"FUNDAMENTALS OF TRACK LATERAL SHIFT FOR HIGH-SPEED RAIL APPLICATIONS"

by

Andrew Kish
Manager, Guideways and Structures
USDOT/Volpe Center, Cambridge, MA, USA
Telephone: 617- 494-2794
Facsimile: 617- 494-3616

Gopal Samavedam
Division Manager, Structures & Transportation Division
Foster-Miller, Inc, Waltham, MA, USA
Telephone: 617-684-4275
Facsimile: 617-890-3489

David Wormley
Dean, College of Engineering
Penn State University, University Park, PA, USA
Telephone: 814-865-7537
Facsimile: 814-863-4749

ABSTRACT

The fundamental mechanics of track lateral shift due to vehicle and thermally induced loads are defined, and an analytic approach is presented for the determination of "limit" loads and deflections on the track to prevent progressive lateral shift. The proposed approach consists of the coupled use of a comprehensive vehicle-track dynamic model to evaluate the lateral loads on the track, and a "dynamic" track lateral response model to determine the residual lateral deflections under multiple load passes. The lateral response model is augmented by a track vertical deflection model for the determination of the "vertically loaded lateral resistance". The lateral response model simulates moving loads, and includes a nonlinear tie-ballast lateral resistance idealization. Results of baseline parametric studies accounting for the influences of lateral resistance, curvature, longitudinal force, and other vehicle and track parameters are given, "limiting" lateral to vertical load ratios (L/Vs) are identified, and stable and unstable regimes of track shift under high speed operating conditions are predicted. Prototype safety criteria for track shift mitigation are proposed based on net axle load (NAL/V) limits versus “allowable” lateral track displacements. This work is part of the US DOT/Federal Railroad Administration’s research effort to develop the technical information required to establish “safe” operating practices for high speed tracks.

1. INTRODUCTION

The evaluation of the influence of vehicle induced forces on the lateral stability of CWR tracks has been a major research concern for several decades. The load capacity of the track or its "lateral strength" to handle these loads is a key requirement for track alignment retention, hence to safe train operation. The growing tendency abroad and in the U.S. toward higher speeds and heavier axle loads tends to exacerbate the problem of track lateral stability assurance. Existing high speed rail systems in Europe and Japan, as well as high speed rail technology endeavors in the U.S. such as proposed for Amtrak invoke the question of lateral strength adequacy, especially since there are no safety requirements currently in place in the U.S. addressing this issue.

In order to provide a clear problem definition addressing the safety requirement of "track alignment retention", is useful to review the fundamentals of the track lateral stability mechanism in terms of track shift and track buckling. This is briefly summarized from [1] in Table 1.

TABLE 1: TRACK LATERAL STABILITY MECHANISM

	EVENT	MAJOR CAUSAL FACTORS
1	FORMATION OF INITIAL TRACK MISALIGNMENTS	(1) HIGH L/V'S AND LONGITUDINAL FORCES (2) REDUCED LOCAL TRACK LATERAL RESISTANCE (3) INITIAL IMPERFECTIONS (WELDS) AND DEFECTS
2	GROWTH OF MISALIGNMENTS	(1) L/V INCREASE DUE TO THE IMPERFECTIONS (2) INCREASE IN LONGITUDINAL FORCES (3) TRACK "DYNAMIC UPLIFT" DUE TO VERTICAL LOADS (4) MANY CYCLES OF L/V'S
3	BUCKLING	(1) HIGH LONGITUDINAL FORCE (2) REDUCED T_N (STRESS-FREE TEMPERATURE) (3) MISALIGNMENTS GENERATED BY TRACK SHIFT (4) DYNAMIC UPLIFT WAVE (5) WEAKENED LATERAL RESISTANCE

For an initial working definition, track lateral shift can be defined as "the formation and growth of lateral track misalignments due to high lateral to vertical load ratios (L/V's) and longitudinal forces". It is construed to be the first two stages of the track lateral stability process as indicated in Table 1. The resulting misalignments are typically "small" in magnitude and may, in conjunction with other conditions, lead to track buckling which is a "large" amplitude instability event. For a comprehensive discussion on the track buckling problem, safety concepts, and theoretical modeling, refer to [2], [3], and [4].

The L/V's are lateral to vertical load ratios where the net lateral load applied to the track by one axle of a truck resulting from the flanging forces and the two lateral components of the wheel/rail frictional force at both wheels on the axle are divided by the total vertical axle load. As will be discussed later, this L/V ratio is very instrumental in the overall track shift mechanism. For a comprehensive review of the state of the art of track shift covering the works of Prud'homme and SNCF, current practices in Europe, Japan and the U.S., and practiced track shift criteria, the reader is referred to [5].

From the above review, it became evident that several key issues and problem areas need to be examined for a more complete understanding of the track lateral shift behavior and applicable safety criteria. These include:

1. A need for a detailed mechanistic evaluation of the track lateral shift mechanism, including the:

- determination of the L/V load generating mechanism (i.e. "moving" L/V load spectra, speed, misalignment and curvature effects, and other influences on L/V such as wind and gust loads, truck hunting loads, vertical impact loads, and dynamic uplift influences)
- determination of longitudinal (thermal) load influences
- determination of curvature influences
- quantification of the dynamic track lateral resistance (i.e. the determination of vertical load influence on track lateral resistance, and its nonlinear characteristics)

2. The development of a rational mathematical model for the prediction of CWR lateral track shift behavior which:

- correctly models the mechanistic behavior of the track lateral response due to combined vehicle and thermal loads
- is comprehensive in the treatment of the many parameters and their influences
- is validated through appropriate experimental and analytic studies

3. The development of a rational safety criteria for both high speed and conventional rail systems for allowable track lateral shift, and establishing measurement techniques and diagnostic procedures for safety assurance.

The above issues have particular practical significance because:

- In the design and maintenance of modern high-speed tracks, adequate track lateral strength must be provided to withstand vehicle and thermal loads. Track shift potential evaluation is a key consideration in determining the required lateral strength.
- Track shifting forces can be a major contributor to the formation and growth of local track geometric imperfections. Operators must know the allowable track shifting forces in order to limit vehicle loads and operating speeds, including when conducting vehicle qualification tests for new systems.
- For high speed operations such as on the North East Corridor in the US with a pre-existing track layout, it is necessary to define the maximum safe speeds for high speed train operations.

The intent of this paper is to provide interim results of the research addressing these issues. Specifically, the paper presents the fundamentals of the track shift problem in terms of governing mechanism and critical parameters, presents a novel tandem vehicle dynamic/track lateral response analysis methodology, provides some key parametric insights, and present a prototype safety criterion for the control of track lateral shift.

2. TRACK SHIFT FUNDAMENTALS

2.1 DEFINITION

Track shift can be defined as the permanent lateral distortion of a track segment, which can occur under vehicle passes due to resulting lateral loads and which can lead to unsafe conditions unless remedial maintenance actions are taken. The permanent lateral distortion can occur cumulatively under many vehicle passes, or can occur more suddenly, under a single or a few passes.

Track shift can occur locally, or can be spread over a long section of track. It is generally caused by vehicles negotiating a preexisting irregularity or by high L/V loads resulting from vehicle hunting. Radial movement of curves under thermal loads or under steady state curving forces is another example of track shift.

2.2 TRACK SHIFTING FORCES AND LATERAL STRENGTH

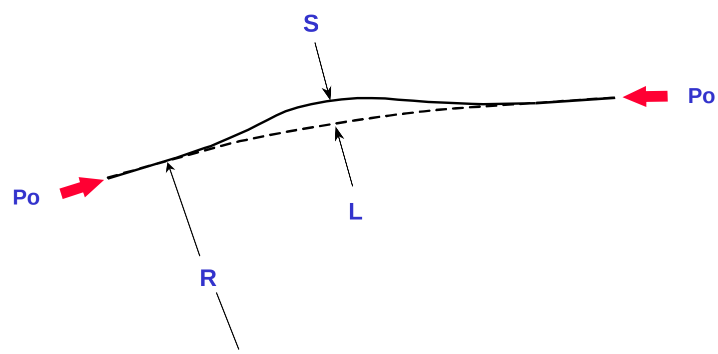

Figure 2.1 Track shifting forces and track reaction definition

Referring to Figure 2.1, the track shifting forces include the vehicle net axle lateral loads, L, and the thermal compressive loads, P_o, in the rail. The net axle loads include the curving force and the dynamic increment due to any initial track misalignment. The vehicle and thermal loads are reacted by the ballast resistance (due to tie bottom, side and end friction). This resultant ballast reaction force in the lateral plane is schematically represented by S. Under dynamic equilibrium conditions, there will be a resulting track lateral dynamic deflection, which may not vanish (i.e. the track may not completely recover to its initial configuration) after the vehicle passage due to the elasto-plastic characteristic of S. Hence, there can be a permanent or residual lateral deflection of the track structure. Under certain conditions, the permanent deflection can accumulate globally (as in the case of curved tracks) or locally (typically at weak spots such as at initial line defects). If the vehicle load exceeds the reaction that can be offered by the track panel, the resulting track deflection can be rapid and become potentially excessive for safe operations of vehicles. The determination of the minimum resistance that can be offered by the track to moving loads without "excessive" residual deflection is a key part of providing adequate restraint. Note that S is "dynamic" in nature, and must be distinguished from the static lateral strength value which is the maximum stationary lateral load that can be sustained by the track structure without "excessive" permanent deflections.

Prud'homme and the SNCF [5] have determined track dynamic strength experimentally by applying a known (slowly moving) lateral load on tracks through a single axle under vertical load. After the passage of the vehicle over the test segment, the mean transverse residual displacement is measured. The lateral load is incremental at each pass. Thus the relationship between the applied axle lateral load and the residual deflection was obtained, and the load at which significant residual deflection began to occur was originally considered as the track dynamic strength. This definition was later refined on the basis of tests with multiple passes at constant lateral axle force. This basic concept is illustrated in Figure 2.2a which relates the track shift to the number of passes. These curves illustrate that for values of lateral force below some limit, the track deflections stabilize at some finite value. Above this limit, the deflection is found to increase at a rapid rate, termed as progressive or "unstable". The lateral load at which the deflections transcend from stable to unstable will be defined here as the *track dynamic lateral strength* (shown by dashed line in Figure 2.2a).

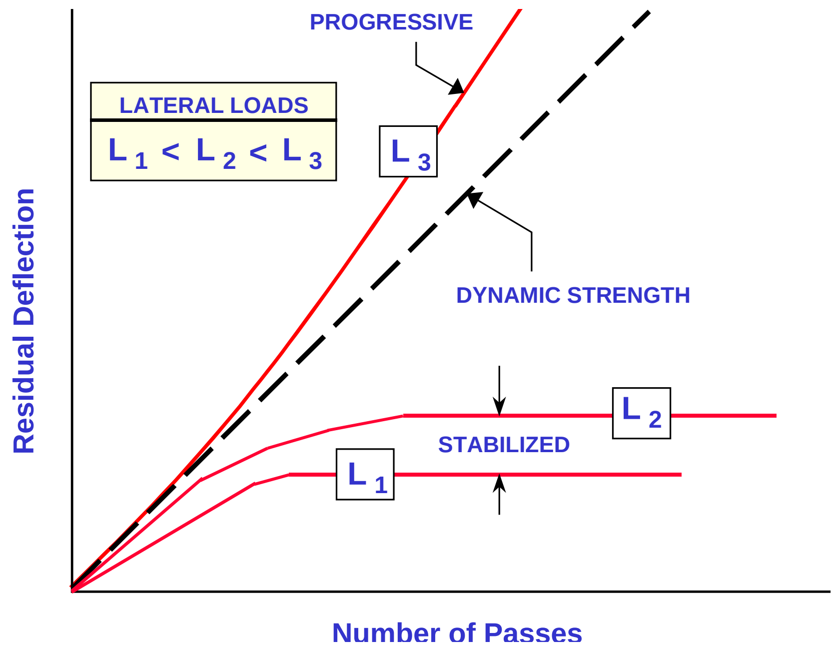

Figure 2.2a Track shift versus number of passes

2.3 ALLOWABLE MISALIGNMENTS AND TRACK SHIFT

From Figure 2.2b it is seen that track shift itself is a form of misalignment for subsequent traffic even though it may reach a stable level. For high-speed traffic, four levels of lateral misalignment are important as recognized by the European railroads. These are:

- initial misalignment after construction or realignment, δ_o
- maximum allowable premaintenance misalignment, δ_m.
- critical misalignment at which operations are impacted and safety is potentially compromised, δ_c.
- stable track shift misalignment levels reached after many passes, δ_1 and δ_2.

The initial misalignment due to realignment or initial construction tolerance for new tracks is represented by δ_o. This misalignment is typically on the order of one to four millimeters for high-speed tracks.

The maximum allowable misalignment prior to maintenance operations according to the indevidual railroad practices is represented by δ_m. (The SNCF, for example, uses 4 mm as the limit for their TGV track maintenance).

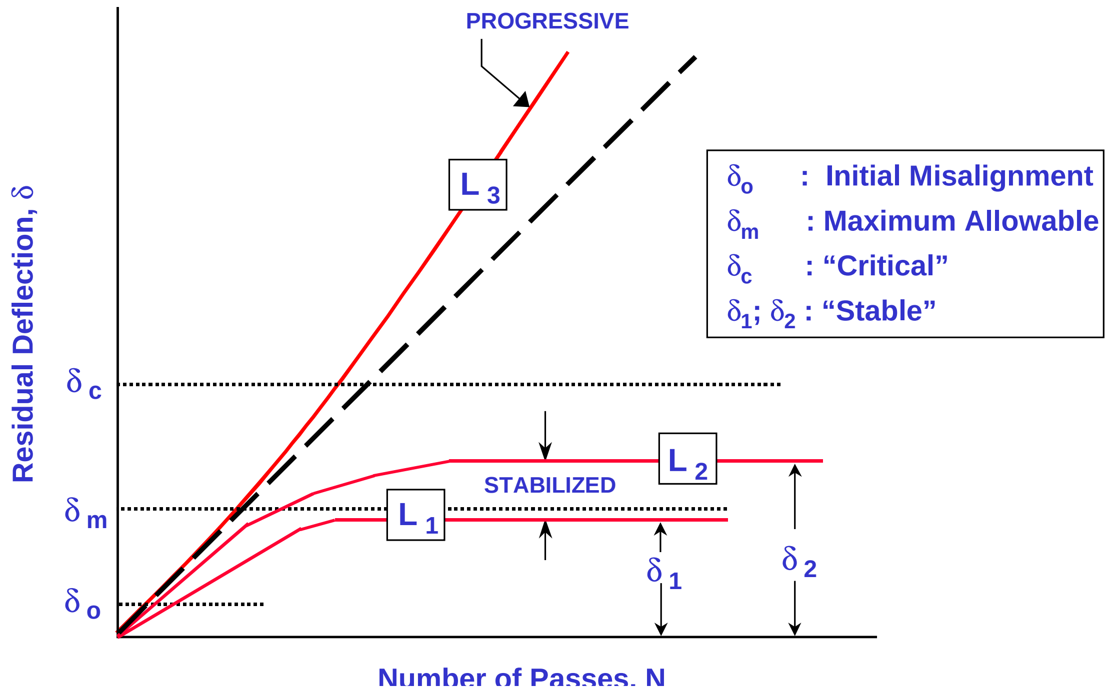

Figure 2.2b The concept of "allowable" misalignment versus track shift

The critical misalignment amplitude at which vehicle operational safety is impacted is represented by δ_c. Several possible "failure modes" and/or design requirements may have to be considered to determine the lowest value of δ_c. These include sudden track shift potential, wheel climb, rail roll, buckling, inadequate ride quality, and exceedence of vehicle design loads. As an example, the SNCF indicates a 12mm peak to peak value for δ_c for TGV operational safety[8].

The displacements δ_1 and δ_2 in Figure 2.2b represent stable deflection levels after a number of passes, and are acceptable only if δ_c is larger than these. For conventional speed tracks these stabilized misalignments can be on the order of 20mm and δ_c can be larger than that. For high-speed tracks, *stabilization may not precede δ_c,* hence the determination of δ_c for high-speed tracks becomes very important.

The critical misalignment δ_c, can be determined from mechanistic considerations for given vehicle parameters, speed, and track lateral resistance characteristics, although at present there is no suitable theoretical model to do this. The pre-maintenance misalignment δ_m, can be derived on a tradeoff basis between the frequency of maintenance (number of safe vehicle passes or MGT) and the margin of safety based on the critical misalignment, δ_c. The construction tolerance, δ_o is usually determined by the railroads as a tradeoff between the cost of construction (tolerance and quality assurance), maintenance, and the number of revenue passes that can be obtained between maintenance cycles.

Although there is no explicit discussion on the wavelengths associated with these misalignments, they are of interest in track shift analyses and derailment predictions. The wavelength associated with the construction tolerance is on the order of a few meters. For δ_m, it can be in the range of 10-20m for typical high-speed track. For δ_c, the wavelength can be in the range of 20-40m.

2.4 TRACK SHIFT CRITERION

In the United States, under current conventional freight and passenger operations, the FRA Track Safety Standards prescribe "allowable" lateral alignment defects as a function of "Track Class" designations. The more stringent requirements imposed by higher speed regimes of the proposed high speed corridor operations, may necessitate "allowables" to be determined based on track shift considerations, more specifically in terms of prescriptions based on δ_o, δ_m and δ_c.

It should be noted that the early Prud'homme formulas (see Section 2.5) based on track shift type considerations became a vehicle acceptance criterion in some of the European railroads, and their applicability to current generation high-speed track lateral shift safety may need reexamination[5].

The criteria for limiting track shift to acceptable values can be proposed as the following:

High-speed track under maximum expected thermal loads should, for a given vehicle, have minimum lateral strength to limit the development of lateral misalignments to within a specified value, δ_L

or

Lateral loads generated by high-speed vehicles operating under maximum speed, cant deficiency, thermal load, and initial line defect conditions should not cause the exceedence of an "allowable" deflection limit, $\delta_{L.}$

Implicit in the above criteria that $\delta_L \leq \delta_C$. In order to determine the limits on "allowable deflections" or to define "minimum lateral strength requirements" applicable to the track shift safety criteria proposed above, an understanding of track shift mechanism and the relevant parameters is required. These will be discussed in the next section.

2.5 TRACK SHIFT MECHANISM PARAMETERS AND TESTS

Table 1 shown earlier illustrates the principal causal factors and parameters relevant to the track shift mechanism i.e. to the development of lateral track deformations. Figure 2.3 schematically displays the functional dependence of the incurred lateral deformations on the major parameters. These parameters constitute the key elements of the track lateral shift analysis methodology as will be described in detail later.

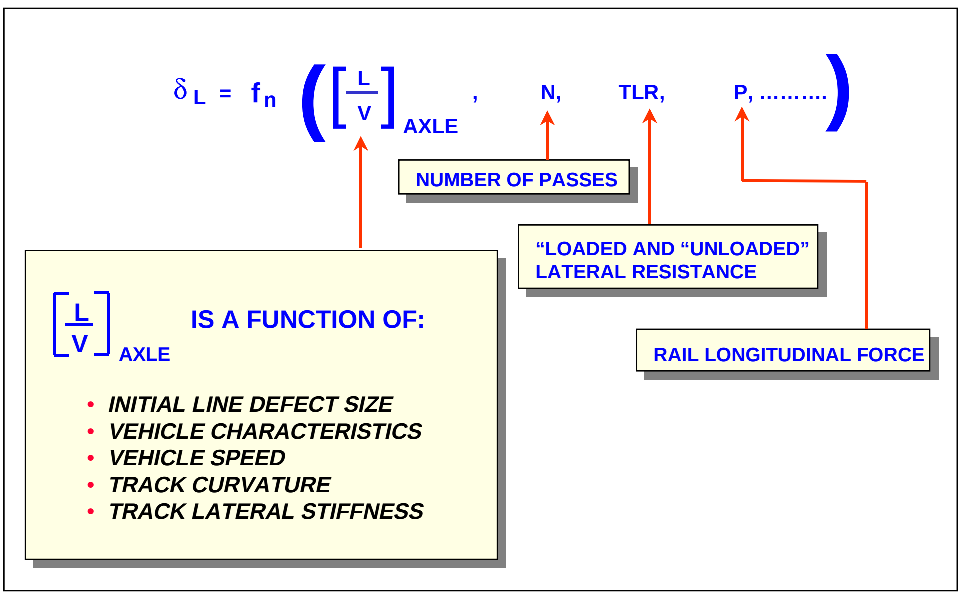

Figure 2.3 Track shift mechanism key parameters

To date, very limited experimental data and analyses are available on track shift, especially as applicable to high-speed rail tracks. For a comprehensive literature review the reader is referred to [5]. Here only the most relevant work by the SNCF will briefly be reviewed.

2.5.1 SNCF/Prud'homme Studies

The SNCF has been the most significant contributor to the subject of track shift. This subject has evolved over the last three decades of research, starting with the historical work of Prud'homme [6] who experimentally evaluated the "lateral strength" of a wood tie track under a moving lateral load. These tests were conducted at Vitry-sur-Seine on U33 (46 kg/m) CWR track with wood ties spaced at 0.58m. The test track had a curvature of 2.2° (800m radius) and was new with no traffic consolidation. Joule heating was utilized to increase the longitudinal thermal stresses in the rail. Two test loading vehicle designs were utilized. The first design was a single "derailleur" vehicle with an 8.2m (27 ft) wheel base and a central axle capable of applying a maximum vertical load of 120 kN (27 kips) and a maximum lateral load of 110 kN (25 kips). The second design, designated as the wagon "tombereau," consisted of two coupled vehicles on parallel tracks. One vehicle propelled the other vehicle and applied a lateral load to one of its axles. The maximum loads for this design were 130 kN (29 kips) vertical and 170 kN (38 kips) lateral. The following two test methodologies were used:

Method 1: *Vertical load constant, and lateral load incremented after every pass or after every ten passes.*

Method 2: B*oth vertical and lateral loads kept constant at all passes.*

Using Method 1, the cumulative residual deflection was obtained as a function of the lateral load, while Method 2 provided a relationship between residual deflections and a large number of passes. Results from both methods were used to define “critical” loads and conditions.

Based on these tests, Prud'homme developed the first empirical equation for the lateral strength of a wood tie track under vertical axle loads. Over the years, this equation has served as a guideline for acceptable vehicle loads on track, sometimes interpreted also a panel shift limit. This Prud'homme limit, L_P is given by:

$$L_p = 10 + V/3$$

where and V is the vertical axle load in kN. This empirical criterion originally defined the *limiting track panel strength* of a wood tie track with tamped ballast required to prevent lateral shift under repeated loads. This formula did not account for the curvature and the rail thermal load effects. Prud'homme later recommended a multiplying factor of 0.85 to L_P for these effects. This is known as 85 percent of the Prud'homme limit. As has been shown in [5], the application of this limit to high speed tracks operating with modern equipment on new track structures and components requires evaluation.

2.5.2 Recent SNCF Tests of TGV Track

More recent tests were conducted by the SNCF on the TGV Paris-South-East line near Tonnere [7] to measure the panel resistance for the new track design and to compare this resistance with previous SNCF experiments conducted on older track. These tests are particularly significant in that a specific criterion for the definition of the "limiting" lateral resistance is provided.

Tests were conducted using the “derailleur" wagon which applied vertical and lateral load to the track through a single center axle. Low speed passes were made with vertical load held constant throughout the testing and lateral load incrementally increased after each set of three passes. The residual lateral displacement was recorded after each pass and the incremental change in displacement due to each vehicle pass was obtained. These data have been analyzed in [5], and recast in Figure 2.4 to more clearly show the incremental trends.

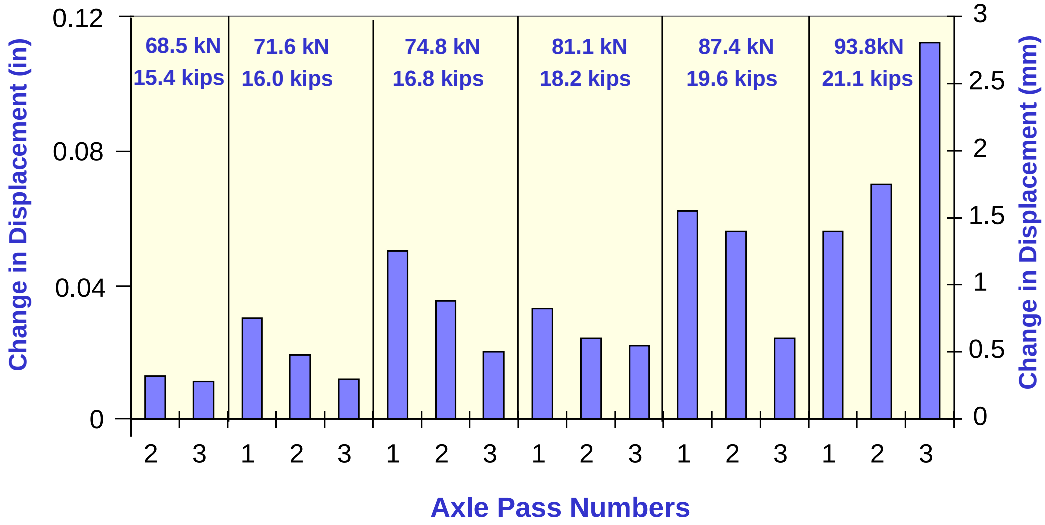

Figure 2.4 Increment in residual deflection as a function of lateral load level and three axle passes

It can be seen from this figure that the *change* in displacement decreases for successive passes at a constant lateral load level for all but the last (93.8 kN) level. According to the SNCF, this indicates that the track residual deflections are "stabilizing" at these levels and that additional passes would not increase these deflections. By contrast, the change in displacement is increasing at the last lateral load level (93.8 kN) and additional passes could be expected to further displace the track. At this load level, the track deflections can be considered to be "unstable" or progressive. Therefore, the "limit" lateral load can be deduced by interpolation between the 87.4 kN and 93.8 kN load levels.

These tests were particularly significant in that they clearly showed the multiple load pass influence, and presented a specific basis for determining the "limiting" lateral loads. It will be later shown that an appropriate track shift analysis requires such a simulation of multiple passes, and that the experimental result above can be analytically predicted.

2.5.3 SNCF Practice

The current SNCF practice on misalignment tolerances and load limits for high-speed trains is given in a recent SNCF paper [8]. During operation of the TGV, deflection limits are utilized to dictate track maintenance operations and adapted versions of the Prud'homme criterion govern vehicle loads. The following operational limits are cited for TGV concrete tie track:

- The maximum repeated lateral axle load which can be applied to the track by the vehicle is defined by 85 percent of the Prud'homme limit; 0.85(10+0.33V), with the 0.85 factor used to empirically account for curvature and thermal loads.

- The concrete tie track must be designed such that the static lateral panel resistance equals 24 + 0.41V for tamped track and 38 + 0.63V for stabilized track, with the latter required for summer operations. For TGV axle load of 170 kN, this limit equals 93.7 kN for tamped track, and 145 kN for consolidated track. (Note that the limiting resistance, here, represents the maximum stationary lateral load that can be sustained by the track under the vehicle vertical loads, without resulting in any permanent displacement of the track panel).

- The rail is manufactured to an initial "straightness" which typically permits maximum defect amplitudes of 0.5mm over 2m of rail length. The track's initial construction tolerance is very low.

- The peak to peak limits for track lateral defects are about 8 mm, below which maintenance may not be required, and 12 mm, above which substantial track repair work will be required.

According to the SNCF, through-out several test measurements to evaluate the maximum lateral forces on track during high speed (408 and 482 km/hr) operating conditions, the Prud'homme limit values not exceeded.

3. THE OVERALL MODELLING APPROACH

The overall approach to analyze the track shift problem is based on two newly developed models, namely:

- The Track Residual Deflection Model.
- The Vehicle Dynamics Model.

The purpose of the first model is to determine the cumulative residual lateral deflections after the passage of each axle. The net axle lateral and vertical loads are assumed to be known in this model. The model also accounts for the rail thermal load, initial misalignments, and track curvature influences on the track lateral movement.

The purpose of the vehicle dynamics model is to compute the axle loads which will be the inputs in the track residual deflection model. The model also predicts potential failure modes that can occur prior to the onset of track lateral shift. It accounts for preexisting track misalignments, track curvature, and the appropriate wheel-rail rolling contact mechanism. The track misalignments may be upgraded by this model on the basis of the results from the track residual deflection model as an iterative process. This new vehicle model also includes the proper representation of track compliance characteristics, for as has been shown in [9], track compliance becomes important for the accurate assessment of loads generated, and for the correct evaluation of failure modes such as wheel climb.

3.1 Coupling of Models

The two component models can be combined into a single comprehensive model and will be called Fully Coupled Approach (as opposed to a Partially Coupled Approach in which the two models may be exercised under separate computer codes). The input parameters, (lateral loads to the track residual deflection model and misalignments to the vehicle dynamics model), are properly connected and updated. For a more comprehensive discussion of the Fully Coupled Approach and the tradeoffs between the two approaches refer to [9]. In [9] it is also concluded that the Partially Coupled Approach may be adequate for most track shift analyses, and that it provides a practical and economic tool for track residual deflection predictions as a function of N number of wheel passes. Figure 3.1 illustrates schematically the proposed approach involving the two component models, including the fundamental parameter inputs, the various submodels, and the outputs. These will be briefly discussed in the following paragraphs.

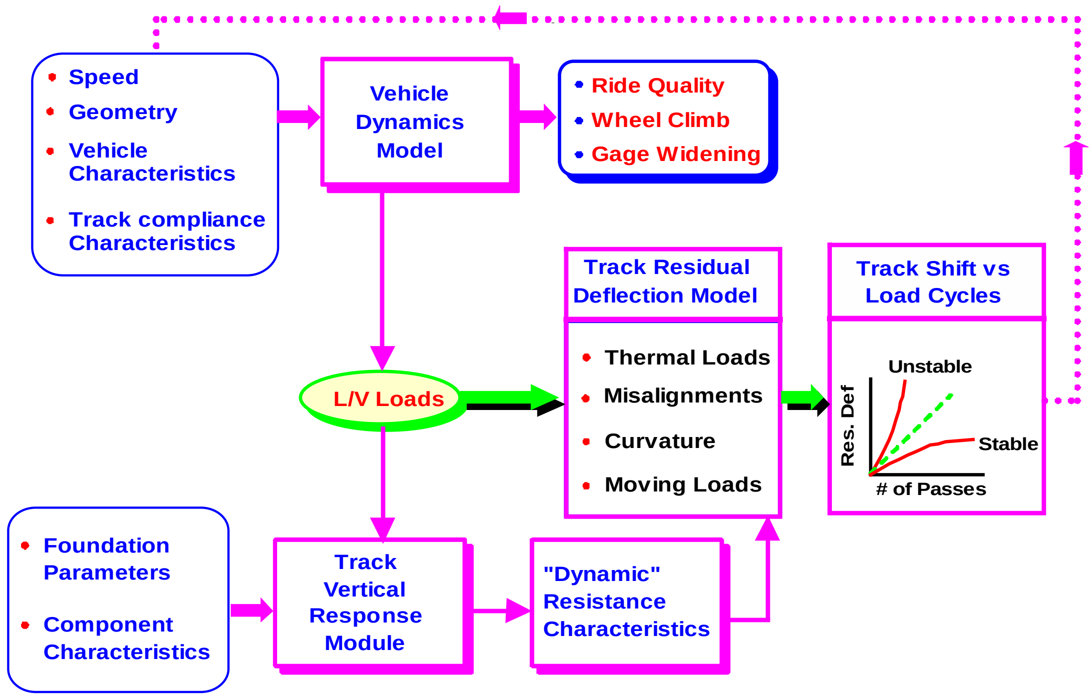

Figure 3.1 Modeling approach for track shift

3.2 Basis of Track Residual Deflection Model

The model is based on the assumption that the moving lateral loads exerted by vehicles can be characterized as quasi-static. The track is considered as a beam on springs with nonlinear elastoplastic "hardening and softening" characteristics. The beam bending inertias in the two planes are the sum of individual rail inertias in the respective lateral and vertical planes. The load input requirements (i.e. moving versus stationary loads, and single axle versus truck loads) are addressed in [9], where it is shown that a moving lateral load predicts the correct behavior of track shift and that the stationary load idealization grossly underestimates the resulting track residual deflection. It is further shown that for most modern high-speed vehicles and loads, the calculated residual deflections do not significantly differ for single axle versus truck loads, with the single axle L/V approach being more conservative. Therefore in all subsequent analytic developments in this paper, the single axle L/V representation is used.

In Figure 3.1, key parameters of the track residual deflection model are also presented. The ballast vertical foundation modulus is required to determine the track vertical response and hence, the tie reaction load distribution. The latter information is used to determine the net lateral resistance offered by the vertically loaded ties, which requires the knowledge and use of the appropriate tie-ballast friction coefficient. Using the thus computed “loaded lateral resistance”, the track response due to prescribed lateral loads can be evaluated, and the residual deflections after each load passage can be determined. An appropriate tri-linear stiffness characteristic for the tie ballast lateral resistance is also required in the track residual deflection model. The track vertical response is considered to be elastic. Track curvature, thermal load effects, and initial lateral misalignments are also accounted for in the residual deflection model.

3.3 Basis of Vehicle Dynamics Model

It is considered essential to simulate the rolling contact mechanism at the wheel/rail interface for the evaluation of vehicle track interaction loads and predictions of potential failure modes including wheel climb. A review of the literature revealed that several codes such as the SYSSIM and NUCARS do satisfy this requirement. However, the existing codes are limited in their track compliance representations. For high-speed vehicle/track interaction, track compliance is considered to be important, as they are expected to influence the load levels generated as well as other response characteristics, including truck hunting.

Furthermore, with laterally compliant track, a more accurate assessment of wheel climb can be made. For such reasons, a new model called OMNISIM has been developed as part of this tandem model. Details of the OMNISIM code are available in [9],[10]. The next section addresses the various key elements of track lateral shift response characteristics on tangent and curved tracks subjected to high-speed vehicle operations, including the effect of thermal loads. (The influence of initial misalignments and their growth under vehicle and thermal loads is addressed in a future study.)

4. TRACK SHIFT UNDER CONSTANT NET AXLE LOADS

The purpose of track shift evaluations is to determine the track residual deflections for a range of track conditions as functions of (initially) constant net axle force ratios (NAL/V). Of particular interest is the stable characteristic response of track lateral movement for a large number of axle passes. The following assumptions are initially imposed:

1. Constant single axle (moving) loads are considered (to be relaxed later).

2. The influence of thermal compressive loads is computed on the basis of a typical summer temperature increase of 50°F(28°C) above neutral. For some European and US tracks, this increase can be higher due changing neutral temperatures or to typically lower installation temperatures.

3. The tie ballast friction coefficient, μ_F, is an important parameter for it determines the track's vertically loaded lateral resistance. A nominal value of 0.8, based on tests performed in conjunction with U.S. dynamic buckling tests, is assumed for concrete ties with rough bottoms. (Recent UIC/ERRI/D202 test results are also in the same range). For wood ties that have been in service for some time, the friction coefficient can more variable, in the range of 0.8 - 1.2.

4. The tie lateral resistance is an important parameter for it provides the track lateral strength to resist the net axle lateral loads. Figure 4.1a represents the idealized lateral resistance function, typically determined by a single tie push test (STPT). This function is usually described by the three characteristic parameters:

F_e: the breaking or elastic resistance
F_p: the peak resistance
w_p: the tie lateral displacement at F_p

The tri-linear idealization introduces "w_e," which is close to zero, but to facilitate numerical work, the program uses a very small finite value of 0.01 inches for w_e. The value of Fp (peak resistance) depends mostly on the track's consolidation state. For good quality consolidated concrete ties on granite ballast 3000 - 4000 lbs/tie (13.3-17.8kN/tie) is appropriate, while for weak, tamped tracks, the value can reduce to 1,800 - 2200lbs/tie (8-9.8kN/tie). The breaking resistance, F_e, depends on Fp, and typically is on the order of Fp/4. Figure 4.1b shows the "dynamic" lateral resistance i.e. the lateral resistance as a function of vertical load. The static F_P and F_e values are increased by the additional friction resistance due to the vertical reaction force, R_V. The tie ballast friction coefficient is represented by μ_F.

5. The foundation modulus is also an important parameter which can vary from 2,000 - 12,000 psi (13.8 - 82.73N/mm^2) with concrete tie tracks having higher values than wood tie track. A conservative value of 6,000 psi is assumed for concrete tie track in the parametric study.

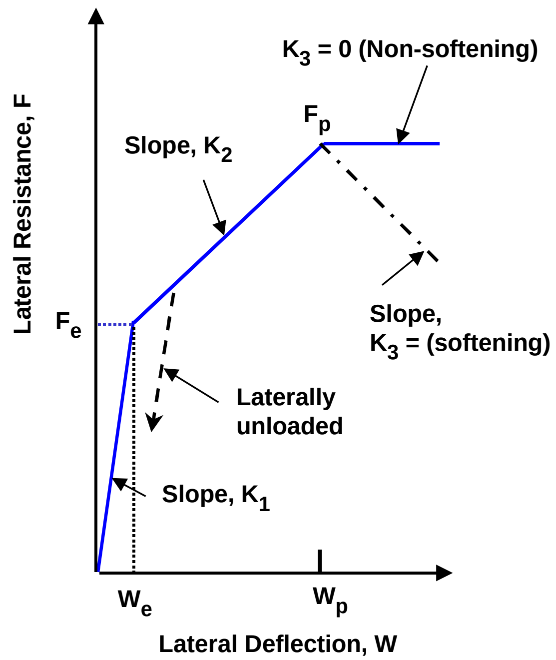

Figure 4.1a Track lateral resistance parameters

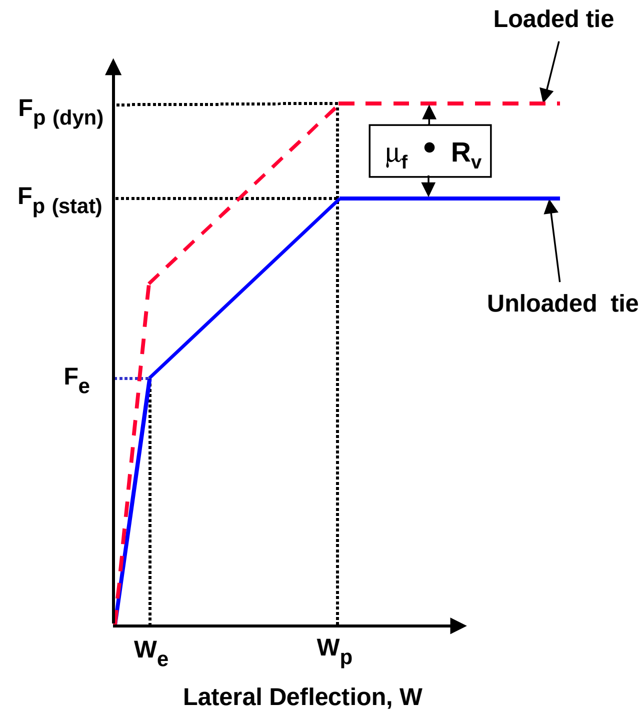

Figure 4.1b "Dynamic" resistance idealization

The track shift response characteristics will be evaluated over the range shown in Table 4-1. When a specific parameter is varied over its range, the other parameters are assumed their nominal values. Through these parametric studies, the effects of the individual parameters on the cumulative lateral deflection of the track are quantified. Some examples are provided below:

Table 4-1 Parameters used in track shift analysis

Symbol	Parameter	Range /Value
V	Vertical axle load	37.4 kips (166 kN)
F_e	Elastic resistance	1000 lb (4.5 kN)
W_e	Elastic displacement	0.05 in. (1.3 mm)
F_p	Peak resistance	2000, 3000, 4000 lb (8.9, 13.4, 17.8 kN)
W_p	Displacement at peak	0.25 in. (6.4 mm)
k_3	Softening stiffness	0
μ_f	Tie-ballast friction coefficient	0.8
NAL/V	Net axle force ratio	0.4, 0.5, 0.6

4.1 Effects of Track Curvature

The effects of track curvature are evaluated using curves ranging from tangent to 6° (R= 291m). For most high-speed rail operations curvatures tend to be mild, however, curvatures up to 6° may be utilized on some existing rights-of-way. The residual deflection after 20 cycles (passes) is used in most of this parametric study, however, as indicated before these deflections may be "unstable", (also see Section 4.6). The results are shown in Figure 4.2 for a lateral resistance (Fp) of 2000 lbs and a net axle force ratio of 0.40. Four temperature levels, which indicate the rail temperature change above the neutral temperature, are used to provide further data on the trends.

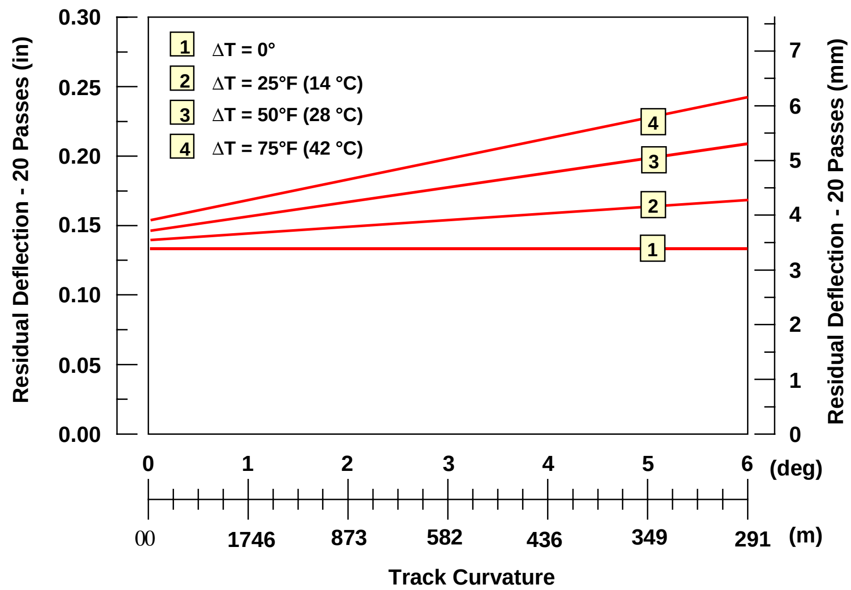

Figure 4.2 Influence of curvature and thermal force on track residual deflection

Curvature in the presence of thermal loads is found to have a significant effect on track shift. For the condition of ΔT = 50° F, a 6° (R=291m) curve will have a deflection 40 percent greater than that of the tangent track under the same conditions. The rate of increase for all conditions shown is linear with respect to curvature.

4.2 Effects of Rail Temperature (Thermal Force)

The influence of rail temperature can also be inferred from the above figure. As with curvature, the increase in residual deflection is linear with respect to temperature. For the case of a 2° (R= 873 m) curve, for example, the deflection is 40 percent greater at a temperature differential of 75°F (42°C) than at the neutral temperature.

4.3 Effects of Lateral Resistance

The track lateral resistance parameters, namely F_p, w_p, and F_e, (as part of the tri-linear idealization of the tie lateral resistance characteristic) are expected to play important roles on the cumulative deflections due to repeated passes. The results of the evaluation of the peak lateral resistance, Fp, are shown in Figure 4.3 for a net axle force ratio of 0.40 and a rail temperature increase of 50°F above the neutral temperature. Weak, tamped track has a lateral resistance generally at or below 2000 lbs/tie (8.9kN/tie). For both the tangent and curved tracks, the residual deflections will be almost double for this condition versus a consolidated track with peak resistance of 4000 lbs/tie (17.8kN/tie).

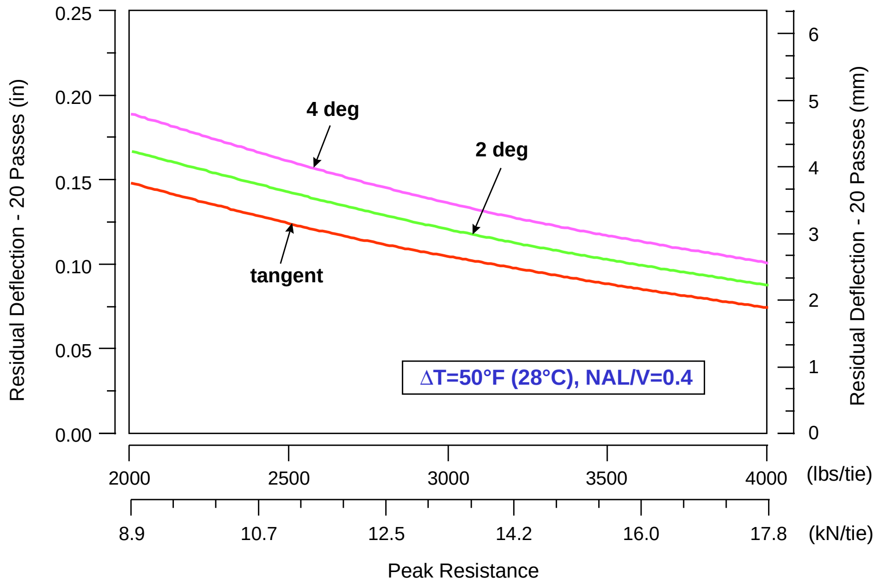

Figure 4.3 Influence of peak lateral resistance on track residual deflection

4.4 Effects of Tie-Ballast Friction

The interaction of the tie bottom surface with the ballast under vertical loading is a key factor in the lateral shift of the track. The lateral resistance of the tie will increase under vertical loading (recall Figure 4.1b) due to frictional shear resistance at the tie/ballast interface, as governed by the friction coefficient μ_F. However, this is not a true Coulomb friction in that wood ties and some very rough concrete ties can partially interlock with the ballast particles. Consequently, the apparent friction coefficient as measured in field tests can, under some conditions, be greater than unity. The evaluation provided here was conducted to show that under higher friction coefficient conditions, the track shift potential is greatly reduced. For this evaluation, the friction coefficient was varied over a practical range of 0.7 (smooth concrete ties) to 1.0 (typical wood ties). The lateral resistance of the ties is increased by the applied vertical load as follows:

$$F = F_S + \mu_F R_V$$

where,

F = Lateral resistance of the tie under load
F_S = Static lateral resistance of the tie
μ_F = Tie-ballast "friction" coefficient
R_V = Vertical load on the individual tie (as calculated by the vertical response model)

The influence of the tie-ballast friction coefficient is shown in Figure 4.4 for a 2^{o} curve with a peak resistance of 2000 lbs/tie (8.9kN/tie), a net axle force ratio of 0.40, and a rail temperature increase of 50^{o}F. The deflection decreases rapidly as the friction coefficient is increased. For the typical concrete tie friction coefficient of 0.8 for example, the deflection is reduced by more than 50 percent when the friction coefficient is increased to 0.9. Therefore, small improvements in the tie/ballast interface friction resistance can offer large reductions in lateral shift.

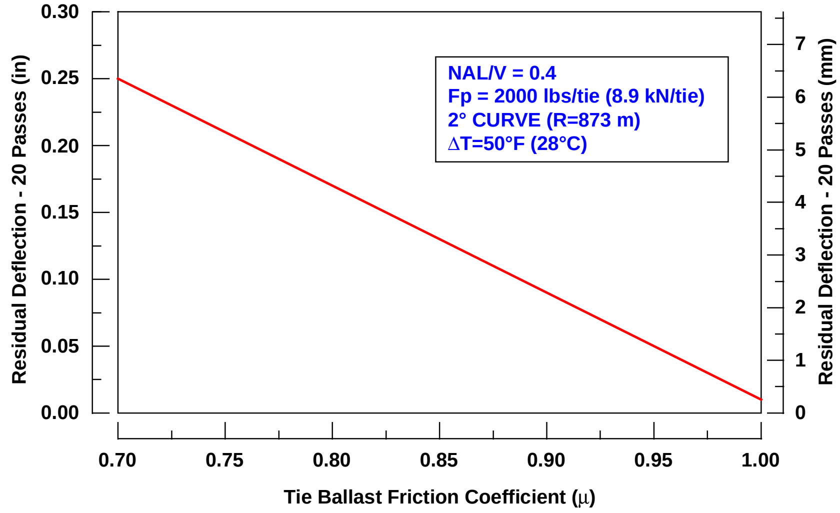

Figure 4.4 Influence of tie ballast friction coefficient on track residual deflection

4.5 Effects of Net Axle Lateral Load

The net axle lateral load is a primary parameter for the evaluation of lateral shift. This load is typically expressed as the ratio of the net axle lateral load to the axle vertical load (NAL/V). As discussed previously, the NAL/V can be determined for a given track geometry and operating conditions by the vehicle dynamics program. The track shift program is then used to evaluate the resultant track shift under the repeated axle passes. For this analysis, NAL/V is varied over a range of 0.3 to 0.5, and the results are shown in Figure 4.5 for a peak resistance of 2000 lbs/tie and a rail temperature increase of 50^{o}F.

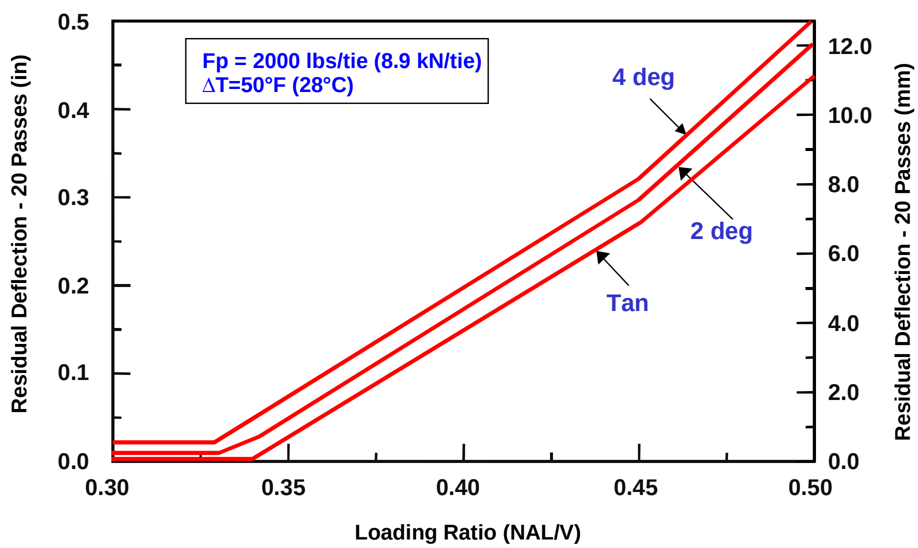

Figure 4.5 Net axle load ratio (NAL/V) influence on residual deflection

Clearly, limiting the lateral load on the track is important for control of track shift. In this case, no significant track shift occurs below a loading ratio of 0.34, which is consistent with the 85% Prud'homme formula.

However, beyond this level, the residual deflection rises sharply, reaching the high residual deflection values at loading ratios of 0.45 to 0.5. As is discussed later in the development of the safety limits, this rapid rise significantly limits the permissible lateral loads.

4.6 Influence of Number of Passes

For all of the cases discussed above, the residual deflection of the track after 20 axle passes has been used as the relative measure of parametric influences. For most cases considered, where the deflection after 20 passes is reasonably low (under 5 mm), only minimal additional deflections may occur after subsequent passes, i.e. track deflections becomes "stable". Conversely, in those cases where the deflections are higher, the track may continue to deflect in an unstable manner beyond 20 passes. This result is illustrated in Figure 4.6 for several cases of NAL/V and peak lateral resistance. While the results are interesting from an analytical standpoint, deflections much greater than 5 mm will likely be unstable and exceed acceptable safety limit values. From the figure one can infer that the combinations of NAL/V and F_P of 0.34 and 2000, and 0.40 and 4000 may be "safe", while the combinations of 0.4 and 2000, and 0.45 and 4000 are not.

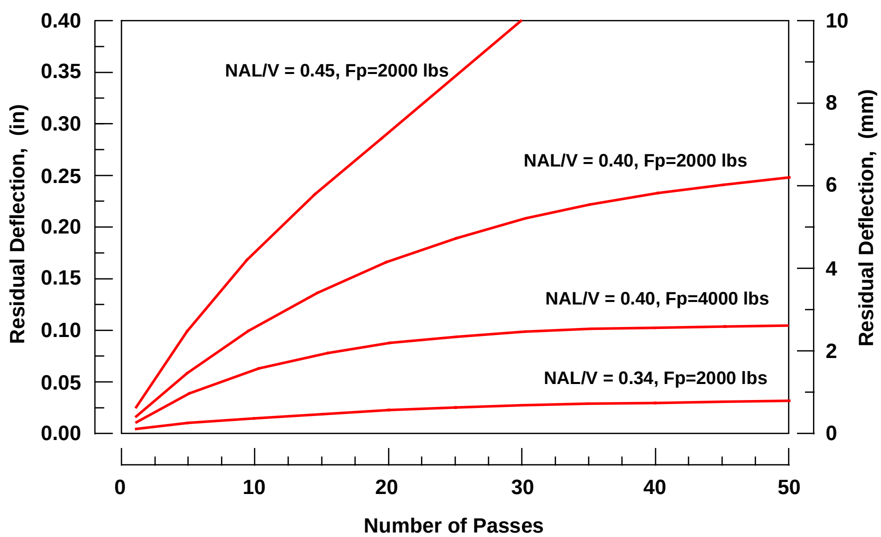

Figure 4.6 Influence of load cycles on cumulative deflection

4.7 Track Shift Model Validation Studies

Throughout the model development effort several studies were conducted to verify the model's predictive capabilities. These included benchmark problems against NIKE3D Finite Element codes (for stationary load cases), test and model prediction comparisons against track panel lateral pull tests, and comparisons against moving load SNCF data of Figure 2.4. Very good agreement was obtained in these comparisons, and further details are available in [9]. Results from more recent field test validation studies employing the Association of American Railroads' Track Loading Vehicle [TLV] (conceptually similar to SNCF's "derailleur wagon") to apply repeated L/Vs to an instrumented wood tie tangent track segment is shown in Figure 4.7. Track parameters required for the model, such as the lateral resistance and the tie ballast friction coefficient were measured prior to the test conduct. Seventeen TLV passes with L/V=0.6, and subsequent six passes with L/V =0.75 were made. Very good agreement resulted between theory and test. Additional validation tests are planned for a more comprehensive treatment of other key variables and parameters. For additional validation results against SNCF data, refer to [11].

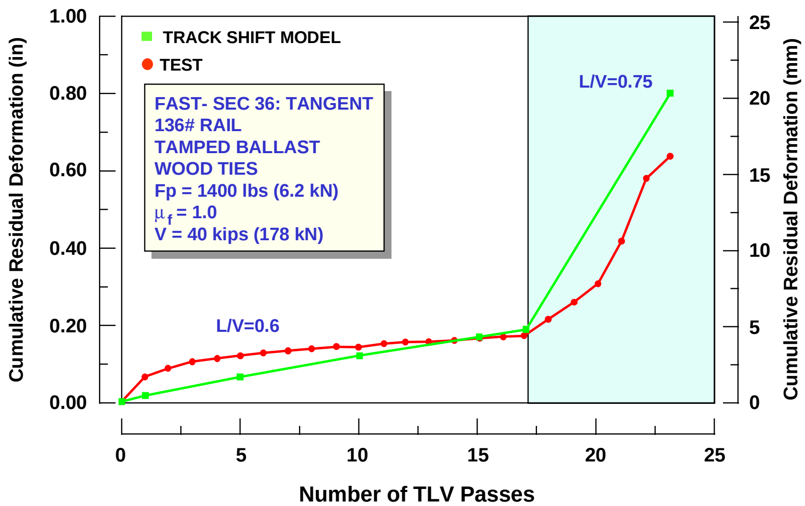

Figure 4.7 Track shift model validation: theory versus test comparison

5. TRACK SHIFT UNDER VARYING NET AXLE LOADS

The net axle lateral load can vary along the track segment as the vehicle negotiates lateral misalignments on tangent or curved tracks. Spirals on curves will also generate varying net axle loads. Gauge narrowing, switch points, and other discontinuities can also produce net axle loads spread over relatively small wavelengths. A typical OMNISIM result showing the variability of the lateral loads when a vehicle traverses a half sine wave type lateral line defect, LD, with an amplitude of 0.5 in (13mm) and a wavelength of 31 ft. (9.45m) at a speed of 160 mph (267km/hr) is illustrated in Figure 5.1.

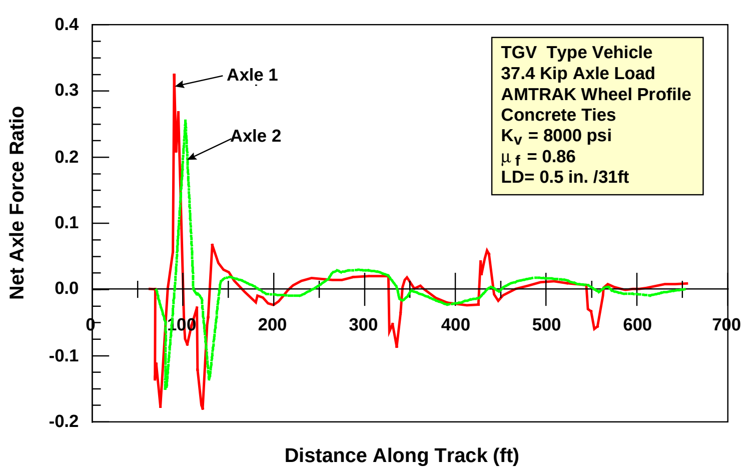

Figure 5.1 Variable net axle force distribution in misalignment

For a simple mathematical representation, the variable net axle load distribution can be represented by two parameters, i.e., the peak value of the force ratio $(NAL/V)_{PEAK}$ and the wavelength, λ, (if the "negative lobes" are ignored) by taking:

$$(NAL/V)=(NAL/V)_{PEAK}\,[1 + \cos(2\pi x/\lambda)]\,/2 \qquad \text{for } |x| < \lambda/2$$

where x is the distance along the track. For $|x| > \lambda/2$, the (NAL/V) is considered to be zero. In the following sections, the influences of variable moving loads as represented by the two parameters of $(NAL/V)_{PEAK}$ and λ will be briefly presented.

5.1 Tangent Track

Figure 5.2 shows the cumulative deflection as a function of number of axle passes for $(NAL/V)_{PEAK} = 0.5$, and varying λ from 20ft (6.1m) to ∞ (representing the constant load case). Here the peak lateral resistance is taken as 2000 lbs/tie (8.9kN/tie). As can be seen, the λ influence can be significant, especially up to a wavelength of 60ft. (18.3m), beyond which the constant load assumption is a good approximation. It can also be noted that for $(NAL/V)_{PEAK} = 0.5$, even at low values of λ, deflections at 20 passes are not stabilized.

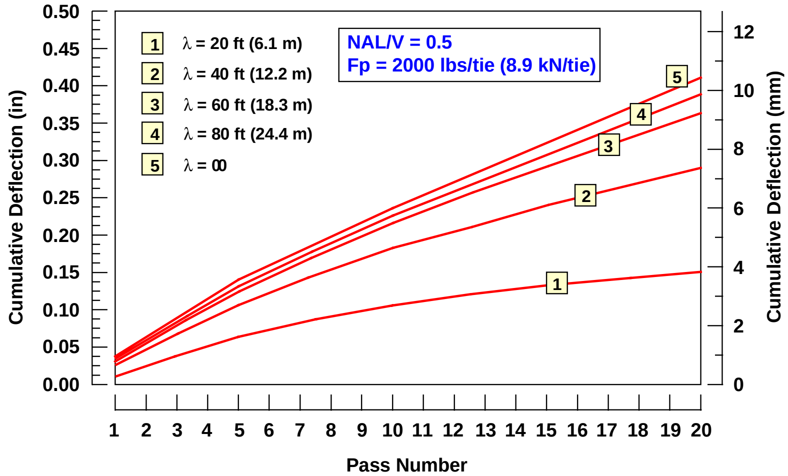

Figure 5.2 Load wavelength influence on cumulative deflection

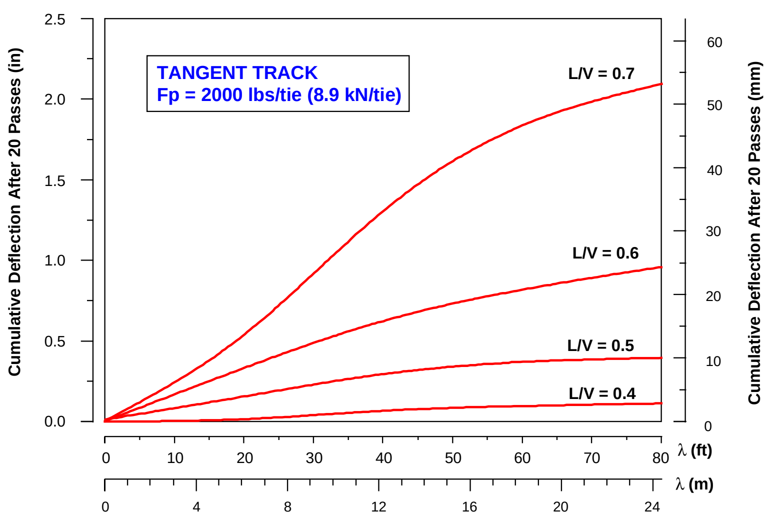

Figure 5.3 Load wavelength influence on cumulative deflections for various axle load ratios

Similarly, Figure 5.3 provides residual deflections for 20 passes for differing $(NAL/V)_{PEAK}$ values as a function of λ . The figure clearly illustrates the pronounced influence of the peak net axle loads on residual deflections, and their sensitivity to λ. These deflections tend to be "large", and even for lower values $(NAL/V)_{PEAK}$ and λ, when deflections are "small", one has to establish if they are stabilized or not for safety considerations.

5.2 Curved Track

Curved tracks have also been analyzed under varying net axle loads. As shown before, rail temperature (thermal load) effects have a pronounced influence on the track lateral shift of curves. In this subsequent curvature and λ influence study, a temperature rise of 50°F (28°C) over the neutral is used. A summary of the results for the 2° curve is shown in Figure 5.4 which gives the cumulative residual deflection after 20 passes for $(NAL/V)_{PEAK}$ of 0.4, 0.5, 0.6, and 0.7 for varying load wavelengths.

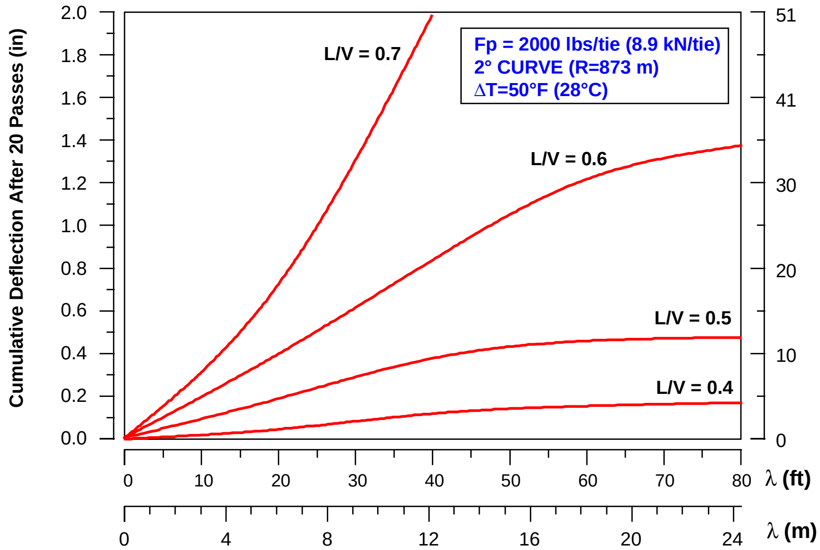

Figure 5.4 Load wavelength influence on cumulative deflection for various axle loads (2° curve)

From Figure 5.4, it may be seen that an $(NAL/V)_{PEAK}$ = 0.5 produces residual deflections on the order of 5mm even for a short wavelength of 20 ft. Hence for $(NAL/V)_{PEAK}$ equal or greater than 0.5, the load wavelength should be under 20 ft, if the residual deflection is to be controlled under 0.2 in. (5 mm).

6. TRACK SHIFT MITIGATION CRITERIA

Track shift mitigation criteria are required to eliminate or control lateral track shift under vehicle and thermal loads. Elimination of track shifting forces will contribute to the reduction of track misalignment growth and the associated alignment and maintenance costs. However, this may not be practical, since high-speed trains need to operate on cant deficient curves, which will generate high track shifting loads. Also, there will be natural misalignments on newly maintained tracks which can contribute to the vehicle dynamic loads. Track shift control can be done by limiting the net axle loads under some threshold values for a given track strength condition. The criterion for the determination of these (NAL/V) values can be based on allowable (stable) residual deflections which do not lead to unsafe conditions such as wheel climb, track buckling, gage widening, or to unacceptable ride quality. Therefore the proposed prototype track shift criteria developed here will be based on allowable net axle loads required to produce either:

- Zero (or negligible) track lateral misalignments, or
- An allowable stable lateral deflection.

A thermal load corresponding to a rail temperature increase above neutral of $\Delta T = 50^{o}$F will be assumed in the evaluation of permissible net axle loads (although higher values of ΔT are easily incorporated into the safety limit development).

The net axle load limits based on the Zero Residual Deflection criterion will be referred to here as Level 1 limits, whereas Level 2 limits will refer to those based on a chosen maximum permissible (stable) lateral deflection. Level 1 limits are more conservative than Level 2 limits, and have some partially proven practical basis from high-speed rail applications in Europe and Japan. Level 2 type limits may be more applicable to high speed operation on systems such as the North East Corridor in the US where existing operational requirements and mixed mode traffic conditions dictate the acceptance of "larger allowable" lateral alignment defects. The Level 2 type limits proposed here should be considered as preliminary and need additional development for the specific operating conditions and parameters. For further discussions on track shift mitigation criteria, refer to [11].

6.1 Level 1 Limits (Elastic Deformation/No Residual Deflections)

Level 1 limits are generated for the parameters shown below:

Axle Load, V = 37.4, 28 kips
Lateral Resistance = 2000 to 4000 lbs/tie
Tie Spacing = 24 in.
Foundation Modulus = 6000psi
Rail Section = 136#AREA
Tie-Ballast Friction Coefficient = 0.8
Curvature = 0, 2, 4 deg
Temperature Increase, $\Delta T = 50^{o}F$
Net Axle Load Wavelength, λ = 20, 40, 60 ft and ∞ (constant NAL)

The results for V = 37.4 kips (166kN) is shown in Figure 6.1a. The results for all lateral load wavelengths are shown in the same figure, for convenience. The peak permissible net axle force ratios are plotted as function of the lateral resistance. The 2000 lbs/tie resistance corresponds to a weak (tamped) track, whereas the 4000 lbs/tie resistance is assigned to a moderately strong (consolidated) track.

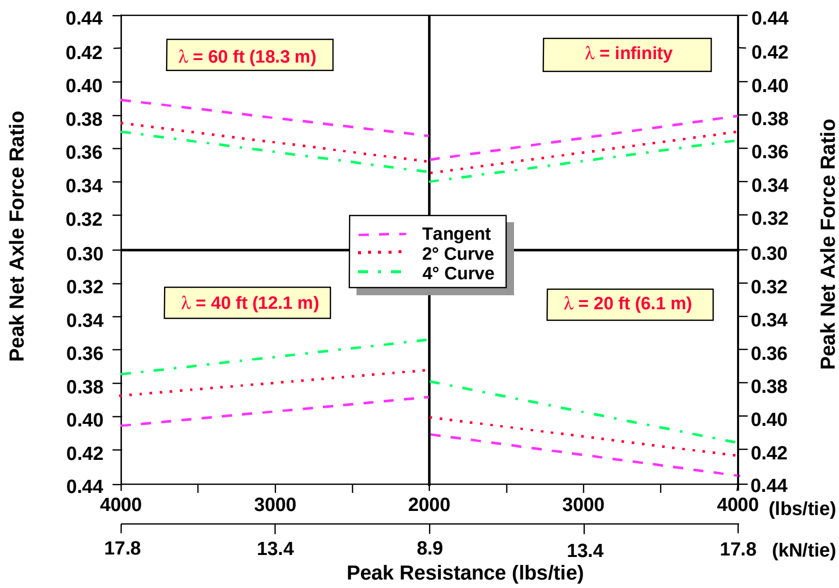

Figure 6.1a Level 1 track shift limits: allowable peak net axle load ratios based on zero residual deflection and V=37.4 kips

Similar results for V = 28 kips (125kN) are shown in Figure 6.1b. It can be seen that permissible (NAL/V) values *increase with reduced axle vertical load*. Although this result is not unexpected, it does highlight the importance of the correct choice of axle vertical loads for track shift analyses, safety limit determinations, and for testing purposes. *Hence track shift limits are not purely L/V dependent, but V is also an important parameter.*

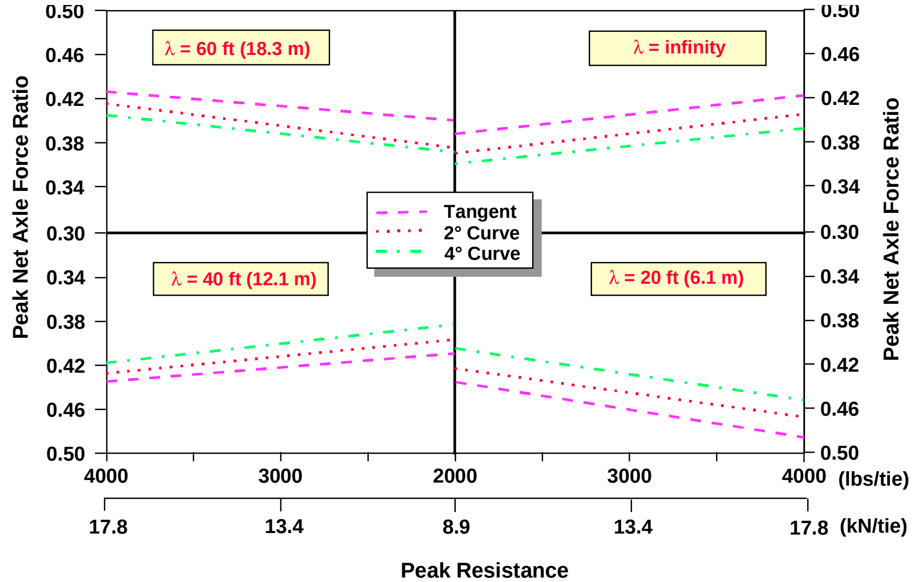

Figure 6.1b Level 1 track shift limits: allowable peak net axle load ratios based a zero residual deflection and V=28 kips

6.2 Level 2 Limits (Allowable Stable Residual Deflections = 5mm)

Level 2 limits are shown in Figure 6.2 for the same parameters as before for the constant lateral load case (i.e $\lambda=\infty$). These limits are based on the net axle loads which produce a stable 5 mm growth in lateral deflection. (*Note that for Level 2, finite λ cases are not considered because of the inherent assumption that the development of the 5mm permissible misalignment initiates from an initially non-misaligned track. In contrast, finite λ cases have been included in the development of Level 1 limits, since the existence of "small" initial misalignments is an apriori assumption. The caveat, however, for Level 1 is that these small initial misalignments are not allowed to grow under the vehicle passes (i.e the application of the zero residual deflection criterion prohibits this growth).* Note that Level 2 NAL/Vs are higher than for Level 1. It also should be noted that these limits coupled with the 5mm deflection should be verified through OMNISIM and other models to ensure that other potential failure modes (such as wheel climb, gage widening and buckling) are not created by this misalignment.

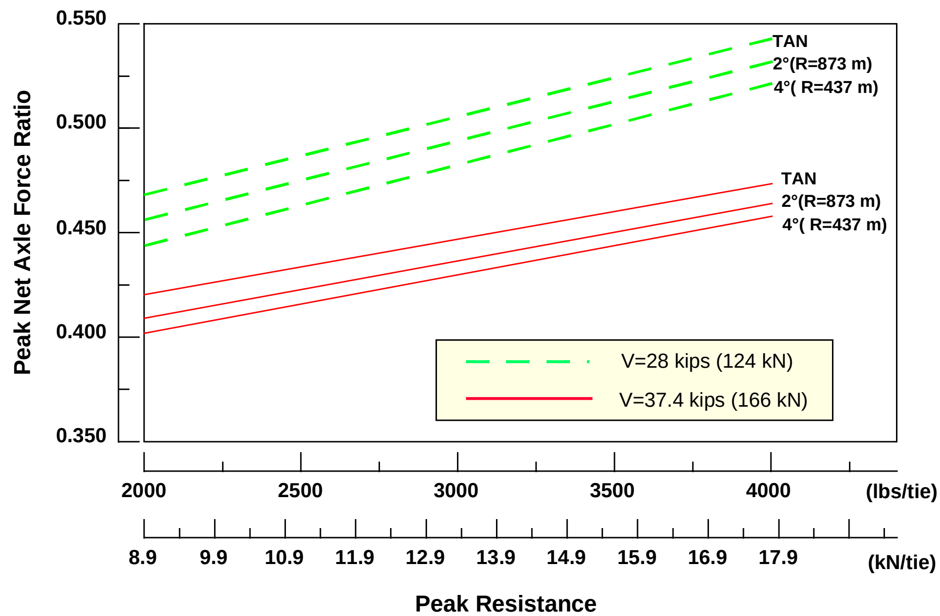

Figure 6.2 Level 2 track shift limits: allowable net axle load ratios based on 5mm stable residual deflection

6.3 Comparison with Existing Limits

The Prud'homme criterion (see Section 2.5) to eliminate or mitigate track shift under vehicle and thermal loads is widely accepted by foreign railroads. Although the criterion was empirically developed using the test data on newly constructed wood-tie track, it has been adopted for other track types and constructions. The criterion has the same aim as the Level 1 limits presented here, namely the allowable net axle loads should not contribute to track residual deflection. Inspection of Figures 6-1a and 6-1b shows that the Level 1 limit is found to be close to the Prud'homme limit (especially for the worst case scenario of F_P = 2000lbs/tie, 4° curve, and $\lambda=\infty$). Note that the Level 1 limit in Figures 6.1a and 6.1b, are for concrete-tie track parameters, while for a more correct Prud'homme comparison, these Level 1 limits should be recomputed for wood tie parameters.

The advantages of the Level 1 and Level 2 type limits proposed here are:

- The limits are readily extendible to different track types, constructions, parameters, and operating conditions
- The limits are based on a rational theory using both constant and variable (NAL/V) characteristics
- Level 2 limits may provide greater flexibility to the railroad operators.

7. CONCLUSIONS

1) The track shift mechanism has been identified as a moving load problem with many influencing parameters. The key elements of the mechanism include the interaction of the vehicle with the track to produce the loads, and the initiation and progressive growth of track lateral deflections under the repeated application of these loads. Important parameters for the net lateral to vertical load ratio (NAL/V) determination include the vehicle characteristics and operating speeds, wheel/rail rolling contact geometry/mechanism, track curvature, initial line defect, and track compliance characteristics. Key parameters for the residual deflection analysis include the track lateral resistance, tie/ballast friction coefficient, track curvature, thermal loads, and initial misalignments.

2) The prediction of track lateral shift has been formalized into a coupled vehicle dynamics model and a track residual deflection model. The vehicle dynamics model computes the axle loads to be used as inputs to the track residual deflection model which predicts the cumulative deflections as functions number of passes. Key features of this model include the constant versus variable moving axle loads, thermal loads, and curvature influences. Baseline validation studies on the track shift model showed very good agreement between model predictions and tests.

3) Parametric studies performed with the track shift model showed the following important results:

    - The tie-ballast friction coefficient is a key influencing parameter for it controls the tracks vertically loaded resistance. This coefficient's variation has a significant influence on track shift.
    - Rail temperature increase over its neutral has an appreciable influence on the curved track's lateral residual deflection response. Depending on curvature, 20-40% increases in the residual deflection can result by a temperature differential of 50°F(28°C).
    - The lateral resistance of ties in the ballast is an important parameter in controlling the track shift. The lateral resistance of highly consolidated CWR concrete tie track (4,000 lbs/tie) will reduce the track shift levels to about 50 percent of the value for the tamped track at half the resistance (2,000 lbs/tie).

- Net axle force levels have significant influence on track lateral shift. For NAL/Vs approaching 0.5, progressive track shift can occur. The *vertical load component* within the ratio also is important.

- When the net axle load is not constant (such as when an axle is negotiating a misalignment), the potential for track shift is governed by both the peak value and the load wavelength.

4) Prototype track shift mitigation criteria has been developed based on Level 1 and Level 2 type safety limits. Level 1 limits are based on "allowable" NAL/Vs to produce no residual deflection. The less conservative Level 2 limits are based on NAL/Vs to produce a finite, stable residual deflection.

5) Level 1 type limits are illustrated for vertical axle loads of 28 and 37.4 kips, for concrete tie track with unloaded track lateral resistances of 2000 to 4000 lbs/tie, friction coefficient of 0.8, curvatures of 0^o, 2^o and 4^o, and lateral load wavelengths of 20 ft, 40 ft, 60 ft and ∞. The infinite wavelength load case represents constant NAL/V. The lower end of these Level 1 limits tend to approach the Prud'homme limit.

6) Level 2 limits are illustrated for a chosen stable residual deflection amplitude of 5 mm. These type limits are envisioned to provide more flexibility for high-speed operations especially with high cant deficiency requirements, (resulting in higher L/Vs). This "controlled track shift" approach, however, may require more stringent inspection and maintenance practices.

REFERENCES

1) Kish, A. and W. Mui, “A Brief Synopsis on the Track Lateral Shift Problem”, American Railway Engineering Association Bulletin, No. 746, May 1994

2) Samavedam, G., A. Kish, A. Purple and J. Schoengart, “Parametric Analysis and Safety Concepts of CWR Track Buckling”, DOT/FRA/ORD-93/26, December 1993

3) Kish, A. and G. Samavedam, “CWR-BUCKLE”, Version 2.00 and User’s Guide, August 1996

4) Samavedam, G., “Theory of CWR Stability”, ERRI D202/RP3, February 1995

5) Samavedam, G., F. Blader and D. Thomson, "Track Lateral Shift: Fundamental and State-of-the-Art Review," DOT/FRA/ORD-96, February 1996.

6) Prud'homme, A., "Resistance of the Track to Lateral Loads Exerted by Rolling Stock," Revue Generale des Chemins de Fer, January 1967.

7) "Measurements of the Lateral Strength of the Track," SNCF Draft Report E. 1210 - 91 - 02, June 1991.

8) Cervi, G., "High Speed Rail Track Structure Design and Maintenance, "Transportation Research Board, Annual Congress, January 1994.

9) Samavedam, G., F. Blader, D. Wormley, M. Snyder, J. Gomes and A. Kish, “Analysis of Track Shift Under High Speed Vehicle-Track Interaction”, DOT/FRA/ORD-97/02, May 1997

10) OMNISIM (Version D), “Program and User’s Guide”, 1998, US DOT/FRA Software (to be published)

11) Kish, A., Samavedam, G., and D. Wormley, “Recent Investigations on Track Lateral Shift Limits For High-Speed Rail Applications”, Proceedings of World Congress on Railway Research, 1997, Volume B, pp. 41-49

ACKNOWLEDGEMENT

The authors would like to gratefully acknowledge the sponsorship and support of the Federal Railroad Administration’s Office of Research and Development, notably Steven Ditmeyer, Director, Claire Orth, Chief, Equipment & Operating Practices and Magdy El-Sibaie, Chief, Track Research Division. Also thanks are due to Dr. Mark Snyder for his tedious efforts on the track shift program development, to Drs. Herbert Weinstock and Fred Blader for counseling on vehicle/track interaction dynamics, and Messrs. Wesley Mui and John Gomes for the conduct of the various parametric analyses.