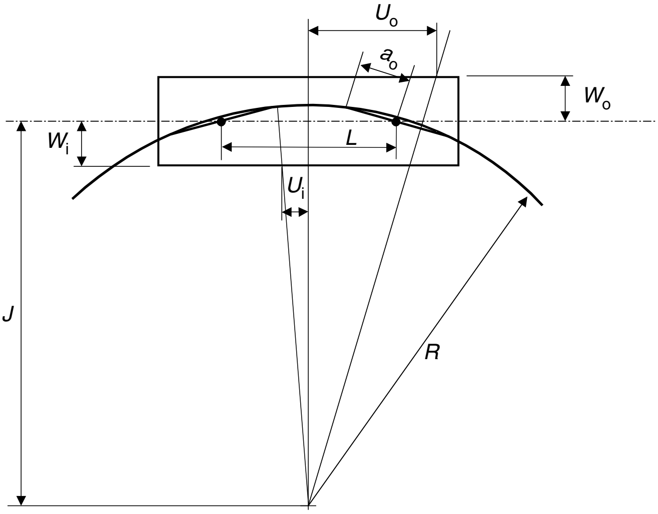

FIGURE 7.7 Curve overthrow diagram.

2. Kinematic Considerations

The kinematic movement of a vehicle is the position adopted by the vehicle resulting from the forces applied, and allowances included. These can be summarised as:

- Sway and roll drop due to curving forces
- Sway, lift, and drop due to motion
- Drops due to loading and suspension condition
- Vertical vehicle tolerances
- Lateral vehicle tolerances
- Lateral, vertical, and roll due to tilting suspension

a. Movement from Curving Forces

A vehicle moves on its suspension in relation to applied lateral and vertical forces. In simple models, the total amount of lateral and vertical suspension travel (limited by bump stops) is used to determine the required clearance, and no relationship is assumed. As stated earlier, there is a low risk in this approach, but it makes poor use of infrastructure space.

BaSS 501 introduced the concept of relating vehicle movements to applied rolling force, expressed as an "equivalent cant." This quasistatic method equates the movements of a vehicle operating in a dynamic environment to an applied static cant. The movement of the vehicle is defined simplistically as having components of vertical, lateral, and roll in a single plane (effects of yaw and pitch are ignored). A sample relationship between vehicle sway and applied cant is shown in Figure 7.8.

Figure 7.8 shows cant on the horizontal axis (cant excess to the left, cant deficiency to the right) and vehicle sway on the vertical axis (positive is sway to the outside of the curve). It can be seen that as cant increases (or decreases), the sway in the appropriate direction (inward or outward) increases (or decreases) also. The relationship is nonlinear, but is simplified into a series of straight-line relationships that relate to the increasing stiffness of the vehicle suspension as travel of the various stages is consumed. The "break points" occur, for instance at lateral bump stop contact, lateral

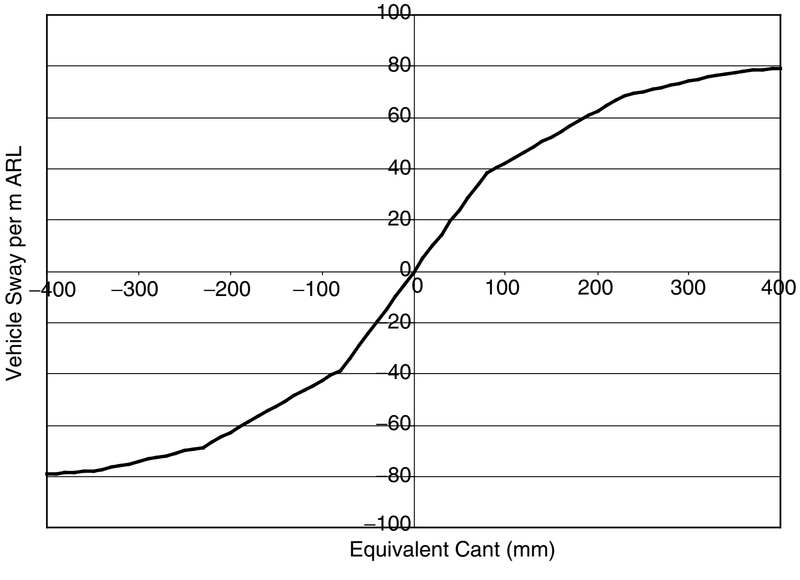

FIGURE 7.8 Typical relationship between applied cant and sway.

metal bump stop contact, secondary vertical bump stop contact, and primary vertical bump stop contact. Similar graphs may be produced for roll drops. The general equations are:

$$\text{Sway} = K_{\text{sway}} D + E$$

$$\text{Drop} = K_{\text{drop}} D + J$$

where D is the (equivalent) cant, K_{sway}, K_{drop}, E, and J are the linear equation parameters for each segment.

These may be found by referring to a drawing for a given vehicle known as the "kinematic envelope."

b. Movement due to Motion

In normal curving, the force applied to a vehicle is related to the vehicle speed (V) according to the following approximate formula (on conventional 1435-mm gauge track).

$$\text{Equilibrium Cant} = 11.82V^2/\text{Radius (m)}$$

If an equilibrium cant of 100 mm is required by a particular combination of radius and speed, then cant deficiency is the amount by which the applied cant is less than 100 mm, or cant excess is the amount by which the applied cant is greater than 100 mm. In an idealised world, this would be the only input of speed on the vehicle.

However, track is imperfect. As a result of unevenness of the rails, there will be local variations of the cant that the vehicle sees. Since this is a dynamic phenomenon, the effect on the vehicle suspension is likely to depend on a number of factors, in particular, the roughness of the track and the mass/inertia system of the train. BaSS 501 considers inputs due to track roughness as a component of equivalent cant (being the sum of actual cant experienced and other roll inducing effects expressed as cants), using a parameter known as K_{speed}. This parameter defines a linear relationship between the notional force applied to the vehicle (expressed as a cant) and the speed of a vehicle. Typically, K_{speed} is around 0.5, meaning that at 100 km/h, the rolling force seen by the vehicle, acting on the suspension, is equivalent to an additional ±50 mm of cant above that caused by curving. It should be emphasised that equivalent cant is an *input* to the suspension relationship given in the previous section. Although the relationship between speed and equivalent cant is linear, the actual suspension movement is unlikely to be so.

Additionally, the vehicle responds to vertical track irregularities. There is no simple method to predict these. Accordingly, upward and downward movements of the vehicle calculated on the remaining suspension travel for given load cases are defined. This is known as "dynamic drop," although the term "dynamic lift" is appropriate for upward movements. Both cases need to be considered simultaneously, since these define the "bounce" of the vehicle. A number of techniques have been used to limit these according to the true amount of suspension travel available once roll drop is considered (by relating it to equivalent cant) and to linearise the value with speed.

c. Critical Speeds

Speed must also be considered in relation to the maximum sways (and drops) of a vehicle that it generates in service. A vehicle will usually be designed to run at a maximum line speed. This is generally limited by cant deficiency based upon passenger comfort. The faster a conventional vehicle travels around curves, the more it will sway towards the outside of the curve, limited only by suspension travel. However, we must consider the possibility that the vehicle may travel at reduced speed, or may even be stationary. The maximum static force on a vehicle to the inside of a curve occurs when stationary, due to an excess of cant. It is frequently assumed that this is the worst

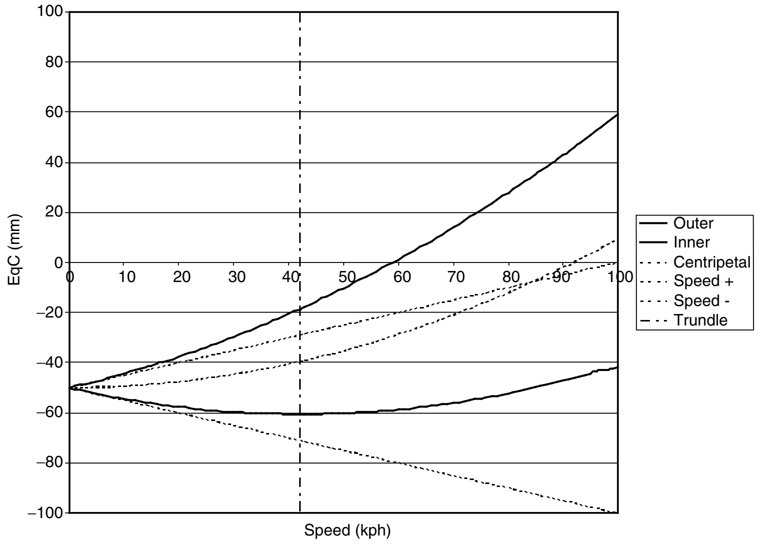

FIGURE 7.9 Components of trundle speed.

case for inside curve clearances. However, Figure 7.9 demonstrates the concept of "trundle speed," a speed at which quasistatic force, and thus sway, to the inside of the curve is maximised.

Figure 7.9 shows a 2000 m radius curve with 50 mm installed cant. The vehicle has a K_{speed} of 0.5. There are three faint lines:

- The two linear lines radiating from -50 mm equivalent cant represent the equivalent cant (leading to sway) as a result of the speed of the vehicle on imperfect track. Thus, at 100 km/h, the vehicle will experience an equivalent cant due to speed of -50 ± 50 mm. This is the same on both straight and curved track, although there would be no installed cant on the former.
- The parabolic line radiating from -50 mm equivalent cant is the component of equivalent cant due to curving, which is towards the outside of the curve and increases with the square of speed. From this line, the balancing speed on this particular curve (considering radius and installed cant) is 92 km/h.

The solid lines show the summation of these forces, the upper being towards the outside of the curve, and the lower being towards the inside. It can be seen that the outside equivalent cant always increases as speed increases, confirming that maximum sway to the outside of the curve occurs at maximum speed. To the inside, it can be seen that the summation results in a minimum at 42 km/h, where the equivalent cant to the inside is a maximum. This speed is known as the trundle speed.

If we consider the equations used to develop this relationship, we can derive this value mathematically:

$$\text{Equivalent Cant } (D) \text{ due to curving} = 11.82V^2/R$$

$$\text{Equivalent Cant } (D) \text{ due to speed} = \pm K_{\text{speed}}V$$

$$D_{\text{outside}} = 11.82V^2/R + K_{\text{speed}}V - C(\text{Installed Cant})$$

$$D_{\text{inside}} = 11.82V^2/R - K_{\text{speed}}V - C(\text{Installed Cant})$$

Differentiating:

$$\mathrm{d}D_{\mathrm{inside}}/\mathrm{d}V = 23.64V/R - K_{\mathrm{speed}}$$

Resolving gives:

$$V_{\mathrm{trundle}} = K_{\mathrm{speed}}R/23.64$$

Trundle speed is thus directly related to radius and K_{speed}. Since the radius of straight track is infinite, this suggests that the trundle speed on straight track is also infinite. In practice, as can be seen from the graph, it means that above certain radii, the graph will not exhibit a minima below line speed and the maximum inward sway will occur at line speed. Trundle speed is lowest on tight curves.

d. Effect of Loading

Different relationships occur for different suspension loading and failure conditions. In particular, Figure 7.10 shows relationships defined as inflated and deflated, referring to airbag condition. The possibility of airbag failure (or accidental isolation) must be considered in analysing clearances. As can be seen from the graph, deflation of airbags results in a stiffer vehicle, but which may have a "locked-in" suspension lateral movement (see also time-related effects later). At lower cants, and particularly on lower parts of the vehicle body, this lateral offset may be the worst defining movement of the vehicle. Note also that there is likely to be some hysteresis, since this locked-in movement requires a force in the opposite direction for it to break out. The value of this friction is not defined in BaSS 501 (this assumes a simple locked-in movement at zero equivalent cant) and analysis must consider that its effect can simultaneously exist to both the inside and outside of curves.

In the deflated case, the sway equation becomes:

$$\mathrm{Sway} = K_{\mathrm{sway}}D + E + C$$

where C is the value of locked-in suspension movement.

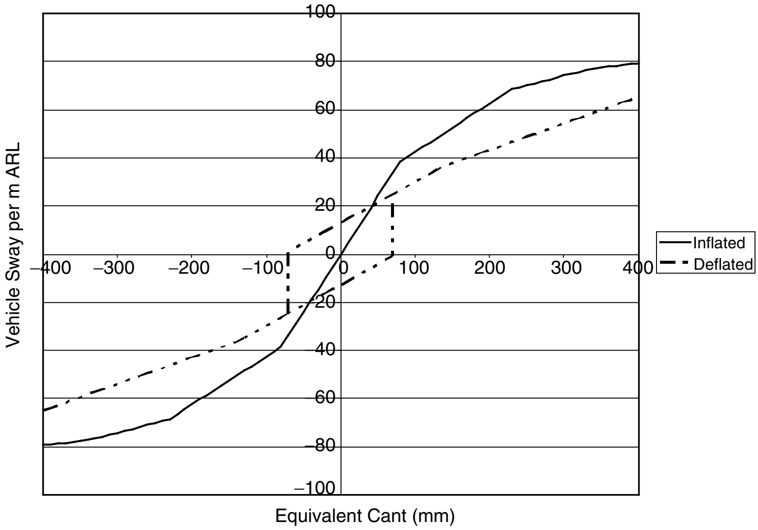

FIGURE 7.10 Relationship between equivalent cant and sway for vehicles with air suspension.

Obviously, the suspension performance relates to many factors, the principal ones being the passenger (or freight) load, and the condition of the springs. The normal conditions analysed are:

- *Tare or tare inflated.* The condition where the vehicle is likely to be tallest, since the springs are least compressed.
- *Laden or crush inflated.* This condition results in the greatest sways, due to the mass of passengers or load and higher centre of gravity.
- *Crush deflated.* This condition has a larger locked-in lateral component, but smaller sways, leading to greater risk to low structures (such as platforms). It is also the lowest position in which a vehicle may operate.
- *Tare deflated.* This is an unusual condition, in that it is only likely to occur on depot routes, where there are no passengers. Its principal use is in clearing low structures where a tare inflated vehicle may not pass, frequently for delivery.

On coil sprung vehicles, failure of springs is considered unlikely, so that these conditions are not generally analysed.

The sway graphs can be calculated theoretically, either by formulae or by using VAMPIRE™ or a similar dynamics package. The results of this modelling can be confirmed by sway testing, where the vehicles are subjected to a range of cants in various conditions, and the sway and drop of different positions on the body measured.

e. Time Factors

Time has not generally been considered in terms of gauging, but increasingly, the effects are becoming significant in the context of accurate analysis. Two particular issues should be considered:

- Air suspension — these systems generally have self-levelling valves that compensate for vehicle asymmetry caused by loading and curving forces, tending to compensate for roll on curves. The time constants for such systems are generally long, and thus unlikely to have a noticeable effect on normal, at speed, analyses. However, where vehicles are moving very slowly, or are stationary, the compensation effect may need to be considered.
- Locked-in suspension movement — where air suspensions are run in deflated failure mode, hysteresis, as shown on the earlier suspension characteristics graph, is gradually shaken out by normal track oscillations over a short period of time. Such effects can only be considered by advanced dynamic prediction methods, as described later.

f. Vehicle Height

A vehicle has a nominal, static height. This would normally be the tare inflated condition. When loaded (passengers or freight) the suspension is compressed depending on the loading, resulting in a lowered static height for this condition. Loading is defined by strict rules, and there may be different operating conditions associated with different loadings. The static height is also reduced in the case of airbag deactivation or failure. Occasionally, overinflation of airbags is considered.

3. Vehicle Tolerances

Commonly considered tolerances are:

- Uncompensated wheel wear — this is the amount of wheel wear that can develop before being compensated by shimming of the suspension. A worn vehicle will be lower than a new vehicle, and thus this parameter must be considered when analysing lower-body clearances (platforms, etc.).

- Suspension creep — with age, rubber suspension components compress (creep) and thus lower the body. This parameter must also be considered when assessing lower-body clearances.
- Body build tolerance (BOD) — this parameter represents tolerances in the building processes, and must be added to the static shape of the vehicle. Construction methods generally produce smaller tolerances at the vehicle solebar, and thus it is possible to have a varying BOD for different positions on the vehicle.
- Height setting tolerance — this value affects both the maximum and minimum height of the vehicle and depends on the accuracy with which the static height of the vehicle air suspension may be set.
- Air bag compensation — a self-levelling system on air suspensions means that over a period of time, the suspension gradually corrects for load imbalance. This is particularly noticeable on canted platforms, either as passengers embark or disembark, or as the cant excess is gradually compensated. Being a relatively slow process, this parameter, on its own, is unlikely to be an issue. Where a vehicle stops on a curve the effect is to reduce sway. However, there may be a tolerance of operation of the self-levelling valves, and these are occasionally considered.
- Vehicle yaw — this is a lateral movement of the end of the vehicle in relation to the centre. It is not strictly a tolerance, but is occasionally included as one. Vehicle yaw affects sections progressively the further they are from the centre of the vehicle. Usually this is only considered if their effect is of significance in relation to the clearance regime under which the vehicle is operating.
- Vehicle pitch — this is the vertical equivalent of yaw, and the same considerations apply.

In defining kinematic movements, it is usual to refer to specific points of significance on a vehicle. Typically, these would be:

- *Cantrail*. A notional line drawn along the vehicle, which for passenger stock represents the upper limit of the body side and the start of the roof contour. This height represents a combination of semiwidth and sways likely to present the greatest risk of infringement to the arch bridges prevalent in the British infrastructure.
- *Waist*. The widest part of the vehicle (statically) which is likely to present the greatest risk of infringement to passing vehicles (with the possible exception of tilting trains).
- *Step*. Traditionally the part of the vehicle designed to come into close proximity to the infrastructure (platforms).

Using BaSS 501, the sways and drops of cantrail, waist, step and occasionally yaw damper may be calculated.

a. Tilting Trains

The basic relationships described are valid for most normal vehicles. However, tilting trains have a more complex relationship. In this case not only do the inputs from curving forces need to be considered but also the effect of the active suspension (which principally operates in roll). The relationship between tilt angle, cant deficiency, and speed varies between trains, and is nonlinear. Whereas the graphs of body sway for conventional vehicles relate simply to cant deficiency or cant excess, in the case of a tilting train the relationship is three-dimensional, having inputs of cant deficiency and speed to determine a series of sways. In general, tilting trains behave conventionally below a cut-in speed known as the tilt threshold speed or on cant excess. Vehicles

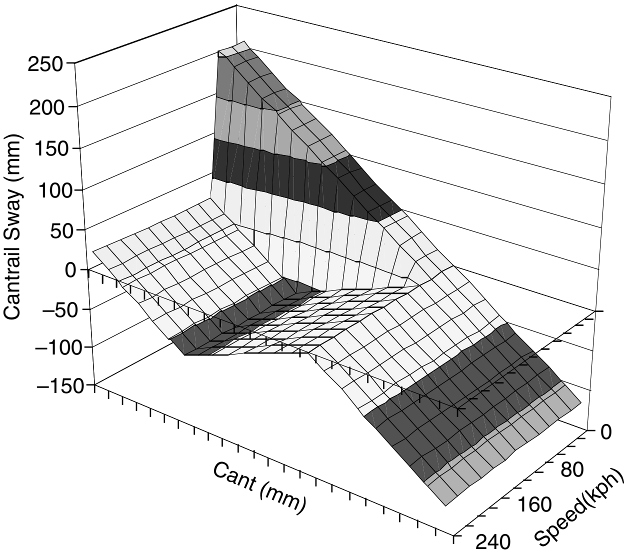

FIGURE 7.11 Relationship between speed, cant, and sway for a tilting train at the cantrail.

with tilt locked out or in tilt failure behave as conventional vehicles, although the positional error of the body in the latter case will also need to be considered.

Figure 7.11 shows an idealised relationship for a tilting train suspension, showing the effects of speed and cant on the sway at the cantrail. The horizontal axis shows cant deficiency as positive, and cant excess as negative. A positive sway on the vertical axis is towards the outside of the curve. It can be seen that at low speeds (<50 km/h on this particular vehicle) and at cant excess (−ve cant), a similar relationship to that of a conventional train can be seen (i.e., a simple linear relationship, where increased cant deficiency results in a greater sway to the outside of the curve). In the tilt active area, it can be seen that the tilt system causes the vehicle to lean inwards where a normal vehicle would lean outwards (i.e., under cant deficiency). As the tilt movement is used up, the vehicle again begins to move outwards at high cant deficiencies. If the point being considered is above the tilt centre (normally the case with the cantrail), then the characteristic inward tilt can be seen.

If the point is below the tilt centre (usually the case with a vehicle step), then tilt angle is additive to the roll caused by cant deficiency. This is closer to the performance of a conventional train, but with additional roll. Vehicles whose tilt centre is high (such as Talgo, where the bodies are suspended from a high level suspension) behave similar to conventional trains, but with significantly greater sways. These vehicles sway more at the step than at the cantrail (Figure 7.12).

For tilting trains, the relative angles of primary and secondary suspensions must also be considered, since at high tilt angles the lateral force of curving may cause a significant compression of the secondary suspension, which is now not operating truly vertically. This component is known as compression drop.

The number of operational cases of tilting trains is higher than the four conventional cases, since the possibility of failure of the tilt system or other parts of the active suspension must be considered. Also, an effect known as tilt lag means that as the train travels onto and off transition curves the active suspension is slightly delayed in its response for electromechanical reasons. For some trains this can be as much as 6°. There is thus an entire range of situations that may occur individually or concurrently, including:

- Tare or laden (various loading factors)
- Inflated or deflated air suspension

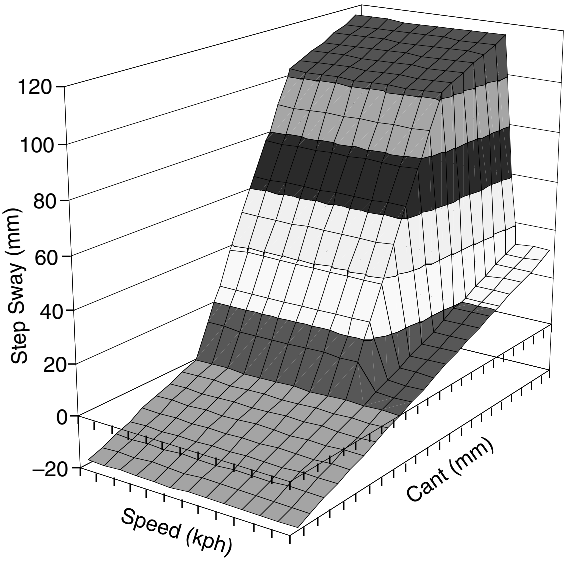

FIGURE 7.12 Relationship between speed, cant, and sway for a tilting train at the step.

- Active, active lagged, passive (locked), or failed tilt system
- Active or failed active suspension components

This may result in many potential situations requiring analysis.

i. Effects of Speed

In the analysis of tilting trains, the speed of the vehicle has been included into the basic relationship between applied force and suspension movement. However, this results in more complicated analyses than those of conventional vehicles, where sway is directly related to speed.

ii. Critical Speeds

For conventional vehicles, maximum speed and trundle speed are the only critical speeds that need to be considered. The nature of conventional suspension means that these cover not only worst sways to the outside and inside, respectively, but also worst drops on each side. With active suspensions, critical speeds are not as easy to calculate. Consider the graph of cantrail sway in relation to speed (Figure 7.11). If the vehicle is operating below the tilt threshold speed, then the worst sway to the outside occurs at maximum speed. If operating above tilt threshold speed, then the outward critical speed is dependent upon cant deficiency (also dependent on speed). At low cant deficiencies, the critical speed is likely to be the tilt threshold speed. However, above the limit of tilt compensation, critical speed can again be the maximum speed. There are a number of intermediate combinations of speed and cant deficiency leading to critical speeds. This is further complicated, for example:

- High-speed cases can lead to sways to the inside greater than low speed cases.
- Points above the tilt centre behave differently to points below it, where more conventional rules apply.
- Worst sway does not necessarily mean worst drop, since this depends on the tilt system geometry.

Crucial parts of the train may need to be assessed over an entire speed spectrum to ensure that all combinations of sway and drop over the speed range are considered.

BaSS 501 provided a simple methodology that allowed the sways and drops of various points of the vehicle to be calculated and related to the position of a structure or adjacent vehicle. Advanced gauging software (ClearRoute™) enables the entire vehicle shape to be modelled, providing a more complete calculation of clearance. The software enables large volumes of structure data to be analysed quickly, and is the only practical method of gauging tilting trains where a large number of load cases and speed combinations must be calculated. This system was used for the entire gauging analysis for the remodernisation of the British west coast main line (1998–2004) for the introduction of class 390 tilting trains.

iii. Time Factors

Tilting and active suspensions, by their nature, have delayed responses either by design or due to the time required to provide a measured response to inputs. The most common form of tilting suspensions measure cant deficiency and curvature on a leading bogie, and calculate the required tilt demand from this, which is applied to the leading vehicle and to trailing vehicles. In order to avoid false responses to track irregularities and ensure that there is only a response to true curving forces, a delay period (normally no more than one second) is provided, during which no tilt is applied to the lead vehicle. This is progressively less pronounced on trailing vehicles where the time lag is less. This effect is known as tilt precedence. A further effect is that the tilt system may not be able to respond at the same rate as transition curves develop. Figure 7.13 illustrates the tilt lag phenomenon.

In Figure 7.13, the horizontal axis shows the position of a train entering into a curve, which starts 100 m into the diagram. The solid line shows a linear cant transition for this curve, in degrees. On this particular curve the maximum cant is 6° (approximately 150 mm), and the transition is 100 m long. At 50 m/sec this represents a cant gradient of 75 mm/sec, typical of a tilting train at its enhanced speed. The dashed line shows the response of the tilt system. The system does not respond for the first 50 m of the curve (1 sec at 50 m/sec) and then responds at a rate of 2° per second. The dotted line shows the imbalance between tilt required and tilt achieved. A maximum tilt lag of 4° develops in this particular scenario.

Tilt lag means that in some cases the use of conventional gauging models will not provide adequate clearance assessment. In these cases it is necessary to use lead-lag models, where the kinematic envelope of the vehicle is expanded to include this error. Tilt lag refers to the error that develops as a vehicle moves onto a transition, and tilt lead (technically a misnomer) refers to the

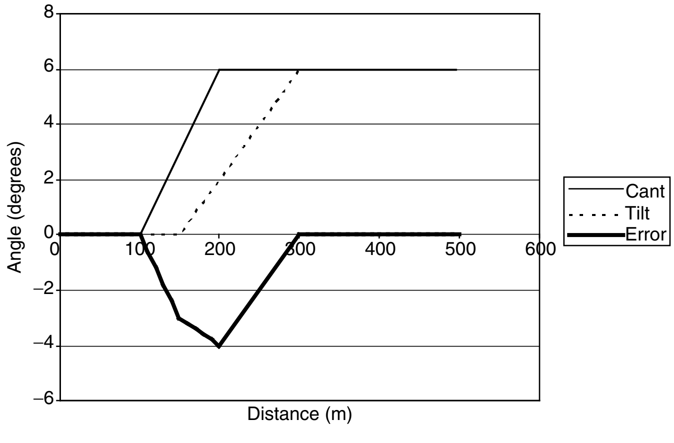

FIGURE 7.13 Tilt lag relationship.

opposite error that develops as a vehicle moves off a transition. In the latter case, it is important to note that the effect can occur on tangent track, where simple analyses would normally be performed.

b. Advanced Modelling

The advent of ClearRoute™ and VAMPIRE™ computer simulation software meant that many of the simplifications inherent in BaSS 501 could be removed given that there was no longer a need to produce a hand-calculation process.

BaSS 501 has a number of inherent simplifications:

- It assumes that all lateral movement of the vehicle is from roll generated by cant forces. Pure lateral irregularities are not considered dynamically.
- It assumes a linear relationship between speed and equivalent cant leading to sway. In practice, this relationship is nonlinear as a result of harmonic responses of the spring/mass system.
- It assumes that all generated sway is upper sway, where the roll centre is low.
- The locked in movements predicted by quasistatic analysis are rapidly shaken-out by dynamic movement of the vehicle.

Using VAMPIRE™ it is possible to perform full dynamic simulations of the vehicle, and thus consider true vehicle behaviour within the bounds of a simulation that is now considered to be extremely accurate. The process is as follows:

- A range of real track data is assembled, according to the probable range of track roughness that will be experienced.
- The vehicle is run, in a variety of suspension conditions, over a full range of applied cants and speeds. (It is not necessary to consider radius, since the cant deficiency or excess drives the behaviour.)
- A series of lookup tables are produced defining lateral, vertical, and roll performance of the vehicle or suite of vehicles (different configurations of the same vehicle can behave differently, and there can be a different behaviour when running in different directions).
- The curving behaviour is calculated (as explained in vehicle–track interaction).

The process of defining the relationships between track inputs and vehicle body dynamic behaviour is statistically based. Track inputs are provided from a variety of typical track geometries appropriate to the speed of the vehicle. In general, lower speed track provides greater dynamic inputs to the vehicle. The resultant body movements generated at each combination of applied cant and speed are summarised statistically as a mean and standard deviation of lateral, vertical, and roll movements, onto which a 95% certainty limit is applied. The definition of appropriate track quality indices, combined with the maintenance regime of the railway are an important factor in determining the level of risk in the gauging calculations. In common with most railway administrations, British railways are seeking to provide an appropriate safety factor without considering all events to be concurrent. Techniques of uncertainty analysis are increasingly being used.

Figure 7.14 shows the sway predicted at the cantrail by the different models on the vertical axis. The horizontal axes show the inputs of cant and speed into the model. The following observations can be made:

- Sways predicted by both methods of analysis are similar, indicating a generally good correlation between the techniques.
- The nonlinearity associated with speed is clearly visible. In some cases BaSS 501 overpredicts and in others underpredicts.

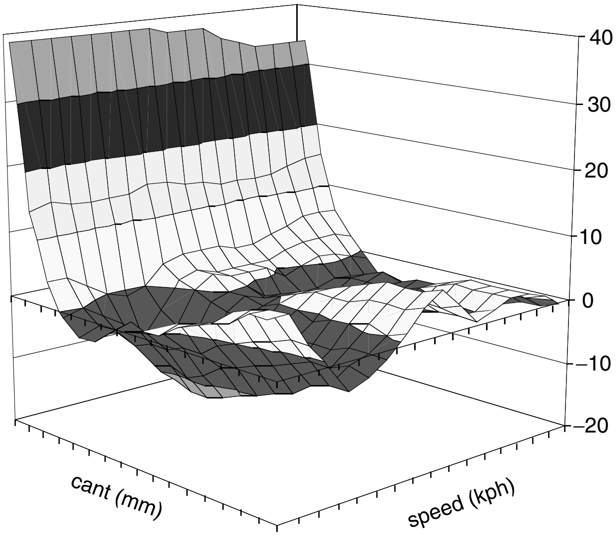

FIGURE 7.14 Comparison of cantrail sways for the same vehicle modelled by BaSS 501 and VAMPIRE™.

- Generally, BaSS 501 overpredicts sways.
- The significant conservatism of BaSS 501 at low cants results from the shakeout of hysteresis due to the movement of the vehicle that is not considered in the quasistatic analysis.

It should be noted that while the above graph shows axes of speed and cant, these are not independent of each other, a factor that should be considered in understanding the effect of speed. On a given curve, increasing speed will have the effect of increasing cant deficiency, while decreasing speed will reduce this or generate cant excess. The dependency between cant and speed is a squared relationship, as described in Section II.C.2.b.

Such dynamic systems can provide vehicle movement information associated with particular track geometry, and in real time. However, real-time gauging is flawed in that it takes no account of the spectrum of track geometry that may develop as track deteriorates, or is maintained. In particular, a track defect that causes a vehicle to sway away from a structure (providing clearance) could cause a gauging infringement if removed.

III. INTERACTION BETWEEN GAUGING COMPONENTS

A. VEHICLE–TRACK INTERACTION

1. Wheelset Movement

The primary interface between vehicle and track occurs at the wheel–rail interface. The wheelset has freedom to move within the rails, limited by flange contact. The size of the gap depends upon the gauge of the track, the wheel flange wear, and the rail sidewear. The various gauging models handle this interface in various ways.

In simple analyses, this interface is ignored since its effect is small.

In more detailed analyses, such as BaSS501, it is assumed that all possible combinations of wide gauge, wheel flange wear, and rail sidewear occur simultaneously. Typical values would assume an 8-mm flange — rail gap, 3 mm of wheel flange wear, and 6 mm of rail sidewear.

Owing to the curving nature of bogies, this latter value is usually reduced to 3 mm, since it would be very unlikely for all wheelsets to be running to either the outside or inside rail (as demonstrated below). Thus, a global value of 14 mm is often used.

In complete analyses, the nature of curving is considered and is used to correct the centreline position of the vehicle for the curving behaviour of the bogies or wheelsets. It has been found that in cant-deficient situations (where there is insufficient installed cant to balance curving force) the bogies (and hence the vehicle) move towards the outside of the curve. Figure 7.15 shows the approximate bogie behaviour as curve radius varies. On tangent (straight) track, the wheelsets assume a mean position running centrally between the rails, and there is generally no offset, although asymmetric running on straight track has been observed on some flexible-frame bogies. As radius progressively tightens, the angle of attack increases as the leading wheelset moves towards the outside rail. The trailing wheelset continues to follow a path more centrally between the rails. At approximately 500 m, the leading wheelset will come into flange contact. This is the point of maximum outward bogie movement. As radius further decreases, the angle of attack increases further by the trailing wheelset moving towards the inside rail. An extremely sharp curve would cause the trailing wheelset to come into flange contact with the inner rail, giving a resultant zero offset. In practice, radii this severe will not be encountered. It must be emphasised that the exact relationship of offset to curve radius is complex and vehicle specific. It requires complex modelling software, such as VAMPIRE™ to generate the exact relationship.

It is necessary to consider a spectrum of operating conditions to determine the maximum and minimum wheelset movements at different radii. This will include modeling various conditions of worn wheel profile. In the gauging analysis, the maximum outward wheelset movement will be applied to cant-deficient cases, the minimum movement will be applied to cant-excess cases.

UIC rules consider the behaviour or wheel–rail interaction, and in particular, gauge widening and bogie alignment as part of the structure-vehicle relationship.

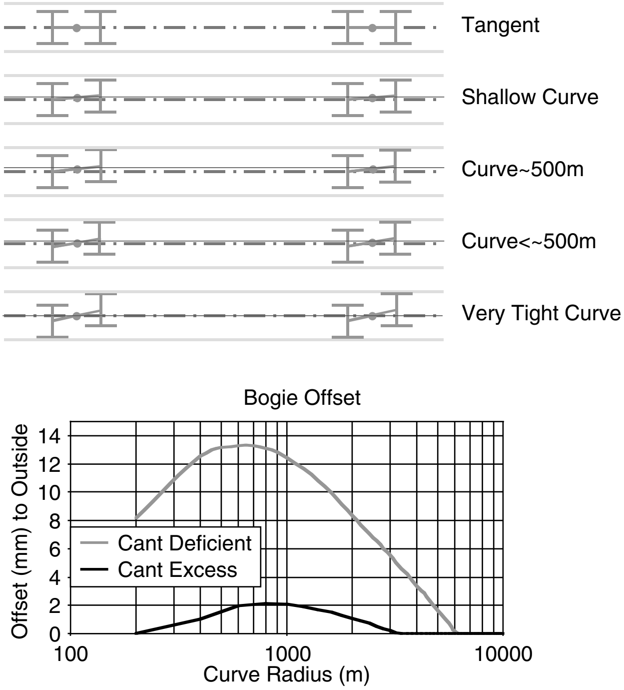

FIGURE 7.15 Relationship between curve radius and outward wheelset movement.

B. TRACK–STRUCTURE INTERACTION

1. Track Tolerances

The relationship between track position and structures is a significant factor to consider in gauging. The following components of track tolerance must be considered.

a. Lateral Track Positional Tolerance

Sometimes known as the "track alignment error," this relates to the possible movement of the track over its maintenance cycle. Normal ballasted track is generally maintained by tamping, with slues being applied to correct geometric errors. In normal circumstances, track is maintained within a tolerance of ± 25 mm. Datum plates are used to provide guidance to machine operators on track position, and overhead contact wire registration (if present) normally requires the track to be maintained to this tolerance. Where the track is nonelectrified, and datum plates are not present, care must be taken to ensure (by more frequent measurement) that track remains within positional tolerance. Normal ballasted track is known as low fixity. High-fixity track, such as slabs, may be held to much tighter tolerances (even zero). Ballast glueing and strutting tracks against platforms are considered medium fixity, with a tolerance of ± 15 mm.

b. Vertical Track Positional Tolerance

Track level deteriorates under the effect of traffic and time. In general, the settlement of ballasted track is logarithmic in nature. Rapid settlement occurring immediately after maintenance becomes more linear as quality deteriorates towards the end of a maintenance cycle. Over a maintenance cycle, of 1 to 2 years, depending on track condition and quality, it would be expected that track would settle around 25 mm from its highest level. Unfortunately, it is difficult to apply this tolerance without knowing the position within the maintenance cycle. Recently maintained track will settle by up to 25 mm, but track which is just about to be maintained could be lifted by 25 mm. By assuming track to be at a position that could be lifted 15 mm and lowered by 10 mm provides a regime which statistically covers a large part of the maintenance cycle.

c. Cross-Level Error

On low-fixity track, it is generally assumed that cross level may vary by ± 20 mm in relation to that required, as a result of differential settlement or measuring errors. It is considered that half of this value (± 10 mm) would be long wavelength and half (± 10 mm) would be short wavelength. The long wavelength (static) component affects steady state curving forces and vehicle position. The short wavelength component affects dynamic performance of the vehicle. In applying this error, it is usual to consider the long wavelength component in relation to track fixity. High fixity (slab track) may be laid to such precision that there is no long wavelength error, and a zero value may be used. However, it is unusual to reduce the short wavelength cross-level error significantly below ± 10 mm. This latter value is usually included in the vehicle model (although it is a track parameter) and is implicitly related to K_{speed} in BaSS 501 calculations and to the track geometry files in dynamic simulations.

d. Sidewear

On tight curves, rail sidewear tends to occur. Its formation can be slowed by lubrication, and is generally a high-rail problem. However, it serves to widen gauge and affect the vehicle positioning on the rails. The amount of sidewear included in analyses depends on whether it can develop (unusual on straight track) and what the maintenance intervention level is: 6 to 9 mm is a normal sidewear limit. However, as discussed earlier, the amount of movement that this can generate in the vehicle is generally less.

C. STRUCTURE–VEHICLE INTERACTION

1. Clearances

Clearance is required for a variety of reasons. Historically, clearance provided the safe boundary between vehicle and structure where there were significant unknowns in each, which has included suspension movements, tolerances, and inaccuracies in the measurement of structures. Clearance provides space to allow for aerodynamic effects and for safe walkways.

As vehicle behaviour and system tolerances are better understood, a differentiation between what is calculable and what remains unknown, is possible. Unfortunately, this has not always led to a relaxation of clearances as tolerances are extracted, which increasingly leads to conservatism — and smaller trains. Modern trains, with air suspension and about which the behaviour is well understood, tend to be smaller inside than their predecessors while occupying what appears to be a larger swept envelope.

Pressures on the infrastructure, especially in the face of an increasing need to move larger intermodal freight containers (notably 9 ft 6 in. high × 2500–2600 mm wide ISO boxes), require clearances to be specified frugally if rail is to survive in the increasingly competitive environment offered by road transport where larger paths routinely exist.

Clearance is about risk management. The larger the clearance provided, the smaller the risk, and thus the need for control measures is minimised. Modern standards specify clearance according to risk regime, where the available clearance dictates what control measures are required.[7,8] Typically, actual clearances greater than 100 mm are defined as normal, whereas below this reduced and special reduced clearances (the latter being clearances >0 mm) require increasingly rigorous control measures. Control measures involve processes to control track position such as slab track, glued ballast, etc. The regime of inspection is also important, ensuring that tight structures are inspected more regularly than those that are well clear of the track.

UIC rules require a reference profile to be enlarged for various effects. Clearance between the developed reference profiles is not specifically mandated.

It is important to consider risk in relation to the methodologies being used. Figure 7.16 presents a number of analytical methodologies and considers the risk associated with using them

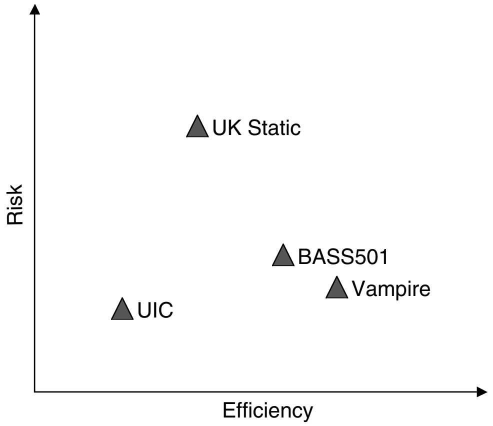

FIGURE 7.16 Risk vs. efficiency for various gauging methodologies.

(based upon the likelihood of there being situations where more clearance is required than is actually provided) and the efficiency of use of space over a typical length of route.

If we consider typical British static gauging, then a fixed clearance is provided, which provides adequate clearance in all but the worst combination of systems failure and extreme track geometry. In most situations, the vehicle is well clear of the infrastructure, and very poor use is made of the infrastructure when the vehicle is not running at these extreme limits (for instance, straight track). In contrast, using VAMPIRE™ analyses allows the actual clearance to be assessed in all situations. By ensuring that this is adequate, risk is low. Through accurate analysis, more use can be made of the infrastructure by only enlarging limiting structures, rather than increasing the gauge of a whole route.

2. Stepping Distances

While not strictly a clearance issue, stepping distances are an integral component of gauging analyses, and are generally the most difficult to resolve. To provide an adequate clearance to a moving vehicle, while still providing safe passenger access and egress to stationary vehicles, involves considering opposite, worst case scenarios.

Clearance analysis involves calculating the tightest reasonable clearance that may develop. Stepping calculation involves determining the maximum distance between a platform edge and vehicle step that may develop. In the latter case, it is customary to consider the static (thrown) position of a vehicle in relation to the platform edge. In Britain, the Health and Safety Executive's Railway Inspectorate[2] require maximum stepping distances of:

- Lateral: 275 mm
- Vertical: 250 mm
- Diagonal: 350 mm

This is known as the "stepping triangle," although it does not conform to Pythagoras' rule.

The values required are theoretical, taking no account of many tolerances that affect the actual stepping distance. In particular, air suspension system performance (self-levelling valves), installed cant, and track tolerances can have a significant effect on the stepping distances measured in relation to those calculated. However, the HMRI *Guidance* values do provide a sensible benchmark for static values.

Improvement of stepping distances is likely to be a characteristic of increasing disability regulation.

REFERENCES

1. Gauging Policy Consultation — Strategic Rail Authority, 2004.
2. Railway Safety Principles and Guidance — Her Majesty's Railway Inspectorate, Health and Safety Executive, 1996.
3. Kinematic Envelope and Curve Overthrow Calculations (Design Guide 501) — Bogie and Suspension Section (BaSS), Department of Mechanical and Electrical Engineering, British Railways Board, 1985.
4. UIC Code 505-1. *Rolling Stock Construction Gauge — UIC*, 8th ed., 1997.
5. UIC Code 505-4. *Effects of the Application of the Kinematic Gauges Defined in the 505 Series of Leaflets on the Positioning of Structures in Relation to the Tracks and of the Tracks in Relation to Each Other — UIC*, 3rd ed., 1977.
6. UIC Code 505-5. *Basic Conditions to Common Leaflets 505-1 to 505-4 — UIC*, 2nd ed., 1977.
7. Railway Group Standard GC/RT5212, Issue 1 — Rail Safety and Standards Board, 2003.

8. Railway Group Standard GM/RT2149, Issue 3 — Rail Safety and Standards Board, 2003.
9. General Gauging Procedure for Class 373 (Eurostar) Trains — Mechanical Systems Engineer Report No. 42, European Passenger Services, British Rail, 1995.
10. Guidance on Gauging GE/GN8573, Issue 1 — Rail Safety and Standards Board, 2004.
11. Johnson, D. M., *Square Boxes into Round Holes*, Paper to the Railway Civil Engineers Association, Institution of Civil Engineers, September, 2003.
12. Johnson, D. M., *Technology for Structure Gauging*, Paper to the Rail Track Association of Australia, Darwin, June 2004.