New Track Shift Safety Limits For High-Speed Rail Applications

Andrew Kish
Manager, Guideways and Structures
USDOT/Volpe Center, Cambridge, MA, USA
Telephone: 617- 494-2794
Facsimile: 617- 494-3616
E-mail: kish@volpe.dot.gov

Gopal Samavedam
Division Manager, Structures & Transportation Division
Foster-Miller, Inc, Waltham, MA, USA
Telephone: 617-684-4275
Facsimile: 617-890-3489
E-mail: gsamavedam@foster-miller.com

David Wormley
Dean, College of Engineering
Penn State University, University Park, PA, USA
Telephone: 814-865-7537
Facsimile: 814-863-4749
E-mail: dnwdo@engr.psu.edu

ABSTRACT

The analytic development of the fundamental mechanics of track lateral shift due to vehicle and thermally induced loads for the determination of *"allowable limit"* loads on the track to prevent progressive lateral shift was presented in an earlier work [1]. This paper presents the results of a follow-on study on improving and validating the model, and applying the analytic and experimental results to the development of new track shift limits for high-speed rail applications. Specifically, this paper reviews current European and US standards for track lateral shift, provides a description of the TREDA analysis model to predict residual track lateral deflections under multiple axle passes, discusses results of recent model verification studies based on field tests at the US DOT's Transportation Technology Center, and applies the model to develop elastic limit based (Prud'homme type) "allowable lateral loads" to prevent excessive lateral shift. It is shown that for a set of fixed track parameters these allowable loads are dependent on curvature, thermal load, vertical axle loads, and on the nature of the lateral forces generated (i.e. constant versus variable). Parametric studies show that the classical Prud'homme limit tends to be conservative. Additionally, the paper presents a prototype system for monitoring in-service net axle lateral forces through wayside and vehicle borne instrumentation. The work presented here is part of the US DOT/Federal Railroad Administration's research efforts to develop the technical information required to establish *"safe"* operating practices for high-speed rail service.

1.0 INTRODUCTION

Track shift is defined as the permanent lateral distortion of a track segment, which can occur due to vehicle induced lateral loads. The permanent lateral distortion can occur cumulatively under many vehicle passes, or can occur suddenly under a single or a few number of passes. Track shift can occur locally or can be spread over a long section of track. The latter is caused in weak curved tracks when a steady-state curving forces are exerted by the vehicles, especially when accentuated by compressive thermal load in the rails. The local shift is caused by vehicles negotiating a pre-existing irregularity. Track shift can also be caused by loads resulting from vehicle hunting. Excessive track shift can lead to unsafe conditions leading to ride quality deterioration, track buckling, or vehicle derailment. The key issues related to track shift can be summarized as follows:

- In the design and maintenance of modern high-speed track, adequate track lateral strength must be assured to withstand vehicle and thermal loads. Track shift mitigation is one primary consideration in establishing and maintaining the required lateral strength.

- Track shift should be eliminated (or controlled to occur at a slow rate with respect to the traffic tonnage) so that periodic track inspection, realignment and other maintenance operations can be performed in an economical manner.

- Vehicle designers must know the allowable track shifting forces to limit vehicle loads and speeds. Vehicle qualification must include acceptance tests for vehicle lateral loads generated on typical track segments.

- For high-speed corridors where tracks (with curvatures and high superelevations) already exist, it is necessary to define the maximum safe speeds for high-speed train operations. Although the speed limits for conventional vehicles are decided from considerations of ride comfort, new high-speed corridor train set designs may need more stringent limits, requiring a better control of the track shift potential.

A state of the art review on the subject of track shift is presented in Reference [2]. This review revealed that there were no adequate analyses and safety limits to cover the variety of track conditions typically found in revenue service. A rigorous analysis [3,7] has therefore been developed under the sponsorship of the Federal Railroad Administration's Office of Research & Development through the Volpe Center, based on which prototype concepts and safety criteria for track shift have been developed [1]. Recently the analysis has been modified and improved by a more accurate modeling of the *"stick-slip"* hysteresis response characteristic, and by the use of the non-linear tie/ballast friction coefficient parameter. This advanced model was validated through a set of full-scale field tests conducted at the US DOT's Transportation Technology Center [4]. The overall objective of this document is to develop appropriate safety limits for track shift prevention applicable to high-speed tracks based on this new analytic and experimental work. The current applicable standards and the need for continued research to develop improved safety standards are discussed in the following section.

1.1 Current Standards

i. The European Standard

Prud'homme developed an empirical expression for the maximum permissible net axle lateral loads on a track based on testing. The Prud'homme limit on the net axle load for the tangent track is:

$$\mathbf{L/V = 2.25/V + 0.33} \qquad \text{(L,V in kips)}$$

Prud'homme proposed a factor of 0.85 on the above limit to account for curvature and thermal loads. The SNCF uses this formula to limit the loads exerted by their vehicles.

The Prud'homme formula has been widely used, despite some railways concern over its potential conservatism. Prud'homme established his formula such that the vehicle will not generate any lateral misalignment or track shift for an indefinite number of axle passes. At loads higher than the Prud'homme limit, the track may accumulate residual lateral deflection which can grow to unsafe levels if timely maintenance is not performed. The track lateral defects do tend to grow under the high-speed traffic due to a variety of other factors, including the possible exceedance of the Prud'homme limit. According to [5], the peak-to-peak lateral defects in a TGV track cannot exceed (8mm) 0.31", at which level realignment and maintenance is required. If the deflections exceed (12 mm) 0.47", the track is unfit for revenue service and requires repair. Other railroad organizations such as in Great Britain, Japan and Germany do not have any formula for allowable net axle loads on the track, other than the Prud'homme limit. Some of these organizations do use the Prud'homme limit for vehicle qualification.

ii. The United States Minimum High-Speed Safety Standard

The US DOT's Federal Railroad Administration (FRA) in its new high-speed track safety standards [6] specifies that high-speed equipment be qualified on its intended route and that measurements of wheel/rail forces must be measured in a representative vehicle on an annual basis. One of the vehicle/track interaction safety limits is that the specified equipment may not exceed a net axle lateral to static vertical load ratio (L/V) of:

$$\mathbf{L/V = 0.5}$$

In 1998, during the development of the high speed standards, a group of technical experts recommended the 0.5 limit for L/V primarily based on the conservative Prud'homme limit and the results of high speed testing of the X-2000 and ICE trains on the Northeast Corridor. The Federal Track Safety Standards, including the high-speed safety standards, establish minimum safety limits. Railroads are expected to establish maintenance limits well above these minimum levels. The 0.5 limit was used for the recent qualification of Amtrak's Acela high-speed trainsets.

iii. Need and Approach for Improved Standards

There is a need to review the current US standard on the allowable net axle load limit in light of new technical developments. There is also a need to re-examine the Prud'homme formula since it was derived over three decades ago by testing relatively weak tracks compared to the modern high-speed tracks. Furthermore, Prud'homme considered the case of constant lateral force only, whereas lateral forces with high peaks over short wavelengths can occur in field conditions. An improved limit is therefore required to better understand the margins of safety under high-speed operating conditions. Such new limits are proposed here based on recent research which involved the development of an improved version of the track residual deflection analysis model (TREDA), the conduct of full scale validation tests at the Transportation Technology Center (TTC), Pueblo, CO, and the conduct of parametric sensitivity analyses to establish appropriate safety limits.

1.2 Objectives

The subsequent sections will:

- Describe the capabilities of TREDA, its validation, and its application to developing track shift safety limits

- Develop and present track shift safety limits for a modern high-speed track using TREDA, which account for both uniform and non-uniform loading scenarios, and curvature and thermal effects.

- Develop baseline concepts for safety compliance via monitoring the vehicle induced net axle lateral forces.

2. TREDA MODEL

2.1 Model Parameters

TREDA, short for **T**rack **RE**sidual **D**eflection **A**nalysis, is a generalized track model that uses several parameters in the quantification of track lateral response behavior as described in [1,3,7]. The key parameters include:

- Lateral ballast resistance
- Tie-ballast friction coefficient (as a function of vertical load and the number of passes)
- Tie-ballast hysteresis (loading/unloading behavior) under cyclic load
- Rail section properties
- Rail temperature differences from neutral representing the thermal load
- Track curvature
- Initial misalignments
- Axle vertical and lateral loads, and
- Vertical foundation modulus

2.2 Model Capabilities

TREDA can consider the following loading scenarios:

- Single or multiple axle vertical loads
- Net axle lateral loads at single or multiple axles
- Net axle lateral loads varying sinusoidally (or other prescribed wave shape over a finite length)

The TREDA output is in the form of residual deflection versus the number of axle passes. From the output, the nature of the track shift characteristic as well as the deflection level can be determined. The TREDA program software and User's Guide is presented in [7].

2.3 Model Validation

Predictions and data from recent tests conducted on wood and concrete tie tracks to determine track shift due to vehicle passage are presented in Reference [4]. Two fundamental parameters that are critical to the track shift phenomenon, namely the elastic recovery and the tie-ballast friction coefficient, are briefly reviewed below:

i. <u>Elastic Recovery:</u> Track shift represents permanent residual lateral tie deflections in the ballast due to the cyclic lateral loads on the rail from the axle passage. Figure 1 shows the tie lateral resistance characteristic under cyclic loading. The solid line OEB represents the (lateral) loading path, whereas BDC represents the unloading path. The loaded displacement at B is partially recovered when the tie is unloaded to C. The displacement at C, denoted by w_r, is the permanent residual deflection representing track shift in one cycle of loading and unloading. The component w_e, representing the difference between the loaded deflection at B and the residual deflection at C, is defined as the elastic recovery. Clearly, if the tie is loaded up to any point on the line OE and then unloaded, the residual displacement is zero and the loaded displacement is completely recovered. The point E represents the "yield point" (or limit of elastic displacement), beyond which the track begins to accumulate residual deflection. If the tie is reloaded at the point C, the reloading path is along CB′ and the residual deflection after unloading is denoted by C′. The elastic recovery after this second cycle is the difference between the deflections at B′ and C′. In a similar manner the residual deflection and the elastic recovery for subsequent cycles can be constructed.

   A number of experiments dealing with wood and concrete tie response under cyclic loads were performed at TTC, based on which a linear relationship was developed between the elastic recovery and the residual deflection of the ties. This is shown in Figure 2 where the initial value of w_e at zero residual deflection is at 0.03"(0.8 mm) (denoted by w_{e1}) for both wood and concrete ties, however the slopes are different. Examination of single tie push test (STPT) data shows that w_{e1} values typically fall in the range of 0.005" (0.13 mm) to 0.03" (0.8 mm). It can be further shown that w_{e1} values have a significant influence on the track shift response since they control the magnitude of the residual deflections. As w_{e1} increases the corresponding residual deflections decrease as a function of train passes for the same L/V. Conversely, the *"allowable"* L/V to produce the onset of non-zero deflection (corresponding to the safety limit criteria defined later) decreases. Parametric studies [4] also show that the initial value influences the track shift response at small displacements whereas the slope influences the response at large displacements.

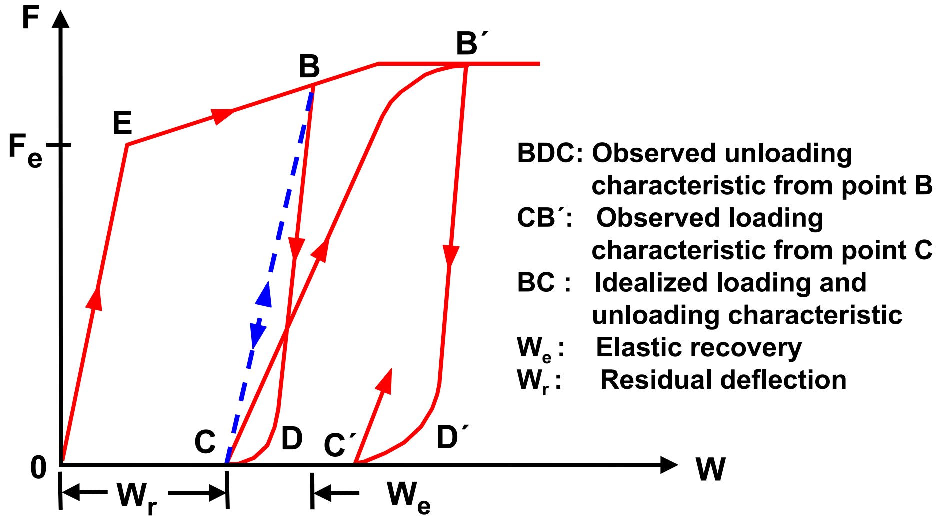

Figure 1. Definition of elastic recovery and residual deflection

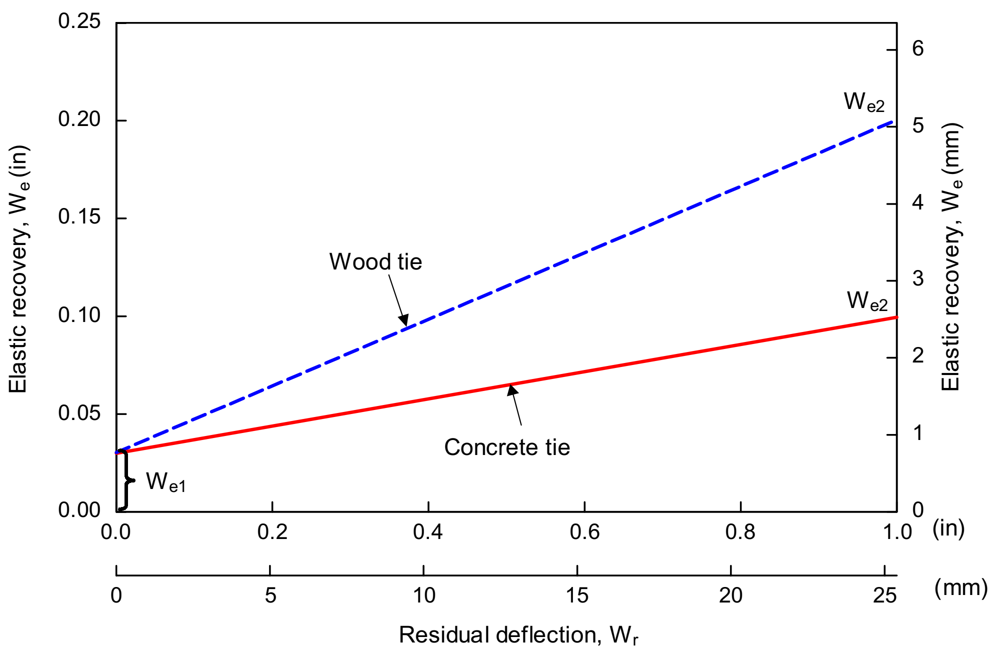

Figure 2. Elastic recovery as a function of residual deflection

ii. Friction Coefficient: The tie-ballast friction coefficient represents the vertical load influence on the lateral resistance. This coefficient's dependence on vertical load has also been determined by tests at TTC, and the result is represented in Figure 3. For analytic purposes the resulting curves are fitted by the following equation:

$$\mu = \mu_2 + (\mu_1 - \mu_2)e^{-\beta R}$$

where R is the vertical load on the tie, μ_1 represents the friction coefficient at zero vertical load, while μ_2 represents the coefficient at large vertical loads (>20 kips) or (>89 kN) . The values of the constants are shown in Table1.

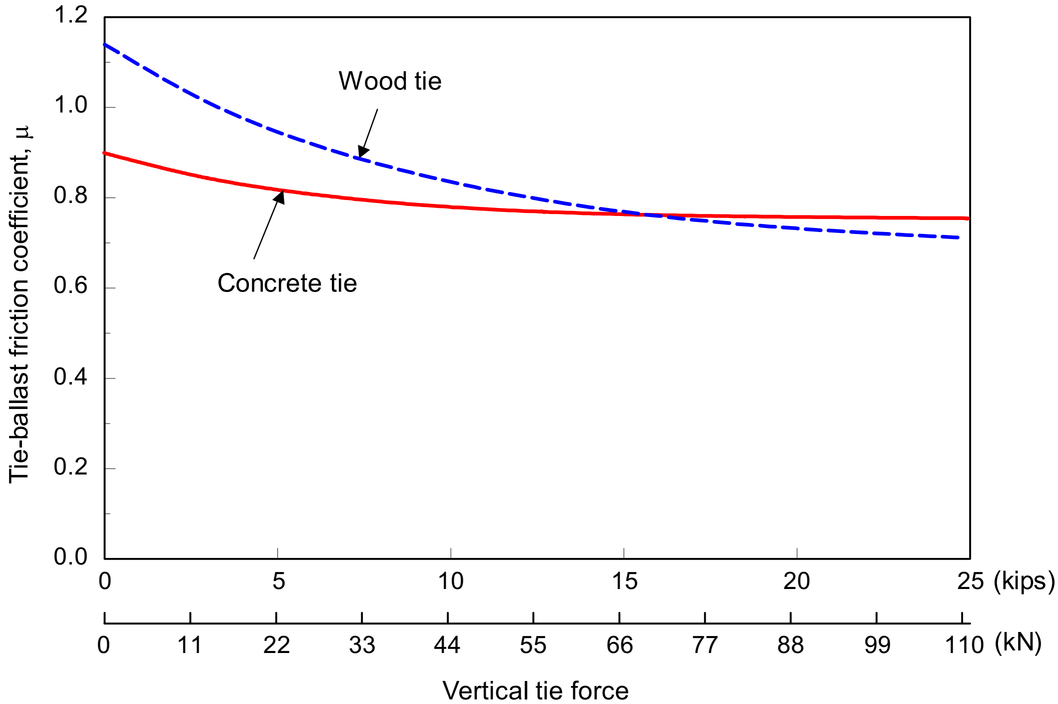

Figure 3. Tie-ballast friction coefficient as a function of vertical tie force

Table 1. Values of constants for wood and concrete ties

	μ_1	μ_2	β(1/Kip)	β(1/kN)
Concrete Tie	0.9	0.75	0.16	0.71
Wood Tie	1.15	0.68	0.11	0.49

In addition, as part of the degradation mechanism, the values of μ_1 and μ_2 are assumed to decrease with the number of load passes due to ballast shear and wear under the vertical loads and cyclic tie lateral movements. The percentage reduction in these constants is calculated to be 0.05% per pass or 5% for 100 passes (after tie movement had occurred) which gives the correct trends observed in the experiments. It must be noted that this reduction in the tie-ballast friction coefficient does not imply reduction in the static (without wheel load contribution) tie resistance. The static value is known to increase with the level of consolidation. This increase is not accounted here and is not considered to be significant for the number of passes involved since it is only a static resistance. Furthermore, the dynamic resistance of the tie (contributed by the wheel load) is much higher than the static value, and is controlled by the tie-ballast friction. The theory proposed here assumes that the dynamic resistance of the tie in the ballast decreases slightly with each pass due to the reduction in the friction coefficient, and the dynamic resistance is a substantial portion of the total resistance of the track under moving vehicle loads.

iii. Test Correlations: Tests were conducted at the Transportation Technology Center (TTC) using the AAR's Track Loading Vehicle (TLV) to exert lateral and vertical loads on the track. The axle vertical load was set at 55 kips (245 kN) (typical of a high speed trainset's power car). Other measured site-specific parameters are shown in Table 2. The residual deflection test results are shown in Figures 3 and 4 for the wood and concrete tie tracks respectively. The TREDA predictions are also shown. The following conclusions are drawn from the test to theory comparisons:

- The test data in the figures represents the average of 12 to 15 tie lateral deflections. There is non-uniformity in the individual tie lateral deflection data. Some of the ties show negligible deflection, while others twice the average value. It is possible that individual ties behave differently, hence an average is required for theoretical comparisons.

- Both the theory and the test data indicate that the residual deflection tends to increase almost in a linear manner after some initial passes.

- For small L/V (≈ 0.4), the theory predicts no residual deflection, whereas the test shows small deflections 0.05 in. or (1.3 mm) which can be considered to be negligible.

- For the cases tested, the general agreement between the theory and test is considered to be good.

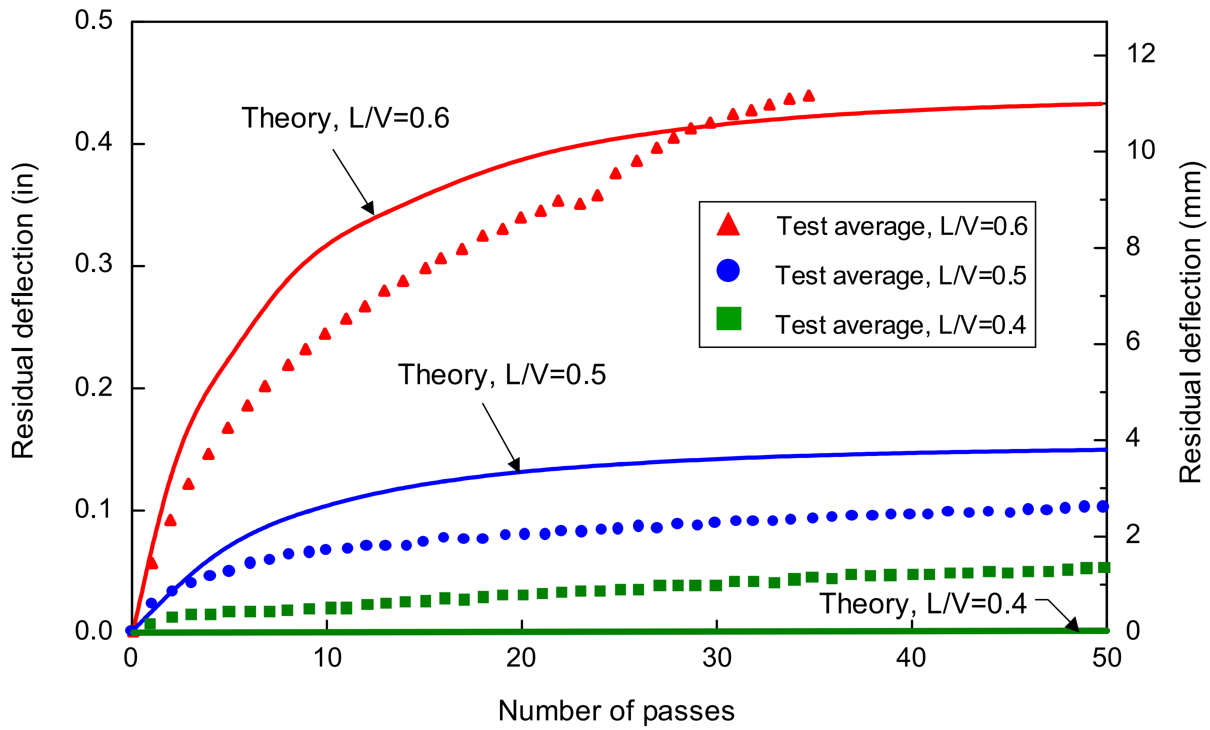

Figure 4. Residual deflection of wood ties versus number of passes

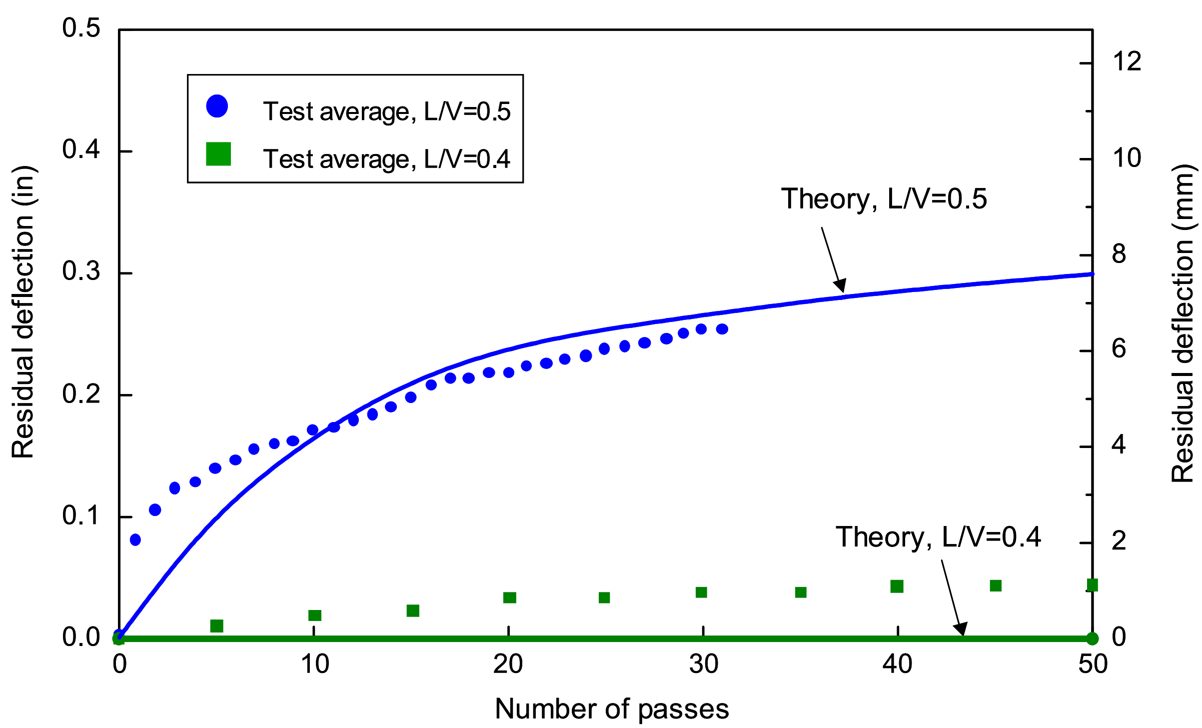

Figure 5. Residual deflection of concrete ties versus number of passes

Table 2. TREDA input parameters for test conditions

Parameter	Wood Tie Track	Concrete Tie Track
Axle Load, V	55 kips (245 kN)	55 kips (245 kN)
Tie Spacing	20 in. (508 mm)	24 in. (610 mm)
Foundation Modulus	10868 psi (75 MPa)	10000 psi (69 MPa)
Rail Section	AREA136	AREA136
Curvature	Tangent	Tangent
Temperature Increase, ΔT	0^{o}F (0°C)	0^{o}F (0°C)
Net Axle Force Ratio	0.4 to 0.6	0.4 to 0.6
Peak Lateral Resistance (F_p)		
L/V = 0.4	1637 lbs (7.3 kN)	3500 lbs (15.6 kN)
L/V = 0.5	1637 lbs (7.3 kN)	2387 lbs (10.6 kN)
L/V = 0.6	2150 lbs (9.6 kN)	2875 lbs (12.8 kN)
Deflection at Fp (w_p)		
L/V = 0.4	0.34 in. (8.6 mm)	0.39 in. (9.9 mm)
L/V = 0.5	0.34 in.(8.6 mm)	0.40 in. (10.2 mm)
L/V = 0.6	0.42 in. (10.6 mm)	0.40 in. (10.2 mm)
Elastic Resistance (F_e)		
L/V = 0.4	1000 lbs (4.5 kN)	1500 lbs (6.7 kN)
L/V = 0.5	1000 lbs (4.5 kN)	1500 lbs (6.7 kN)
L/V = 0.6	1000 lbs (4.5 kN)	1500 lbs (6.7 kN)

Note: Elastic recovery and friction coefficient parameters are assumed as shown in Figures 2 and 3.

3.0 SAFETY LIMITS

On the basis of the validated TREDA model, safety limits on the allowable net axle load to prevent track shift under the passage of high-speed trains have been derived for the baseline parameters indicated below. In exercising the TREDA model for the given vertical load, the lateral load is increased in steps until the track just begins to accumulate residual deflection (i.e. just beyond the elastic limit value) with increasing number of passes. This is the baseline criterion for the track shift safety limit determination.

3.1 Safety Criteria

The safety criteria for track shift mitigation is based on the performance requirement that *lateral loads generated by high-speed vehicles operating under maximum speed, cant deficiency, thermal load, and initial line defect conditions should not produce any permanent lateral track displacements.* For numerical computational purposes, this translates to the determinations of the net axle L/V's (for a given track condition) which produce the onset of non-zero residual deflections under the influence of a large number of train passes. Figure 6 illustrates the procedure for the determination of the "allowable" L/V's for a vertical axle load of 55 kips (245 kN), 2º curve (R=873 m), and constant lateral load. As can be inferred from the figure, the limit of "safe" L/V is 0.37 for the case shown. Note that this criteria is the "elastic limit" or Level 1 Safety Limit presented in [1], where a Level 2 Limit concept is also postulated based on an *permissible finite lateral deflection*.

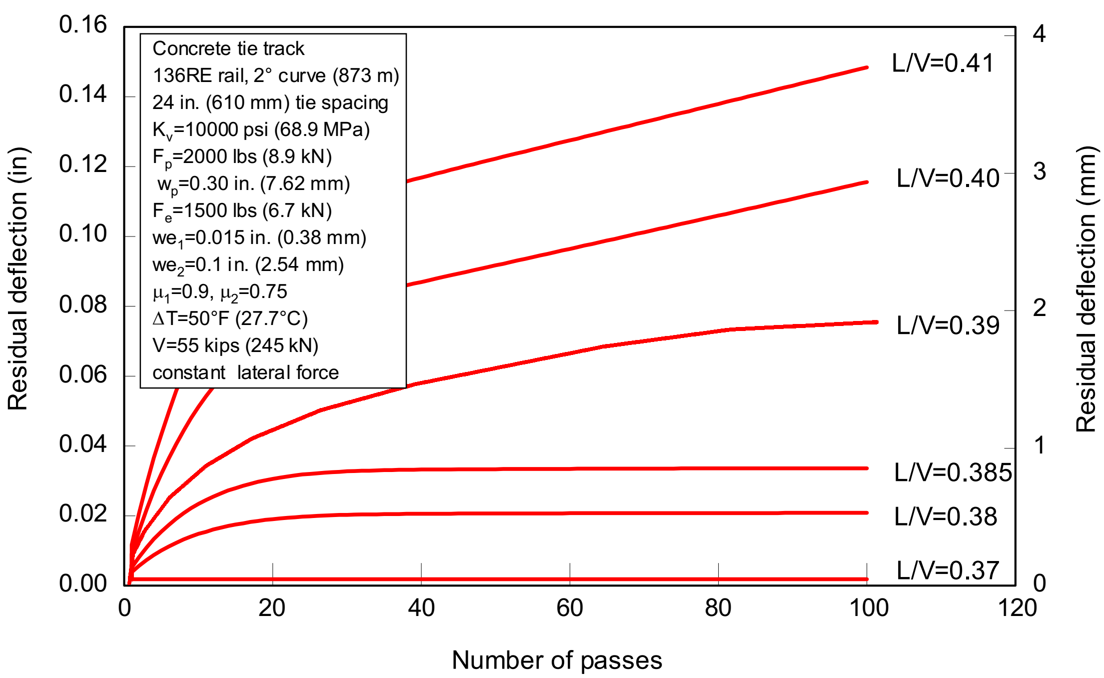

Figure 6. Safety limit concept illustration

3.2 Baseline Parameters For Safety Limit Determinations

i. **Lateral Resistance:** The peak lateral resistance, F_p, of a tamped concrete tie track is usually in the range of 2000 to 2400 lbs/tie or (8.9 to 10.7 kN/tie). A conservative value of 2000 lbs/tie or (8.9 kN/tie) is used for the limits developed here. The conventional tie spacing for US concrete tie track of 24 inches (610 mm) is assumed. In addition to the peak value of the lateral resistance, a key adjunct parameter (see discussion under 2.3i) is the elastic limit deflection, w_{e1}. Although the magnitudes of this parameter are *"small"* (typically range from 0.005 in. to 0.03 in.) or (0.13 to 0.76 mm), their influence on accrued residual deflections, hence on *"allowable"* L/V's, is significant. In the subsequent safety analysis the intermediate value of 0.015 in. (0.38 mm) is used.

ii. **<u>Vertical Modulus</u>:** The vertical modulus for concrete tie track is taken as 10000 psi (69 MPa) based on the data from US and European field tests.

iii. **<u>Curvature and Thermal Load</u>:** High-speed train operations are generally confined to *"low"* degree curves, hence safety limits are developed for tangent through 6° curves (R=291 m). A thermal load corresponding to a temperature differential of 50°F (28°C) over the neutral is assumed.

iv. **<u>Axle Loads</u>:** The axle vertical load is a critical parameter. The allowable lateral to vertical load ratio is presented as a function of the axle vertical load.

v. **<u>Lateral Load</u>:** The lateral load is assumed to be a constant. This case has shown to be the more conservative as opposed to the sinusoidal lateral load distributions which typically occur in the presence of lateral misalignments [1,4]. Also it can be shown that sinusoidal load wavelength of 80 ft (24.4 m) or above approximate the constant lateral load case.

vi. **<u>Initial Line Defects:</u>** For the baseline case, a good quality high-speed track alignment condition is assumed, namely that no initial line defects are present. For comparison purposes results are also shown for *a "slightly misaligned track condition",* namely for a 0.5 in. (12.7 mm) line defect within a length of 32 ft. (9.8 m)

3.3 Numerical Results

The limits are presented in Figures 7 to 10 for the above track conditions/parameters. Figures 7 and 8 show the results for the no line defect case, and Figures 9 and 10 with the assumed 0.5 in. (12.7 mm) within 32 ft (9.8 m) line defect. The Prud'homme limit is also shown on the figures for comparison (noting that for curved tracks and thermal loads Prud'homme's 85% value is applicable). The current FRA track shift limit of 0.5 is also indicated in the figures. Figures 7 and 9 present the allowable L/V ratio limits, whereas Figures 8 and 10 give the absolute lateral force limits with the corresponding linear best-fit equations.

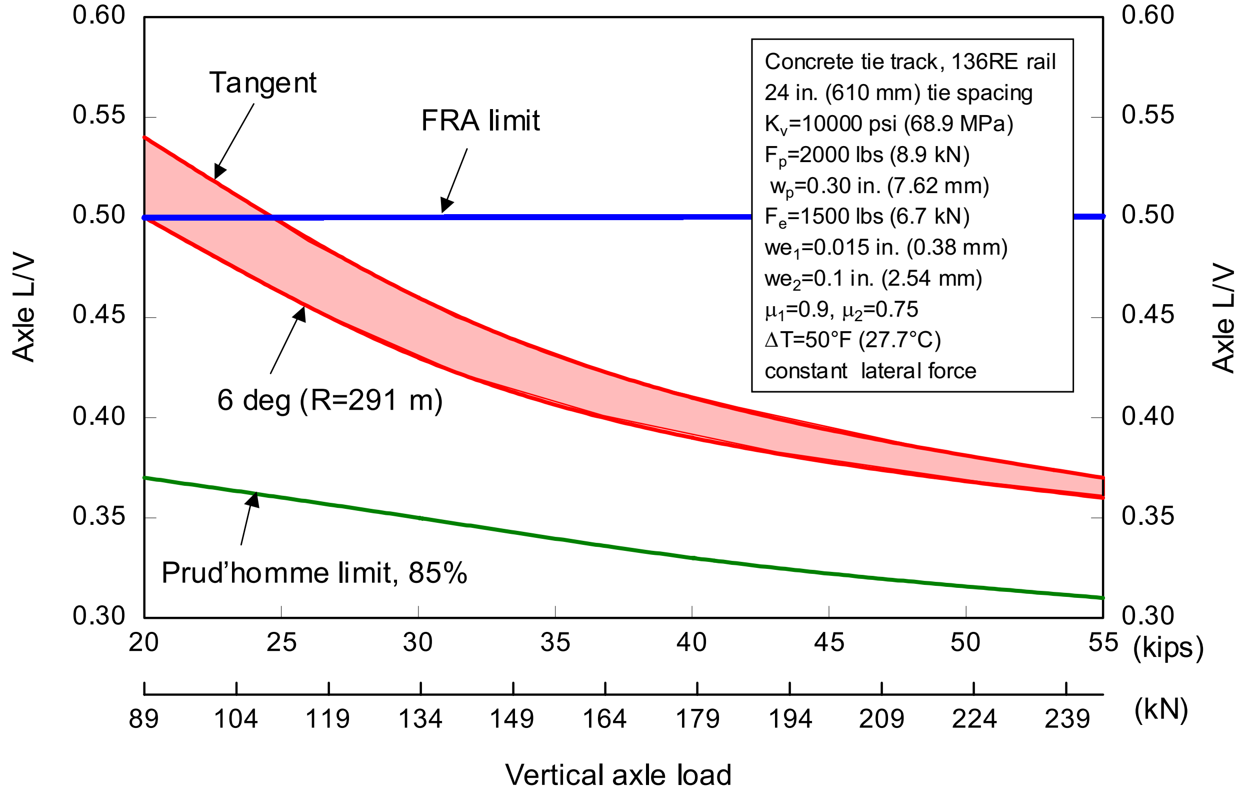

Figure 7. Allowable L/V limits as function of vertical axle load with constant lateral load

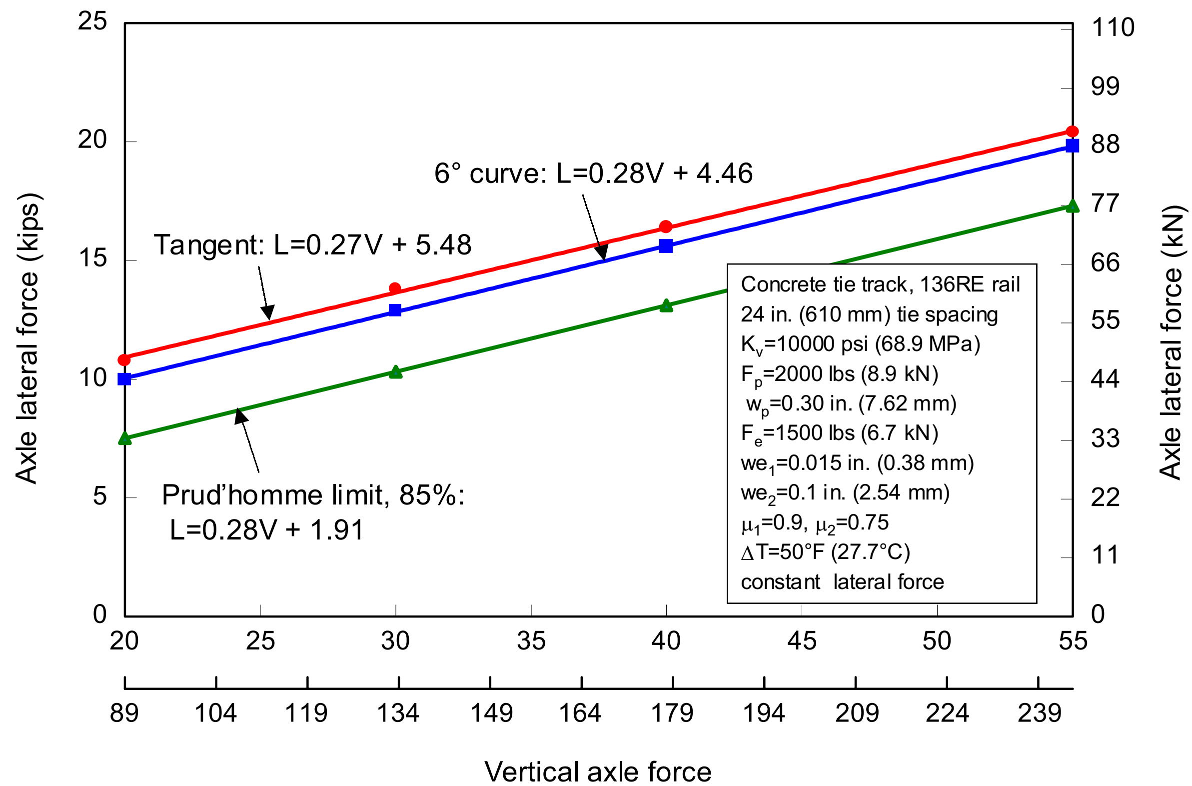

Figure 8. Allowable lateral force limits as a function of vertical axle load

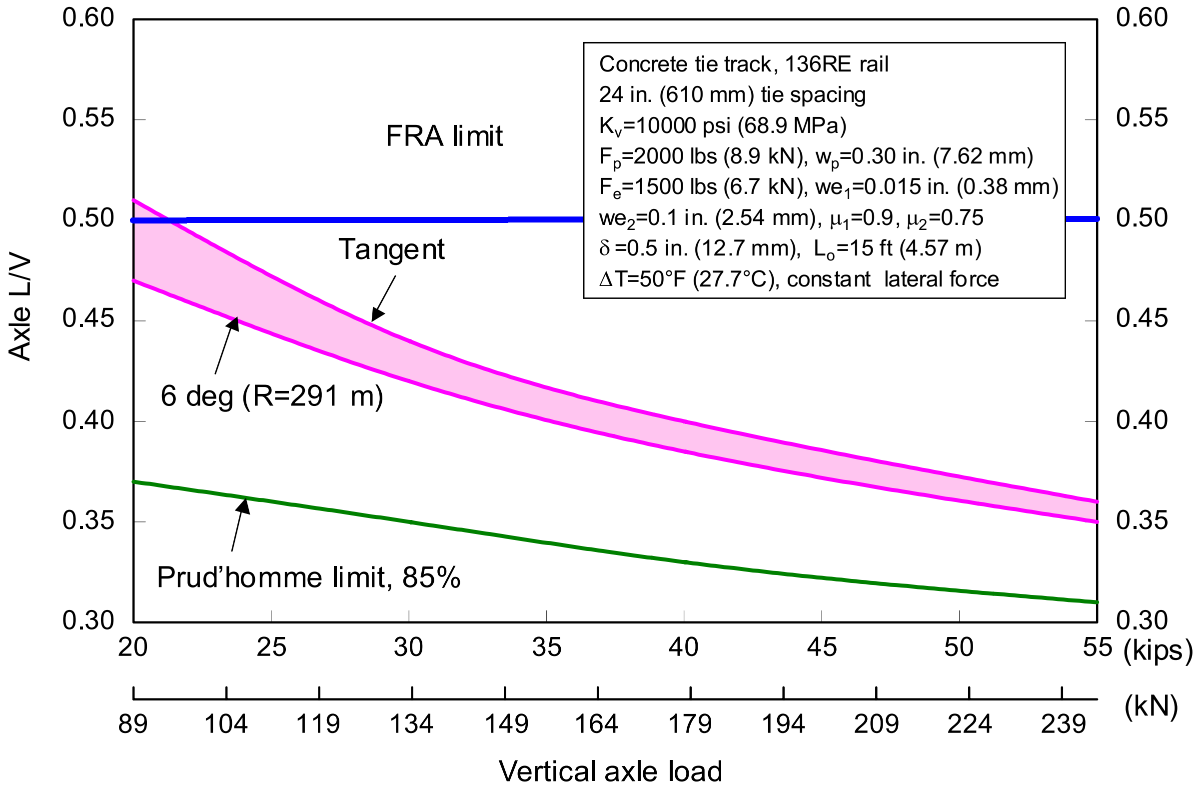

Figure 9. Allowable L/V limits as function of vertical axle load with constant lateral force and line defect

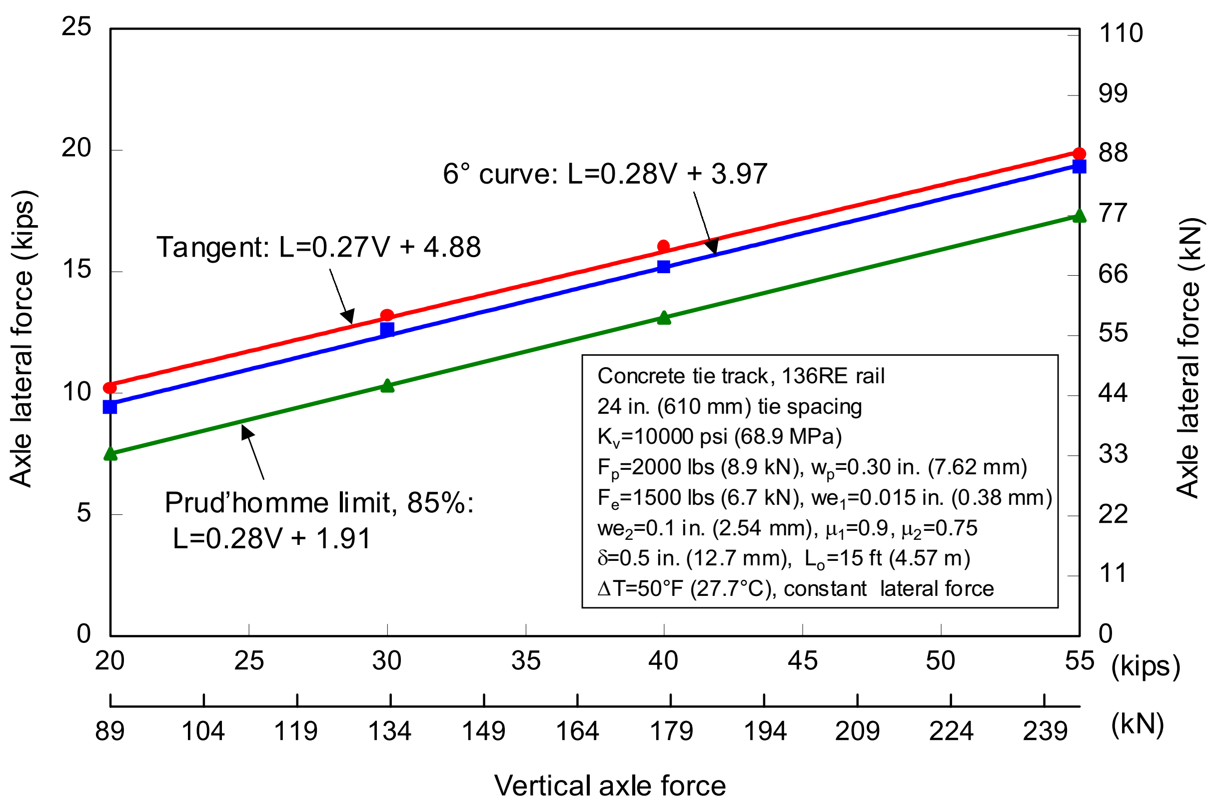

Figure 10. Allowable lateral force limits as a function of vertical load and line defect

3.4 Safety Limits for High Speed Rail Applications

Simplified limit(s) for application to high-speed train operations can be proposed from the safety limits data presented in Figures 7–10. If we assume that high-speed train operations are restricted to CWR with curvatures 6° (R=291 m) or under, then the results for 6° (R=291 m) can be used for all such operations, depending on the track's alignment defect condition. Hence from Figures 8 and 10:

$$\mathbf{L/V = 0.28 + 4.46/V} \qquad \text{(L, V kips, no alignment defect)} \qquad (1)$$

$$\mathbf{L/V = 0.28 + 3.97/V} \qquad \text{(L, V kips, with alignment defect)} \qquad (2)$$

These formulae may be compared with that of Prud'homme for curved tracks:

$$\mathbf{L/V = 0.28 + 1.91/V} \qquad (3)$$

Note that the slopes of the lines in the present analysis and Prud'homme formula are equal, but the intercepts on y-axis are at higher values, indicating higher allowables than given by Prud'homme in (3).

It is instructive to compare the results for different values of vertical axle loads. Table 3 shows the results for V = 20, 30, 40 and 55 kips (V= 89, 133, 178 and 245 kN). The results based on the current FRA specifications (L/V = 0.5) are also shown.

Table 3. Comparison of proposed net axle L/V limits to Prud'homme's and to current FRA limits

V (kips)	V (kN)	Present Formula		Prud'homme Formula Equation (3)	Current FRA specification
		Equation (1)	Equation (2)		
20	89	0.50	0.48	0.38	0.50
30*	133	0.43	0.41	0.34	0.50
40	178	0.39	0.38	0.33	0.50
55**	245	0.36	0.35	0.31	0.50

* Approximate values for a high-speed coach car
** Approximate values for a high-speed power car

The results in Table 3 illustrate the conservative nature of the Prud'homme limit. On the other hand, the comparison also suggests that the current U.S. panel shift limit of 0.5 may be less conservative at higher value of the axle load than previously thought. Further research activities are planned in this area to establish more definitive recommendations for possible revision of the current rule. Also, the current FRA specification does not account for the dependency of the permissible L/V on the vertical axle load. It should be noted that recent Acela train-set high-speed testing on the Northeast Corridor did measure L/V values of 0.35 – 0.40 for the power car [8].

It should be also noted that the track lateral shift test results (Section 2.3 and Figure 5) are also in line with the V=55 kips (245 kN) limits of Table 3. As the test results in Figure 5 indicate for a concrete tie track for a V=55 kips (245 kN), at an L/V=0.4 the track experienced some lateral deformation as a function of axle passes, hence the "allowable limit" should be somewhat below the 0.4 ratio. Table 3 gives 0.35 to 0.36 for this case.

3.5 Comparison with Prud'homme Limit

- Prud'homme developed his formula on the basis of test data on a weak wood tie track. TREDA is a validated theoretical model which can be applied for any type of track with known parameters.

- The Prud'homme formula is conservative. TREDA gives an allowable lateral load which is 32% larger than Prud'homme for the 20 kip (89 kN) axle load. For larger axle loads, the difference between Prud'homme and TREDA diminishes, but even in the case of a 55 kip (245 kN) axle load, the Prud'homme formula is conservative by about 16%.

- Prud'homme developed his formula (as well as the treatment here) for the *constant lateral load* case. If needed, TREDA can account for a variable lateral load distribution, as well as predict the track lateral response characteristics when the loads exceed the allowable limits presented here.

- Both Prud'homme limits and the proposed limits are based on the elastic limit criteria (i.e. after many wheel passes, the lateral deflections are limited to zero or negligible deformations only). However, TREDA can be used to develop track shift limits based on alternate criteria such as an "allowable finite residual deflection" after a number of passes.

4.0 SAFETY COMPLIANCE: *MONITORING NET AXLE LATERAL FORCES*

4.1 Monitoring Methods

Monitoring the vehicle generated lateral forces in the revenue service is an important part of assuring safe train operation. The following methods may be used in the assessment of the lateral forces on revenue lines:

i. Wayside Instrumentation System, (WIS)
ii. Instrumented Wheel Sets, (IWS)

Wayside instrumentation (WIS) involves vertical and lateral force measuring strain gages (or equivalent devices) affixed to the rails to give the wheel-rail forces at a specific location of the track where loads from all axles of all cars thus can be monitored. The system can also be remotely monitored as required. On the basis of the data from WIS, potential *"bad acting cars"* can be identified.

Use of instrumented wheel sets (IWS) is an accepted practice for measuring axle L/V's. The instrumented wheel set can be used to measure L/V's on a dedicated car with *"dynamic response characteristics that are representative of other equipment assigned to service"*, as indicated in the current FRA Track Safety Standards [6]. It should also be possible to perform some initial dynamic simulations to identify the worst "actor" cars for which the instrumented wheel set can be used and to anticipate the highest L/V for permissible track geometry variation in the revenue conditions.

Both types of systems (IWS and WIS) are recommended for monitoring the high-speed train-set loads. The WIS identifies bad wheels/cars in the train consist, whereas the IWS can identify bad track conditions. The frequency of track inspection using the IWS for track shift safety depends on the level of lateral loads generated, the track type/ condition, and other parameters. If the lateral loads generated are under the limit proposed here, then an indefinite number of vehicle passes can be allowed and the inspection interval may be based on issues other than track shift. If however, the lateral load has exceedences over the proposed limits, then special track geometry measurements at these locations will be required to detect potential track anomaly conditions causing the exceedences. If the allowable limits are exceeded, then one or more of the following remedial actions can be taken for assurance of safety:

a. Reduce operational speeds at the locations:

The speed reduction is a potential solution to reduce high lateral loads. Using the theoretical basis such as the one in the OMNISIM vehicle dynamics model [9], one can reduce the speed (almost in proportion of the square root) to reduce the peak lateral load to the desired level. However, this solution may not be satisfactory for real time implementation, hence the following alternatives may need to be followed.

b. Fix Track Locations

The track locations experiencing the large net axle loads that can cause track shift can be repaired. The repair can involve fixing the alignment conditions, and increasing the radius, spiral lengths and lateral strength. There are alternate (new design) methods such as the installation of slab track or ties anchored to piles or other means that can reduce or eliminate cumulative residual deflection due to track shift, which are currently being considered by several European railways. Note that even if the net axle loads are below the accepted limits, but are *"near"* the limit, they can contribute to excessive wheel/rail wear and wheel/rail contact geometry degradation.

c. Check and Fix Vehicle Problems

Redesign of existing vehicles is not always an acceptable option, but may provide a viable solution for new and emerging designs. The vehicle weight can be reduced through optimization studies and by using lightweight materials such as composites or stringer-skin or honeycomb-laminate construction. The wheel/rail contact geometry and vehicle suspension characteristics can also be changed or optimized to reduce the lateral loads.

The steps required in safety evaluation through field monitoring of allowable net axle loads is outlined in Figure 11 below:

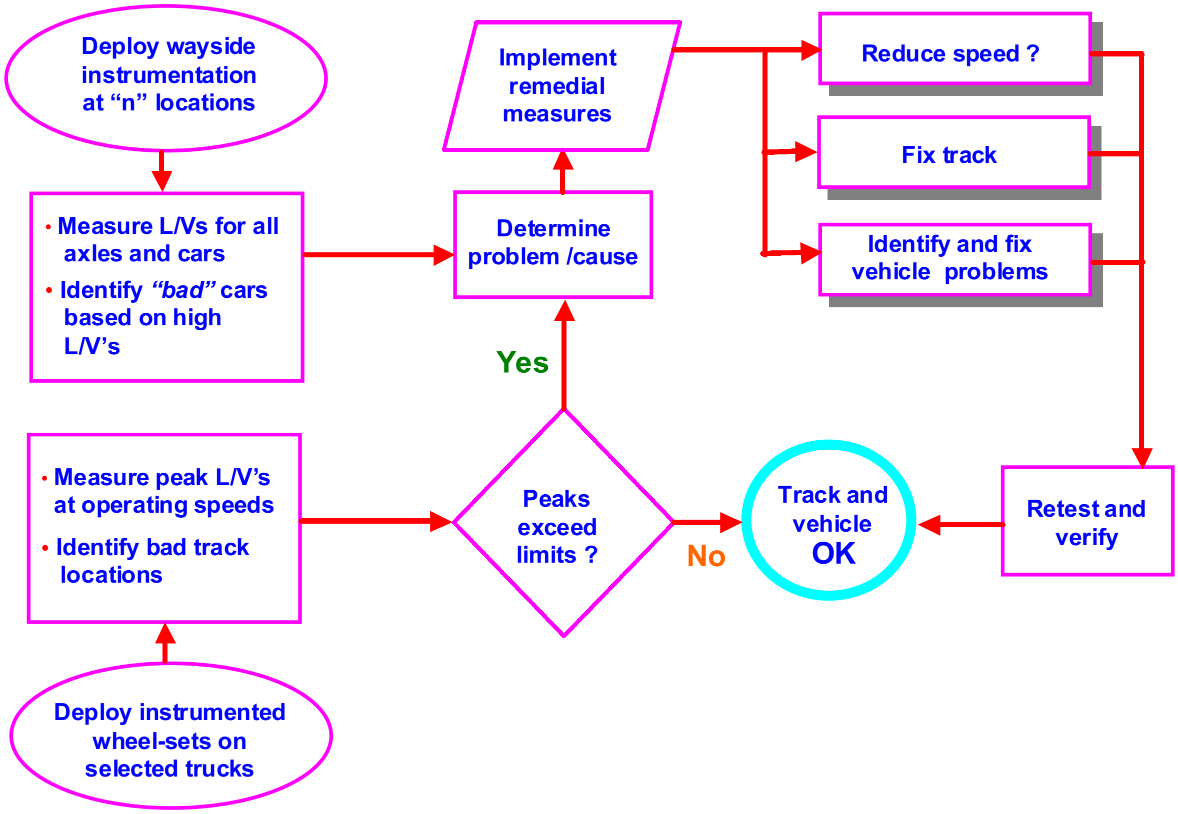

Figure 11: Track shift safety assessment through field monitoring

5.0 CONCLUSIONS

- On the basis of TREDA model predictions and track shift testing at the Transportation Technology Center, new track shift safety limits are presented here. The limits are presented in the form of a simple formula relating the permissible net axle lateral force to vertical axle load. They are based on the "onset of nonzero deflection" criteria i.e. loads which produce no or negligible track lateral shift with a large number of axle passes. For modern high-speed tracks, this formula is more appropriate than the Prud'homme formula which is conservative in many cases. For non-uniform axle lateral loads, the Prud'homme formula is not applicable.

- The track residual deflection analysis (TREDA) model has been validated through field tests, and can be used to evaluate track shift lateral response under moving loads accounting for many track conditions/parameters. As shown, the model can easily be applied for the development of safety limits.

- The current limit of 0.5 for US tracks for the net axle force ratio does not account for the effect of vehicle vertical load, curvature and thermal effects. The new formula presented in this paper offers a more appropriate alternative.

- Monitoring the net axle loads in field conditions to assure track safety through coupling instrumented wheel set and wayside instrumentation based diagnostics appears to be the best method for safety assurance. If the net axle load exceeds the allowable limit prescribed here, timely remedial measures must be implemented for safe operations. These measures include possible speed reduction, effecting appropriate track repairs, and improving vehicle parameters/characteristics.

6.0 REFERENCES

1. A. Kish , G. Samavedam and D. Wormley, "Fundamentals of Track Lateral Shift for High-Speed Rail Applications", ERRI Interactive Conference on Cost Effectiveness and Safety Aspects of Railway Track, 8-9 December1998, Paris.

2. G. Samavedam, F. Blader, D.Thomson , "Track Lateral Shift: Fundamentals and State-to-the-Art Review," DOT/FRA/ORD-96/03, Final Report, 1996.

3. G. Samavedam, F. Blader, D. Wormley, M. Snyder, J. Gomes, and A. Kish, "Analysis of Track Shift Under High-Speed Vehicle-Track Interaction – Safety of High-Speed Ground Transportation," DOT/FRA/ORD-97/02, Final Report, 1997.

4. G. Samavedam, et.al., "Track Lateral Shift Model Development and Test Validation," DOT/FRA/ORD Technical Report, in preparation.

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

6. Track Safety Standards Part 213, Subpart G, Class of Track 6 and Higher, DOT/ Federal Railroad Administration - Office of Safety, September 1998.

7. **TREDA** Program – Version 2.0 and User's Guide, DOT/FRA/ORD Software, February 2000

8. B. Whitten, et. al., "Assessment of High-Speed Trainset Testing on the Northeast Corridor", DOT/FRA/ORD Technical Report, in preparation

9. **OMNISIM** Program and User's guide, DOT/FRA/ORD software, September 1998

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 Wayne Kong of Foster-Miller for making the TREDA program modifications, and Mr. Wesley Mui of the Volpe Center for the conduct of the various parametric analyses. Special thanks are also due to the staff at Transportation Technology Center, Inc. (TTCI) notably Dr. Dingqing Li and Messrs. David Read and Randy Thompson for performing the Track Loading Vehicle (TLV) based validation tests.