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[redacted]

DEVELOPMENT OF A NEW DISTANCE BASED CRITERION FOR FLANGE CLIMBING DERAILMENT

R-975

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13. Abstract
A bi-parameter flange climbing distance criterion is developed for vehicles with AAR-1B wheels running on a new AREMA 136 RE rail. The two parameter that affect flange climbing distance are angle of attack and lateral to vertical force ratios.

14. Subject Terms	**15. Availability Statement**
NUCARS™, AREMA 136 RE Rails, Bi-Parameter Flange Climbing, Track Loading Vehicle, AAR-1B Wheel, Nadal's Limiting Value	Transportation Technology Center, Inc., a subsidiary of the Association of American Railroads P. O. Box 79780 Baltimore, Maryland 21279-0780

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EXECUTIVE SUMMARY

Transportation Technology Center, Inc. (TTCI), a wholly owned subsidiary of the Association of American Railroads (AAR), has developed a bi-parameter flange climbing distance criterion for vehicles with AAR-1B wheels running on AREMA 136 RE rails. This criterion is based on tests results from TTCI's Track Loading Vehicle (TLV) and simulations with TTCI's *NUCARS™ program.

The bi-linear characteristics between the distance to climb, wheelset angle of attack (AOA) and lateral-to-vertical (L/V) wheel/rail force ratio were obtained by least squares fitting. The accuracy of the fit was improved by using a gradual linearization methodology. The bi-parameter distance criterion, based on the simulation results, was partially validated using TLV test data.

This report also presents the application to two AAR Chapter XI performance acceptance tests and limitations of the bi-parameter criterion.

The effects of running speed and wheel/rail friction coefficients on flange climbing distance were investigated through simulating the TLV test cases by using the measurement data derived from the test. The application conditions and limitations of the criterion are also discussed, including the application to AAR Chapter XI performance acceptance tests.

The following conclusions are drawn from the results of simulations and tests:

- A bi-parameter flange climbing distance criterion that uses the AOA and the L/V ratio as parameters is proposed for vehicles with AAR-1B wheel operating on AREMA 136 RE rail profiles:

  $$\text{L/V Distance (feet)} < \frac{1}{0.001411 \times \text{AOA} + (0.0118 \times \text{AOA} + 0.1155) \times \text{L/V} - 0.0671}$$

  where, AOA is in mrad. L/V is the average value of L/V ratio during the flange climbing.

- The following simplified flange climbing distance criterion is proposed according to the track curvatures for the situation when the average L/V ratio is higher than 1.13 and lower than 1.6. It is considered rare for the average L/V ratio to be higher than 1.6.

* NUCARS™, a vehicle dynamics modeling software, is a trademark of Transportation Technology Center, Inc.

Curvature (degrees)		0	5	10	20
Flange Climbing Distance Limit (feet)	Vehicles with IRW and Worn Three Pieces Trucks	3	2	1.5	1
	Other Vehicles	4.5	3	2	1.5

- The L/V ratio in the criterion must be higher than the L/V limiting ratio that corresponds to the AOA and the friction coefficient as shown in Reference 8. The L/V limiting ratio is equal to Nadal's limiting value when the AOA is larger than 10 mrad. No flange climbing occurs when the L/V ratio is lower than the L/V limiting ratio.

- The flange climbing distance increases with increasing vehicle speed and converges to a value. The bi-parameter flange climbing distance criterion derived from the speed of 5 mph is conservative for higher operating speeds.

- The bi-parameter flange climbing distance criterion was partially validated using TLV test data. Since the vehicle speed in TLV tests was only 0.25 mph, the validation of the bi-parameter flange climbing distance criterion is limited. A full-scale validation test is recommended.

- Application of the bi-parameter flange climbing distance criterion to an H-frame truck undergoing AAR Chapter XI tests shows that the bi-parameters distance criterion is less conservative than the Chapter XI criteria and the 50-msec duration limit.

- Application of the bi-parameter flange climbing distance criterion to empty tank car derailment test results shows that the bi-parameter distance criterion could have been used effectively for wheel flange climbing derailment analysis in this case.

The following are some limitations for applying the bi-parameter flange climbing distance criterion:

- The bi-parameter flange climbing distance criterion is obtained by fitting the bi-linear data in the range where the AOA is larger than 5 mrad. It is conservative at lower angles of attack (<5 mrad) due to its nonlinear characteristic. The criterion is based on the simulation results for an AAR-1B wheel profile operating on a 136 RE rail. It is only valid for vehicles with this combination of wheel and rail profiles. For different wheel and rail profile combinations, the bi-parameter flange climbing distance criterion needs to be derived based on further simulation results.

- The criterion can not be used directly where there is a guard rail.

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1.0 INTRODUCTION

To ensure railway vehicle safety, it is important to avoid flange climbing derailments. Several flange climbing derailment criteria have been derived for use in the railroad industry. However, they can be shown to be over or under conservative in certain situations. An accurate criterion is needed for the evaluation of a vehicle's flange climbing derailment performance.

This report by the Transportation Technology Center, Inc. (TTCI), Pueblo, Colorado, a wholly owned subsidiary of the Association of American Railroads (AAR), describes an investigation of the flange climbing derailment mechanism through simulation and test. It proposes a new flange climbing criterion based on wheelset angle of attack (AOA), lateral-to-vertical (L/V) wheel/rail force ratio of the flanging wheel, and the forward rolling distance.

1.1 Background

Wheel flange climbing derailments occur when the forward motion of the axle is combined with an excessive ratio of lateral-to-vertical (L/V) wheel/rail contact forces. This usually occurs under conditions of reduced vertical force and increased lateral force that causes the wheel flange to roll onto the top of the rail head. The flange climbing may be temporary, with wheel and rail returning to normal contact, or it may result in the wheel climbing fully over the rail.

Researchers have been investigating the wheel flange climbing derailment phenomenon since the early 20th century [1, 2, 3, 4, 5, 6, 7]. During these studies, six flange climbing criteria have been proposed. These criteria have been used by railroad engineers as guidelines for safety certification testing of railway vehicles. Briefly, they are:

- Nadal Single-Wheel L/V Limit Criterion
- Japanese National Railways (JNR) L/V Time Duration Criterion
- General Motors' Electromotive Division (EMD) L/V Time Duration Criterion
- Weinstock Axle-Sum L/V Limit Criterion
- FRA High-Speed Passenger Distance Limit (5 feet)
- AAR Chapter XI 50-millisecond Time Limit

The Nadal single-wheel L/V limit criterion [1], proposed by Nadal in 1908 for the French Railways, has been used throughout the railroad community. Nadal established the original formula for a limiting L/V ratio to minimize the risk of derailment. He assumed that the wheel was initially in two-point contact with the flange contacting the rail ahead of a vertical line through the center of the wheel. He observed that the wheel material at the flange contact point was moving downwards relative to the rail material. He theorized that wheel climbing occurs when the downward motion ceases with the friction saturated at the contact point. Based on his assumptions and a simple resolution of forces between wheel and rail at the point of flange contact, the following limiting criterion for the ratio of lateral to vertical forces can be derived by Equation 1:

$$\frac{L}{V} = \frac{\tan(\delta) - \mu}{1 + \mu \tan(\delta)} \qquad (1)$$

Equation 1 allows the L/V ratio, at which flange climbing starts, to be calculated. This limiting L/V ratio is dependent on the flange angle δ and friction coefficient μ. Figure 1 shows the solution of this expression for a range of values appropriate to normal railroad operations. The AAR has developed its Chapter XI single-wheel L/V ratio criterion based on Nadal's theory using a flange angle of 75 degrees and a friction coefficient of 0.5.

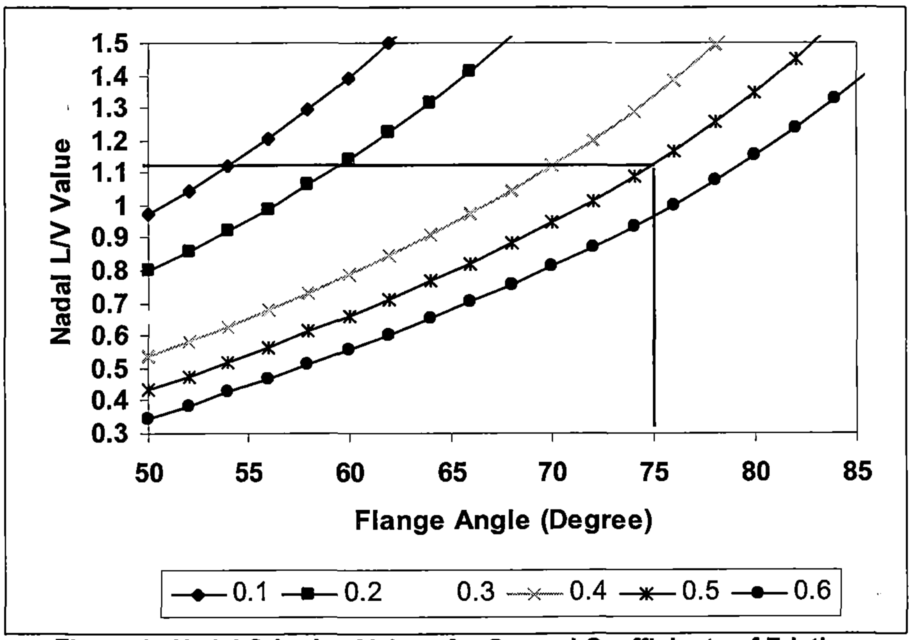

Figure 1. Nadal Criterion Values for Several Coefficients of Friction

Following a large number of laboratory experiments and observations of actual values of L/V ratios greater than the Nadal criterion at incipient derailment, researchers at JNR proposed a modification to Nadal's criterion [2]. For time durations of less than 0.05 seconds, such as might be expected during flange impacts due to hunting (lateral instability), a higher L/V ratio than the Nadal criterion [2] was allowable. However, small-scale tests conducted at Princeton University indicated that the JNR criterion was unable to predict incipient wheel-climbing derailment under a number of test conditions.

A less conservative adaptation of the JNR criterion was used by General Motors EMD in its locomotive research [3].

More recently, Weinstock, of the United States Volpe National Transportation Systems Center, observed that the balance of forces at the wheel/rail interface does not depend on the flanging wheel alone [4]. He proposed a limiting criterion based on the sum of the absolute value of the L/V ratios seen by two wheels of an axle, known as the "Axle Sum L/V" ratio. He proposed that this sum be limited by the sum of the Nadal limit (for the flanging wheel) and the coefficient of friction (at the non-flanging wheel). Weinstock's criterion was argued to be not as overly conservative as Nadal's at small or negative AOA and less sensitive to variations in the coefficient of friction.

Based on the JNR and EMD research, and considerable experience in on-track testing of freight vehicles, a 0.05-second (50-millisecond) time duration was adopted by the AAR for the Chapter XI certification testing of new freight vehicles. This time duration has since been widely adopted by test engineers throughout North America for both freight and passenger vehicles.

A flange climbing distance limit of 5 feet was adopted by the FRA for their Class 6 high speed track standards [5]. This distance limit appears to have been based partly on the results of the joint AAR/FRA flange climbing research conducted by TTCI and also on experience gained during the testing of various commuter rail and long distance passenger vehicles.

Over the past several years, TTCI has been investigating the fundamental aspects of the flange climbing phenomenon.

TTCI conducted a full-scale wheel climbing derailment test with its Track Loading Vehicle (TLV) during 1994 and 1995 [6]. The primary objective of the test was to re-examine the current flange climbing criteria used in the Chapter XI track worthiness tests described in M-1001, *AAR Manual of Standards and Recommended Practices*, 1993.

In 1999, TTCI conducted extensive mathematical modeling of single wheelset flange climbing behaviour using its dynamic modeling software, NUCARS™ [7]. The objective of this work was to gain a detailed understanding of the mechanisms of flange climb. This research resulted in TTCI proposing a new single-wheel L/V ratio criterion and a new flange climbing distance criterion for freight cars. Subsequently, some revisions were made to the proposed criteria [8].

The proposed L/V and distance to climb criteria were developed for freight cars with an AAR1B wheelset with a 75 degree flange angle. These were developed based on fitting L/V and distance to climb curves to numerous simulations of flange climbing derailment. The criteria were verified by comparison to single wheel flange climbing test results. Because the test and simulation results showed considerable sensitivity to axle AOA, the criteria were proposed in two forms. The first form is for use when evaluating test results where the AOA is being measured. The second form, which is more conservative, is for use when the AOA is unknown or can not be measured. Since AOA is usually difficult to measure, the second form is the mostly likely to be used.

The following are the proposed criteria. The criteria are shown graphically in Figures 2 and 3.

With the capability to measure AOA during the test, Equation 2 and 3 (see Figure 2):

$$\text{Wheel } \frac{L}{V} < 1.0 \qquad \{\text{for AOA} > 5 \text{ mrad}\} \qquad (2)$$

$$\text{Wheel } \frac{L}{V} < \frac{12}{\text{AOA (mrad)} + 7)} \qquad \{\text{for AOA} < 5 \text{ mrad}\} \qquad (3)$$

Without ability to measure AOA, Equation 4 (see Figure 3):

$$\text{Wheel } \frac{L}{V} < 1.0 \qquad (4)$$

Correspondingly, the L/V distance criterion was proposed as:

With onboard AOA measurement system, Equation 5 and 6:

$$\text{L/V Distance (feet)} < \frac{16}{\text{AOA (mrad)} + 1.5} \qquad \{\text{for AOA} > -2 \text{ mrad}\} \qquad (5)$$

$$\text{L/V Distance (feet)} = \infty \qquad \{\text{for AOA} < -2 \text{ mrad}\} \qquad (6)$$

Without onboard AOA measurement system, the proposed L/V distance criterion depends on the track curvature, Equation 7:

$$\text{L/V Distance (feet)} < \frac{16}{\text{Curve (degree)} + 3.5} \qquad (7)$$

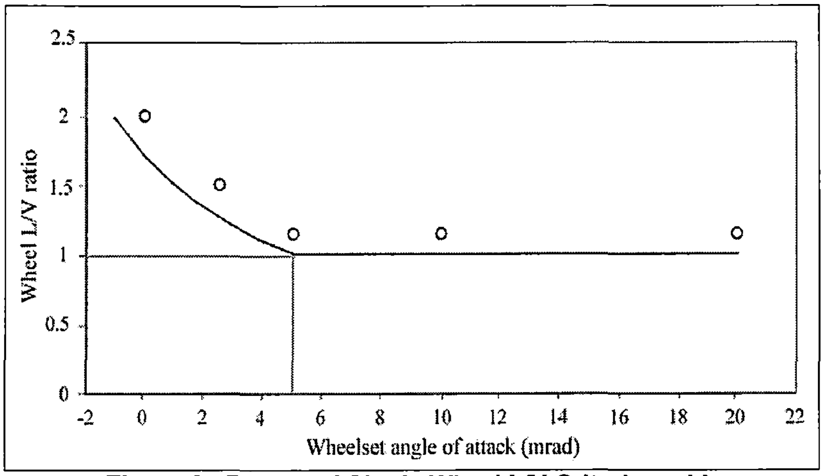

Figure 2. Proposed Single Wheel L/V Criterion with Wheelset AOA Measurement (Equations 2 and 3)

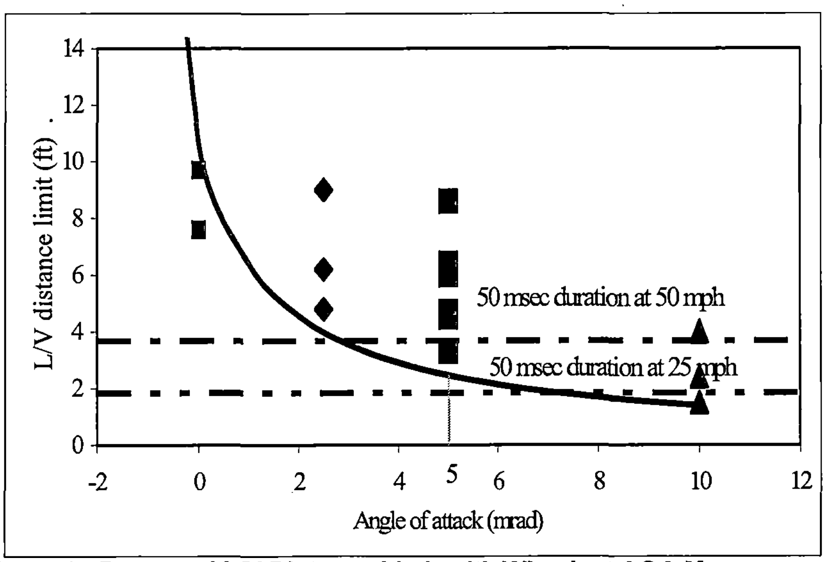

Figure 3. Proposed L/V Distance Limit with Wheelset AOA Measurement (Symbols represent NUCARS™ results; line represents the proposed distance limit) (Equations 5 and 6)

The research to develop these criteria was based primarily on tests and simulations of wheel and rail profiles and loading conditions typical for the North American freight railroads. Analyses were limited to 50 mph.

In 2004, TTCI conducted a program of developing wheel/rail profile optimization technology and flange climbing criteria at the request of the Transportation Research Board's Transit Cooperative Research Program (TCRP) D7 Committee. Flange climbing derailment criteria specific to different types of transit systems and transit vehicles were proposed in this program [9].

TTCI is undertaking strategic research on Car Performance Evaluation & Standards for the AAR (SRI 14a). One of the tasks is to examine the present Chapter XI derailment criteria and develop new flange climbing derailment standards.

Based on the previous research on flange climbing derailment, this report describes the methodologies and the new flange climbing distance criterion and further develops a simplified criterion for practical use. The validation and application to Chapter XI performance acceptance tests are also presented in this report.

1.2 Objectives

The objectives of work reported here are:

- To further investigate wheel/rail flange climbing mechanisms
- To propose a more accurate and less conservative wheelset flange climbing derailment criterion using NUCARS™ simulations of single wheelsets
- To validate the criterion through test data

1.3 Methodology

1.3.1 Single wheelset flange climbing derailment simulations

The effects of different parameters on derailment have been investigated through single-wheelset simulation in previous research [7, 8, 9]. This report focuses on the role of the wheelset AOA and L/V wheel/rail forces ratios on flange climbing derailment.

As shown in Figure 4, the same basic simulation methods used in TTCI's previous flange climbing studies were adopted here. To perform the flange climbing derailment simulations with NUCARS™, the wheelset AOA was set at a fixed value. A high yaw stiffness between the axle and ground ensured that the AOA remained approximately constant throughout the flange climbing process. A vertical wheel load that corresponded to the particular vehicle axle load was applied to the wheelset to obtain the appropriate loading at the wheel/rail contact points.

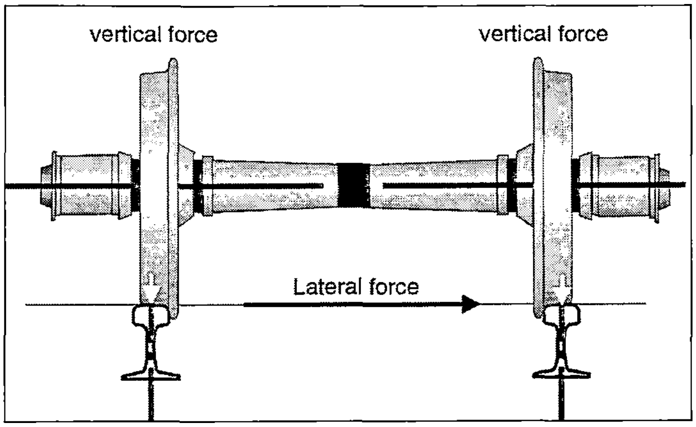

Figure 4. Single Wheelset Flange Climbing Derailment Model

To make the wheel climb the rail and derail, an external lateral force was applied, acting towards the field side of the derailing wheel at the level of the rail head. Figure 5 shows a typical lateral force distance history. While the wheelset was moving forward at a constant speed, an initial lateral force was applied at either 50 percent or 80 percent of the expected L/V ratio for steady-state climbing (based on Nadal's theory). This initial load level was held for 5 feet of travel to ensure equilibrium. The lateral force was then increased to the final desired L/V ratio (starting from A in Figure 5). This high load was held until the end of the simulation. From point A the wheel either climbed on top of the rail, or it traveled a distance of 40 feet without flange climbing – the latter was not considered as derailment.

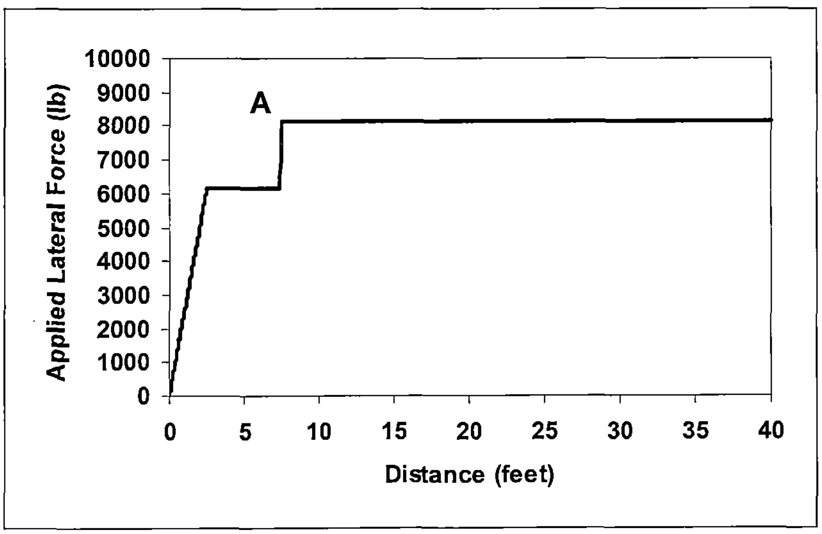

Figure 5. Lateral Force Step Input

1.3.2 Nonlinear transformation and gradual linearization

Flange climbing distance formulae are usually obtained by fitting a relationship to simulation results. The least squares fitting method is the most accurate method for a linear relationship. Linear relationships between the function and the variables are especially important for fitting with multiple parameters since there are few convenient fit methods for nonlinear multi-parameters.

A nonlinear transformation is used to linearize the relationship between the climb distance and the two parameters AOA and L/V ratio. Due to the bilinear characteristics between the transformed climbing distance and these two parameters, a bi-parameter formula is obtained with the least square fitting method. The fit of the formula is further improved through a gradual linearization methodology.

2.0 A BI-PARAMETER DISTANCE CRITERION FOR FLANGE CLIMBING DERAILMENT

The flange climbing distance criterion proposed in TTCI's previous research work [7, 8] for freight cars was based on single-wheelset simulations at a 2.7 L/V ratio for a range of different AOA. An L/V ratio of 2.7 was considered conservative for freight cars. The general flange climbing distance criterion in Section 1.1 of this report was derived from simulation results at a fixed L/V ratio of 1.99 for different AOA, which was considered conservative for transit cars. Both criteria were conservative at low L/V ratios, but not conservative enough at L/V ratios higher than the fixed L/V ratio used in the simulations, although the chance of encountering sustained L/V ratios this high is small in practice. To avoid this dilemma, it is desirable to include the L/V ratio as a variable parameter in the flange climbing distance criterion.

Results from testing [6] and simulations [7, 8, 9] show that flange climbing distance decreases with increasing L/V ratio. No flange climbing occurs when the climbing distance is infinite if the L/V ratio is lower than Nadal's limiting value. Since the L/V ratio is another important factor affecting flange climbing besides the AOA, a criterion including the L/V ratio and AOA is expected to reveal more about the physical nature of flange climbing and produce more accurate results. However, including all these variables makes the fitting process more complicated than if only one variable is being considered.

2.1 Nonlinear Transformation and Linearization

Test [6] and simulation results [7, 8, 9] show that flange climbing distance decreases with increasing AOA. The relationship between climbing distance D and AOA is nonlinear as shown in Figure 6.

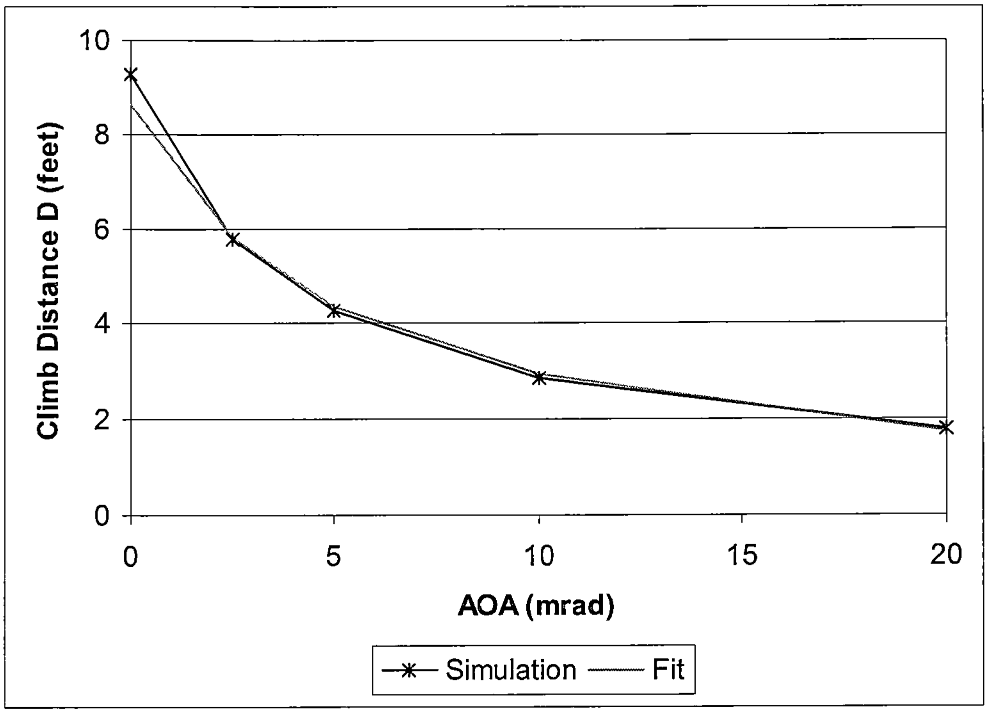

Figure 6. Effect of AOA on Climbing Distance, 63 degree Maximum Flange Angle, L/V=1.4

To develop a general flange climbing distance criterion with multiple parameters, a methodology was adopted in which the nonlinear relationship between the distance to climb and the parameters was linearized. This was achieved by using the following nonlinear function to transform the AOA and distance, D, in Figure 6 to (x, y) as shown in Figure 7 for a wheelset with a 63 degree flange angle, Equation 8:

$$\begin{cases} x = AOA \\ y = 1/D \end{cases} \qquad (8)$$

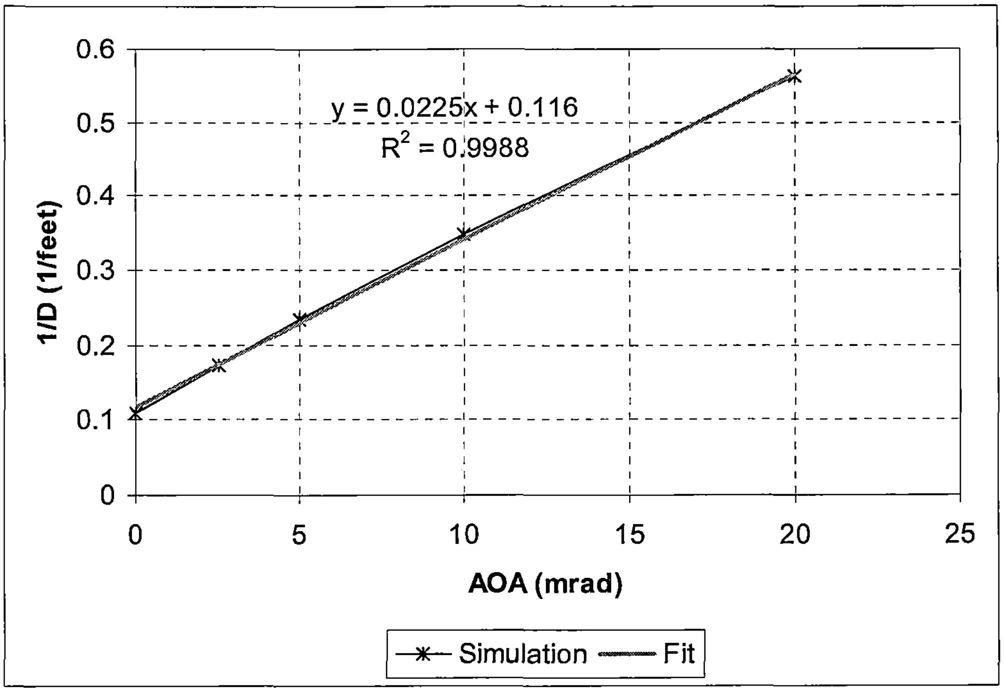

Figure 7. Linear Relation between 1/D and AOA, 63-Degree Maximum Flange Angle, L/V = 1.4

A straight line was then fitted to the transformed simulation results in Figure 7 with high accuracy (R^2 of 0.9988), shown as "fit" in Figure 7. The linear fit was then transformed back and plotted in Figure 6.

Figure 8 was adapted from Reference 10 to show the effect of the AOA on flange climbing distance at different L/V ratios for the same 63-degree flange angle wheelset. It is clear that the effect of AOA on flange climbing distance is strongly influenced by the L/V ratio.

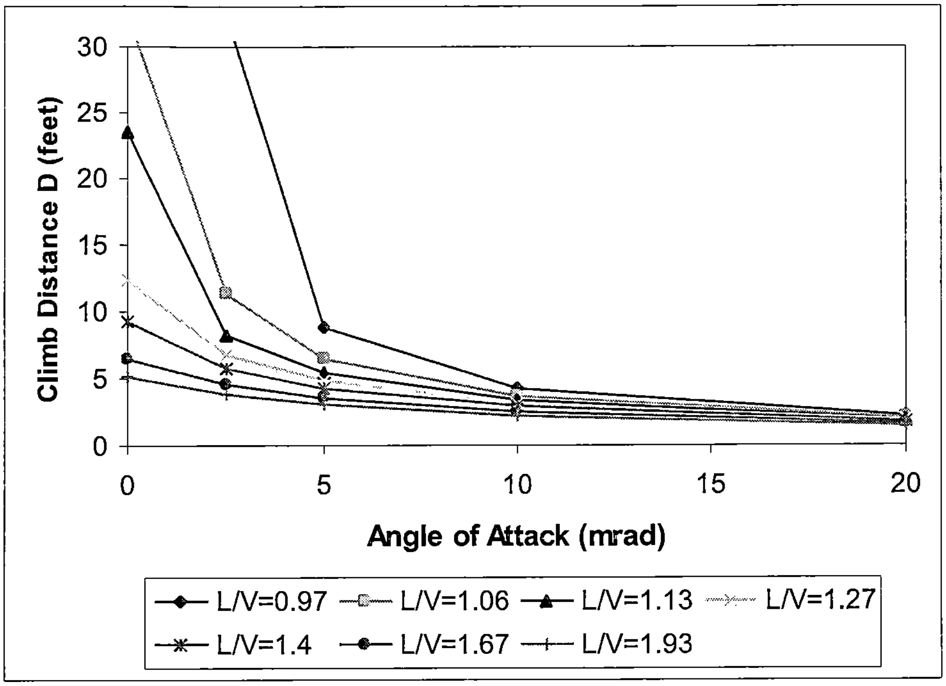

Figure 8. Effect of AOA on Climbing Distance at different L/V Ratios, 63-Degree Maximum Flange Angle, Adopted from Reference 10

By using the nonlinear transformation in Equation 8, linear relationships between 1/D and AOA at different L/V ratios were obtained as shown in Figure 9. Through this nonlinear transformation and linear fit methodology, the relationship between the climbing distance D and the two parameters AOA and L/V ratio is further analyzed in the following section.

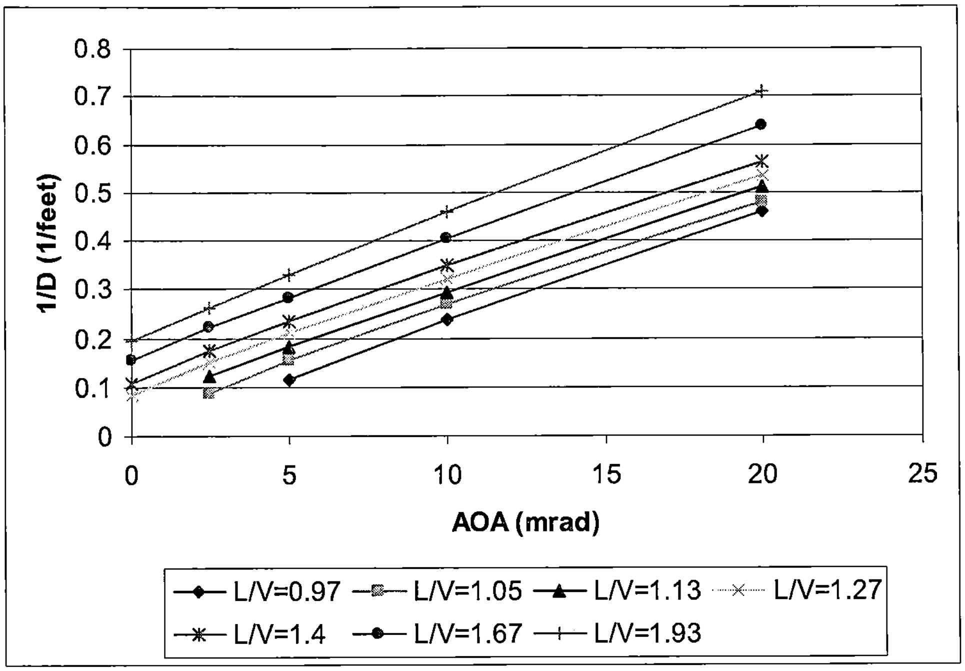

Figure 9. Linear Relation between 1/D and AOA for Different L/V ratio, 63-Degree Maximum Flange Angle

2.2 Bilinear Relationship between 1/D and The Parameters AOA and L/V Ratio

In this and the following sections, a combination of AAR-1B wheels and AREMA 136 RE rail profiles were used in simulations to develop a multi-variable fit formula. Figure 10 shows the simulation results of a single wheelset climbing at different L/V ratios and AOA.

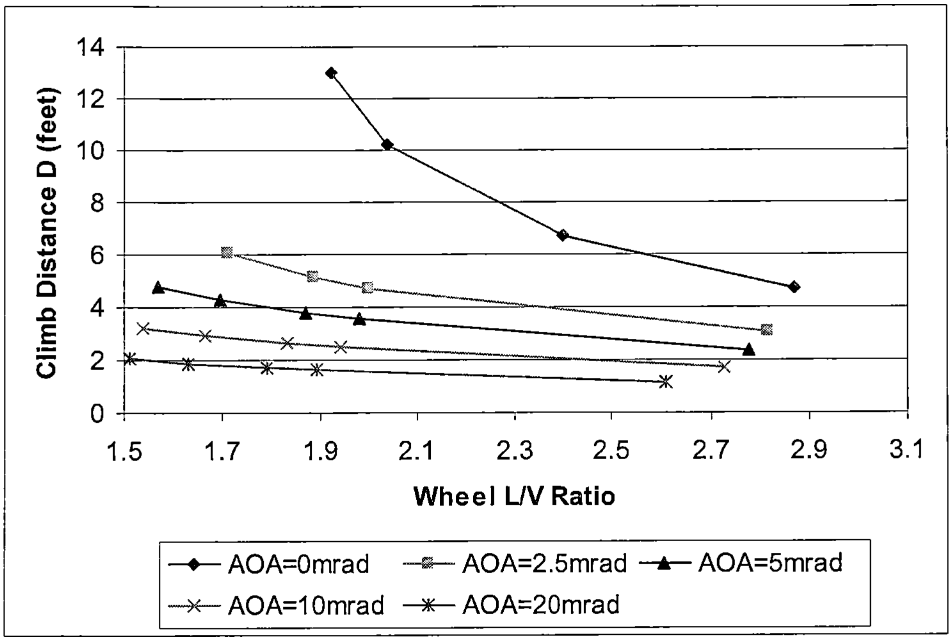

Figure 10. Effect of L/V Ratio at Different AOA, 75 Degree, AAR-1B Wheel, 136 RE Rail

Figure 10 shows that the relationship between the climbing distance D and the L/V ratio is nonlinear for the AAR-1B wheel/AREMA 136 RE rail combination. Through a nonlinear transformation similar to that described in Section 2.1, a linear relationship between 1/D and the L/V ratio was found as shown in Figure 11.

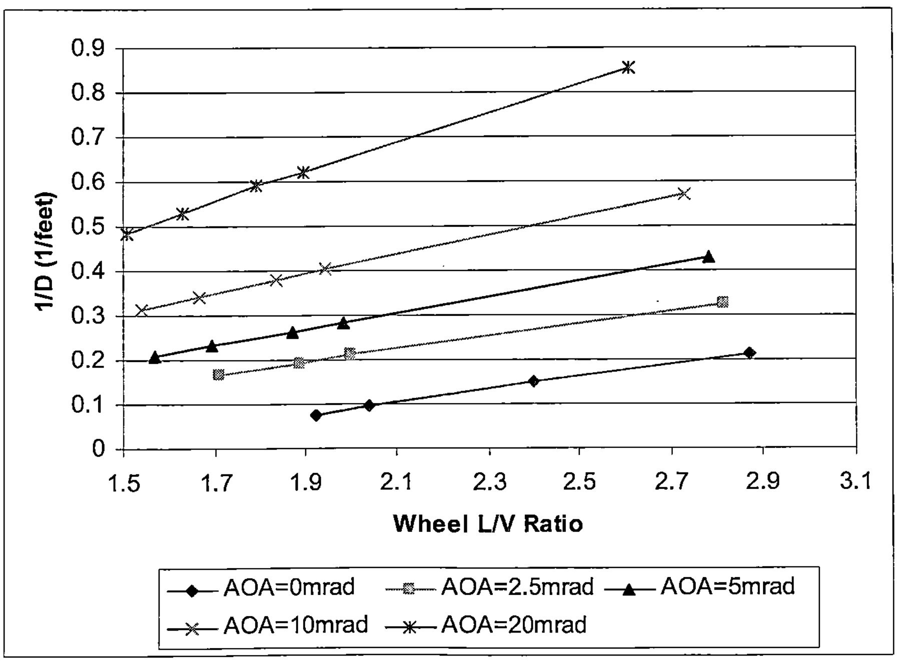

Figure 11. Linear Relation between 1/D and L/V Ratio, AAR-1B Wheel, 136 RE Rail

Due to the effect of AOA on the lateral creep force, the wheel L/V ratios shown in Figures 10 and 11 were not the same value for different angles of attack even though the same group of lateral and vertical forces was applied to the wheelset.

For example, when a 21,700 pound lateral force and 6,000 pound vertical force were applied to the wheelset at different angles of attack, the wheel L/V ratios varied with the AOA as shown in Table 1.

Table 1. Effect of AOA on L/V Ratio

AOA (mrad)	L/V Ratio (Average value during climb)
0	2.87
2.5	2.82
5	2.78
10	2.73
20	2.61

An average L/V ratio (L/Va) is defined as the average for a wheelset being subjected to the same group of lateral and vertical forces at different angles of attack. The L/Va ratio for the example shown in Table 1 is calculated as Equation 9:

$$L/Va = (2.87+2.82+2.78+2.73+2.61)/5 = 2.76 \quad (9)$$

L/Va ratio is used in the following section to further describe the relationship between climbing distance and AOA for different L/V ratios.

The relationship between the climbing distance D and the AOA is also nonlinear, as shown in Figure 12. Again, a nonlinear transformation was performed, as described in Section 2.1, giving the results shown in Figure 13. Figure 13 shows that there is an approximately linear relationship between 1/D and an AOA higher than 5 mrad. However, it can be seen that the relationship between 1/D and an AOA lower than 5 mrad is nonlinear.

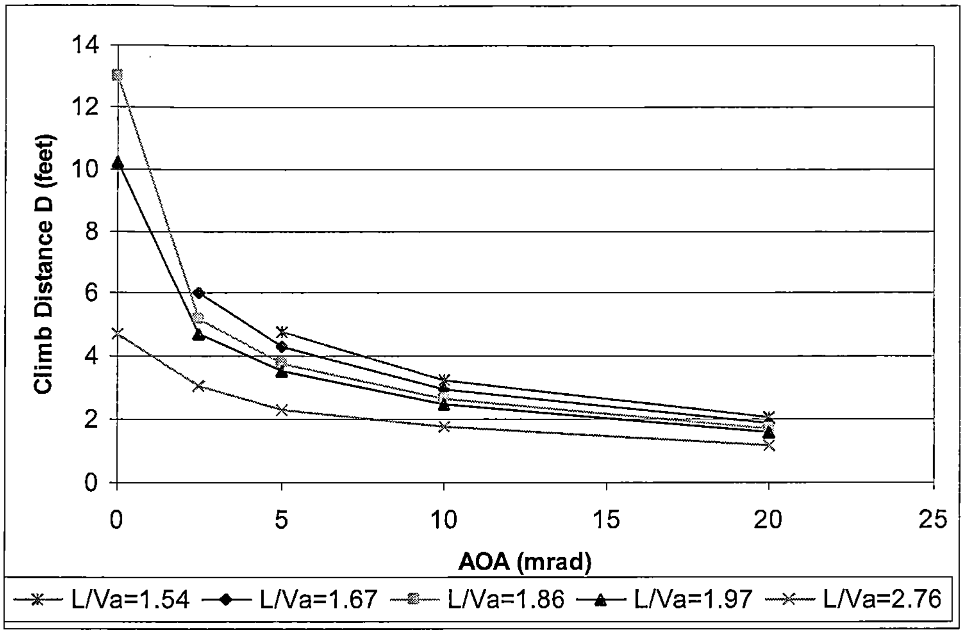

Figure 12. Effect of AOA at Different L/V Ratios, AAR-1B Wheel, 136 RE Rail

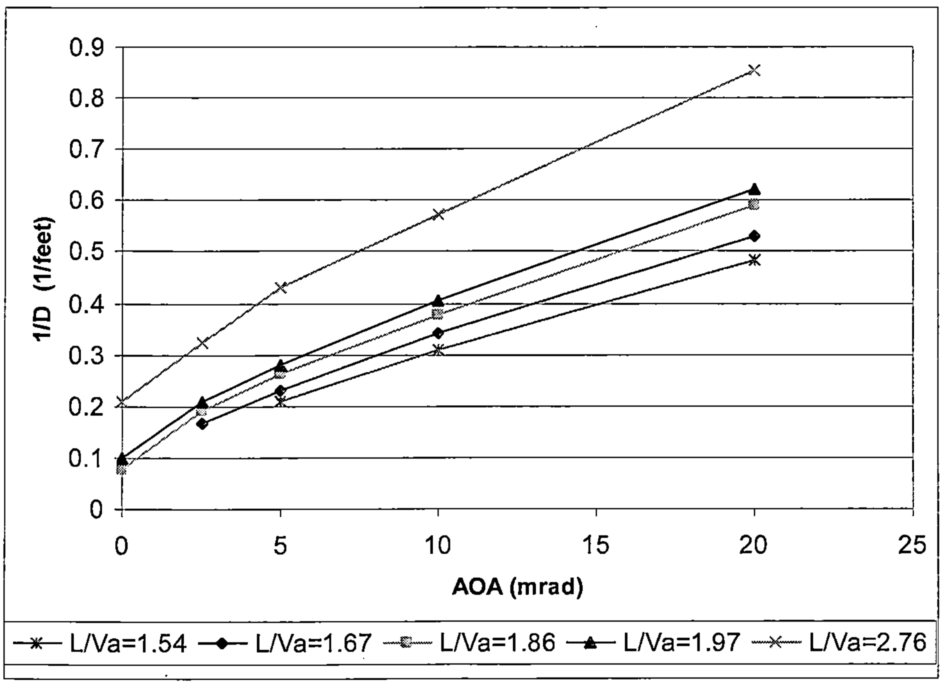

Figure 13. Relationship between 1/D and AOA, AAR1B Wheel, 136 RE Rail

2.3 Bi-Parameter Flange Climbing Distance Formula and Criterion

Due to the bilinear characteristics between the function of 1/D and the two variables AOA and L/V ratio shown in Figures 11 and 13, a gradual linearization methodology involving the two steps described below was developed to obtain a formula that fits the data accurately.

In the first step, the least squares fitting method for two variables was used. Since the relationship between 1/D and the L/V ratio is linear for all L/V ratios in the simulations (shown in Figure 11), the whole data range of L/V could be used. However, due to the nonlinear relationship with AOA shown in Figure 13, only the data range for AOA from 5 mrad to 20 mrad could be used. The resulting formula is thus conservative for AOA less than 5 mrad. The resulting two-parameter equation from the first step is Equation 10:

$$1/D = a_1 \times L/V + a_2 \times AOA + a_3 \qquad (10)$$

The accuracy to which Equation 10 fits the data depends on the simulation model, wheel/rail profile, and the data fitting range. It can be improved through a further linearization process known as "gradual linearization". This is performed in the second step.

In the second step, the wheelset AOA was kept constant by constraining the axle yaw motions in the simulation. The L/V ratio was allowed to vary during the flange climb, and the average value was used in the fitting process. Thus, in Equation 10, the coefficient a_1 is less accurate than a_2 due to the variation of the L/V ratio. Using the following transformation, Equation 11:

$$Y = 1/D - a_2 \times AOA \qquad (11)$$

The simulation results were grouped by AOA. For each AOA simulation group, an accurate fit ($R^2 > 0.99$) was obtained in the following linear form, Equation 12:

$$Y = b_1 \times L/V + b_2 \qquad (12)$$

The correlation analysis between the coefficient b_1, b_2, and the AOA for different groups shows that the coefficients b_1 and b_2 are linear functions of the AOA ($R^2 > 0.999$), Equation 13 and 14:

$$b_1 = Kb_1 \times AOA + Cb_1 \qquad (13)$$

$$b_2 = Kb_2 \times AOA + Cb_2 \qquad (14)$$

Substituting Equations 11 to 14 into Equation 10, the resulting fitting formula is Equation 15:

$$D = \frac{1}{0.001411 \times AOA + (0.0118 \times AOA + 0.1155) \times L/V - 0.0671} \tag{15}$$

where, AOA is in mrad.

Thus, to avoid derailment of a AAR-1B wheel operating on a 136 RE rail, the distance, the AOA and the L/V ratio are maintained should be less than that given by Equation 15.

Table 2 compares the fitting errors between Equations 10 and 15. The fitting accuracy was greatly improved through the "gradual linearization" methodology. The fitting error in Table 2 is defined as Equation 16:

$$\text{Fitting Error} = \frac{\text{Formula Value - Simulation Value}}{\text{Simulation Value}} \tag{16}$$

Table 2. Fitting Errors of Equations 3 and 8

Case	L/V Ratio	AOA (mrad)	Fitting Error of Equation 3 (%)	Gradual Linearization Fitting Error (Equation 15) (%)
1	1.69	5	20.70	1.58
2	1.87	5	1.68	1.23
3	1.98	5	-8.12	1.31
4	1.67	10	16.91	-1.24
5	1.83	10	1.82	-0.89
6	1.94	10	-6.64	-1.01
7	1.63	20	19.31	0.92
8	1.79	20	4.76	-0.20
9	1.89	20	-1.38	0.97

The following limitations need to be considered when applying the derived bi-parameter distance criterion:

- The L/V ratio in the criterion must be higher than the limiting L/V ratio corresponding to the AOA, because no flange climbing can occur if the L/V ratio is lower than this limit.
- The bi-parameter distance criterion is obtained by fitting in the range where AOA is larger than 5 mrad. It is conservative if AOA is less than 5 mrad.

- The bi-parameter distance criterion was derived based on the simulation results for the AAR-1B wheel operating on 136 RE rail. It is only valid for this combination of wheel and rail profiles. Similar bi-parameter flange climbing distance criteria need to be derived for other wheel/rail profile combinations.

3.0 COMPARISON BETWEEN THE SIMULATION DATA AND THE BI-PARAMETER FORMULA

The comparison between the simulation data and Equation 15 for all L/V ratios at different AOA is shown in Figure 14. Overall, the results are consistent especially at AOA greater than 5 mrad.

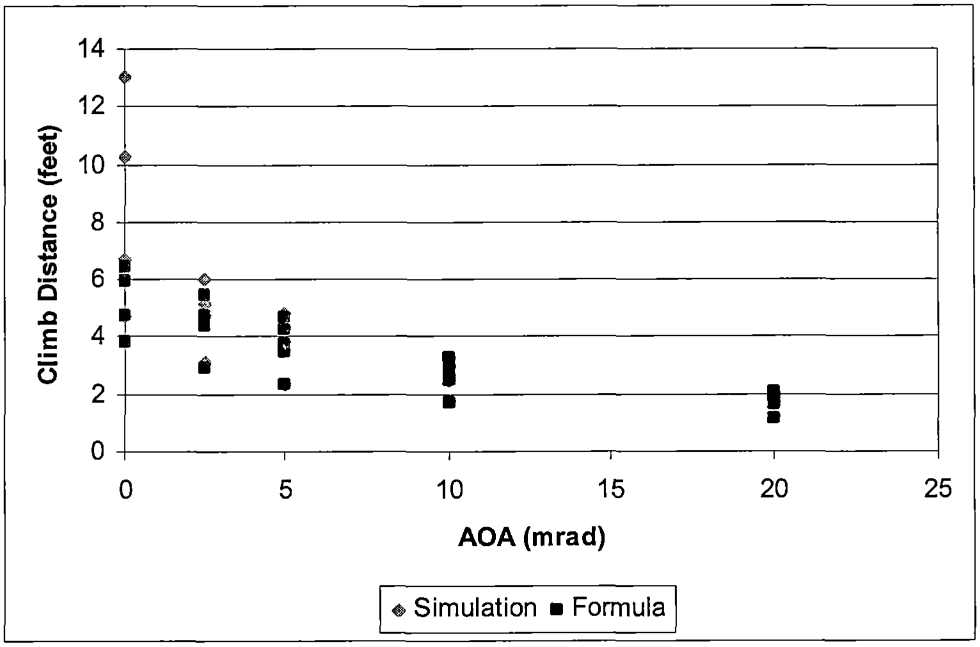

Figure 14. Comparison between the Simulation and Equation 15 for All L/V Ratios

Figures 15 through 19 compare the simulation results with results of Equation 15 for a range of AOA. Figures 15 and 16 show that Equation 15 is conservative for AOA less than 5 mrad – the calculated climbing distances are shorter than the corresponding values from the simulations. Figures 17, 18, and 19 show that for AOA equal to and greater than 5 mrad, the simulations and Equation 15 match very closely.

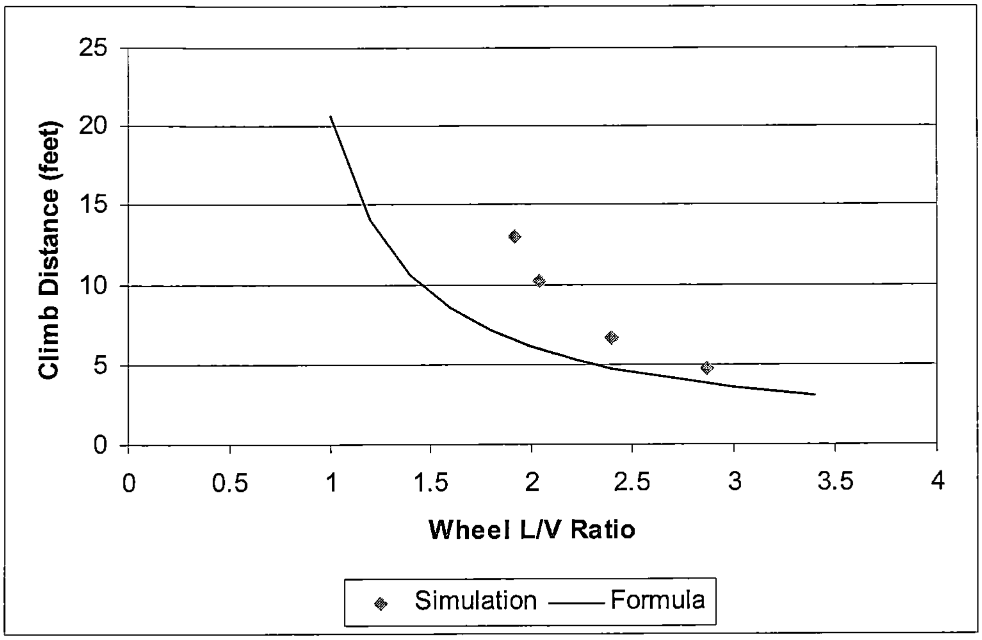

Figure 15. Comparison between the Simulation and Equation 15, AOA = 0 mrad

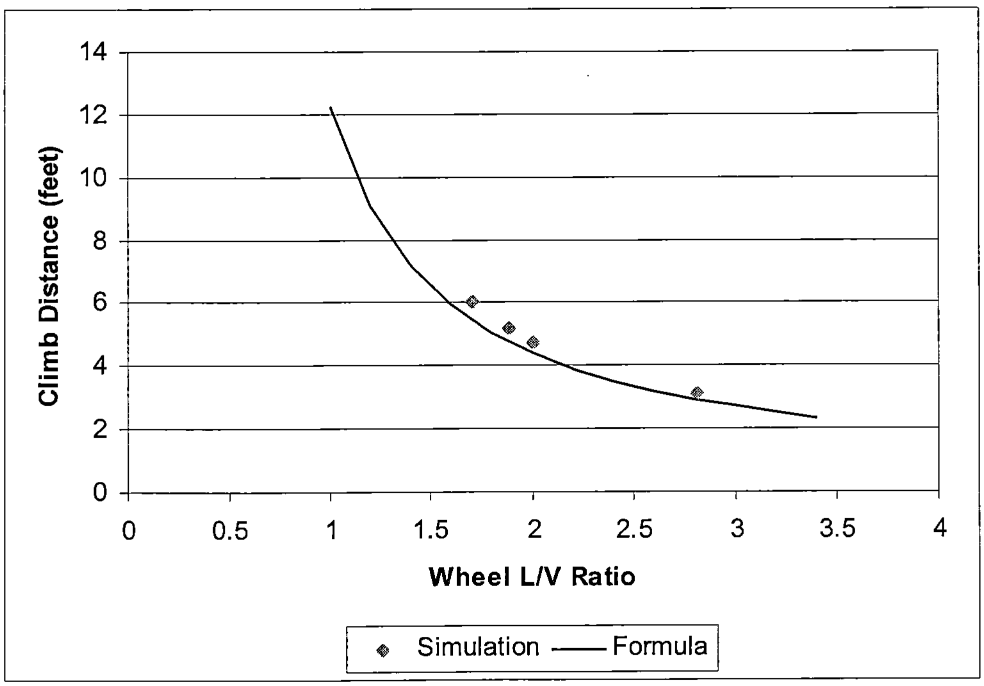

Figure 16. Comparison between the Simulation and Equation 15, AOA = 2.5 mrad

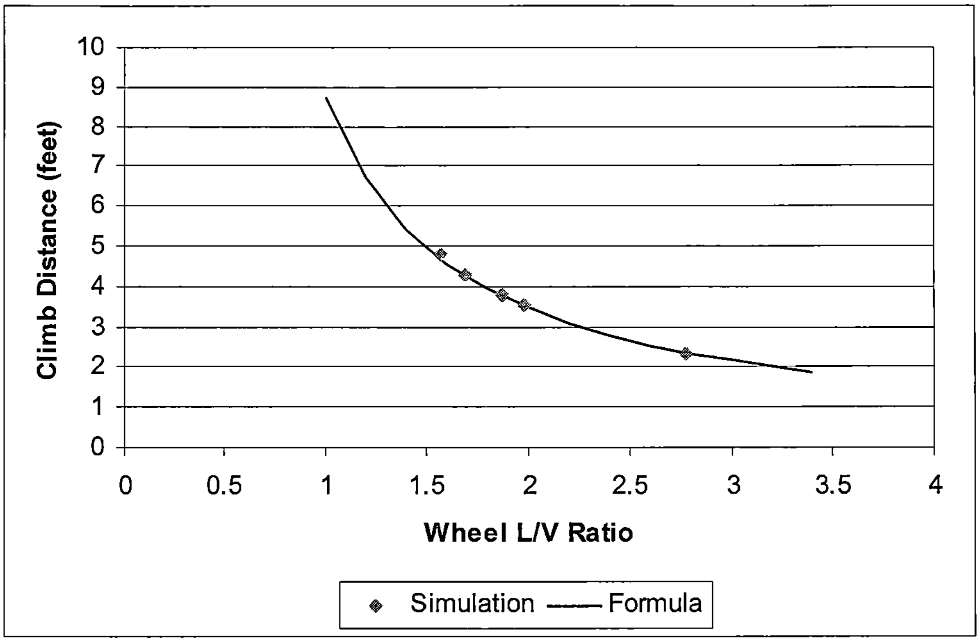

Figure 17. Comparison between the Simulation and Equation 15, AOA = 5mrad

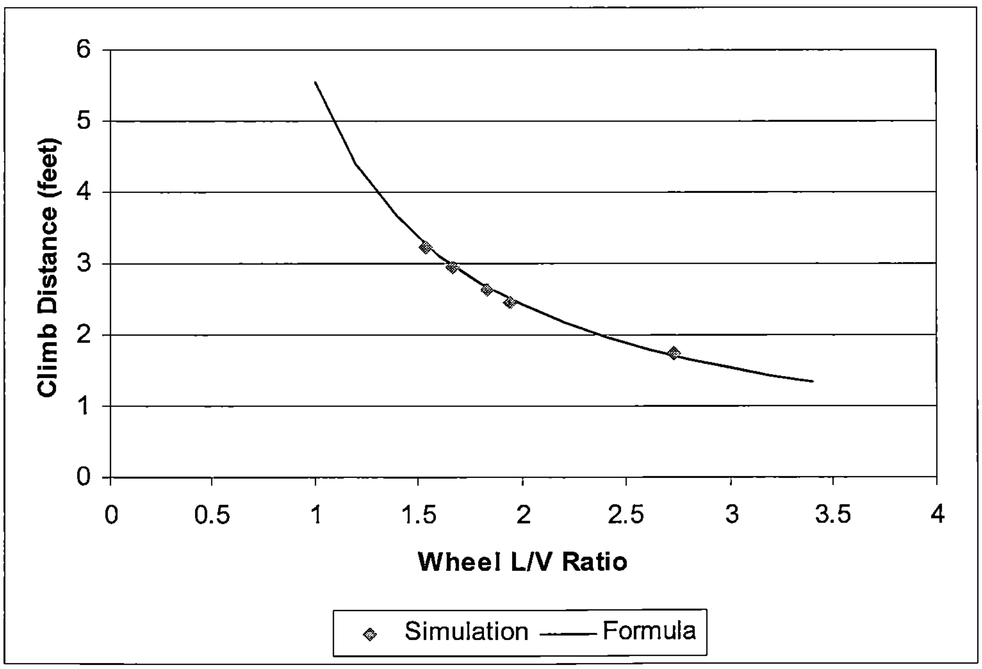

Figure 18. Comparison between the Simulation and Equation 15, AOA = 10 mrad

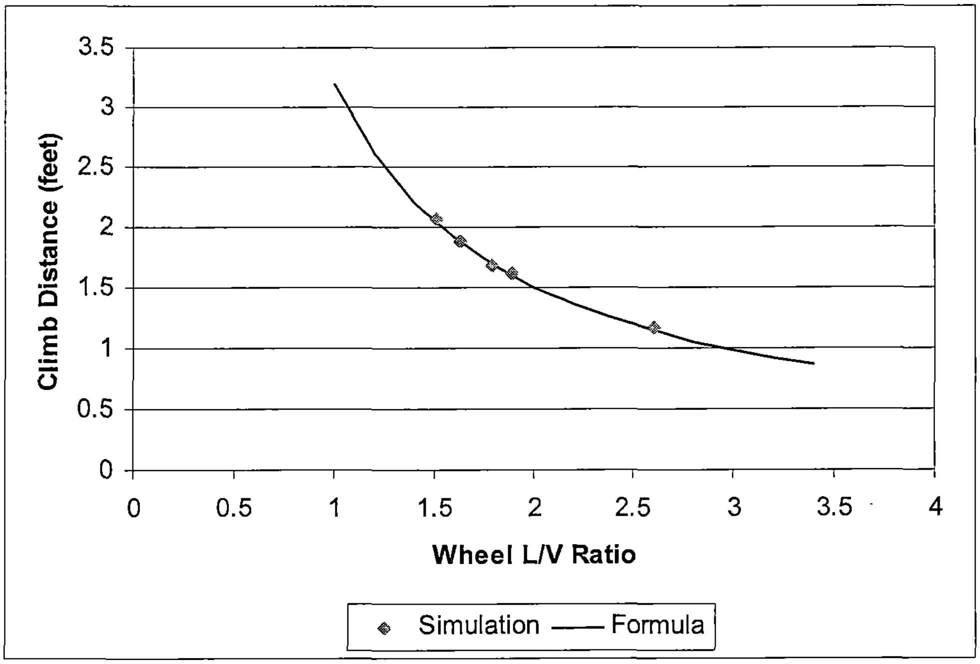

Figure 19. Comparison between the Simulation and Equation 15, AOA = 20 mrad

4.0 VALIDATION THROUGH TLV TEST

The bi-parameter flange climbing distance criterion was validated with flange climbing test data from a Track Loading Vehicle (TLV) test performed on August 25, 1997 [6]. This test was conducted on new rails. Since the climbing distance is sensitive to AOA, the AOA values were calculated from the test data by the longitudinal displacements (channel ARR and ARL) measured by sensors installed on the right and left side of the wheelset by using Equation 17:

$$AOA = \frac{ARL - ARR}{93.5} \qquad (17)$$

where AOA is in mrad, and *ARL* and *ARR* are in inches. The distance between the right and left sensor was 93.5 inches.

Figure 20 shows the overall comparison between the test data and Equation 15 for all L/V ratios at different AOA.

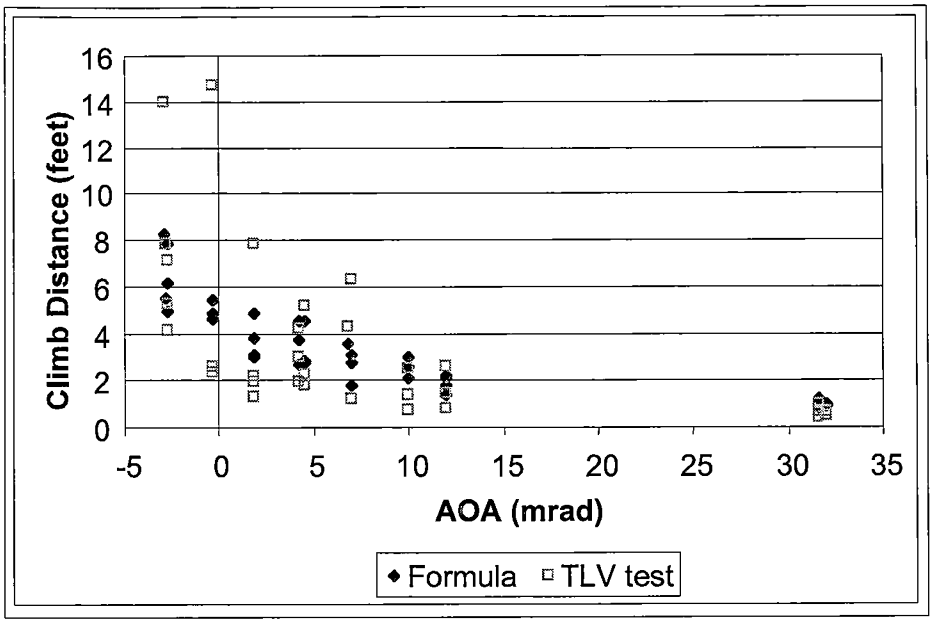

Figure 20. Comparison between the TLV Test and Equation 15 for All L/V Ratios

Figures 21 to 24 compare the TLV test data with results from Equation 15 for several of the controlled angles of attack. It can be seen that there is less scatter in the test results at higher AOA.

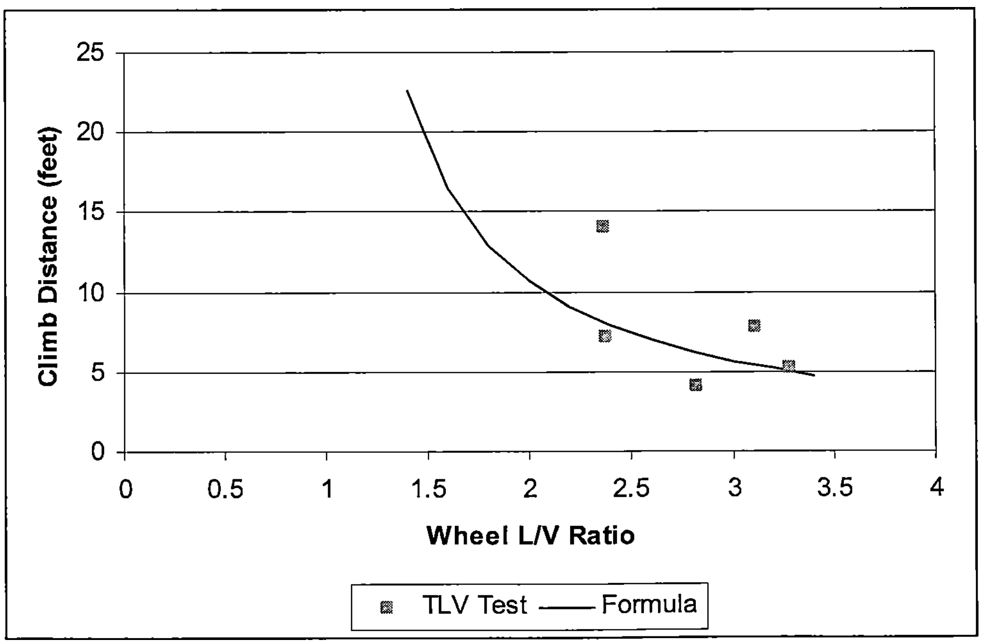

Figure 21. Comparison between the TLV Test and Equation 15, AOA = -2.8 mrad

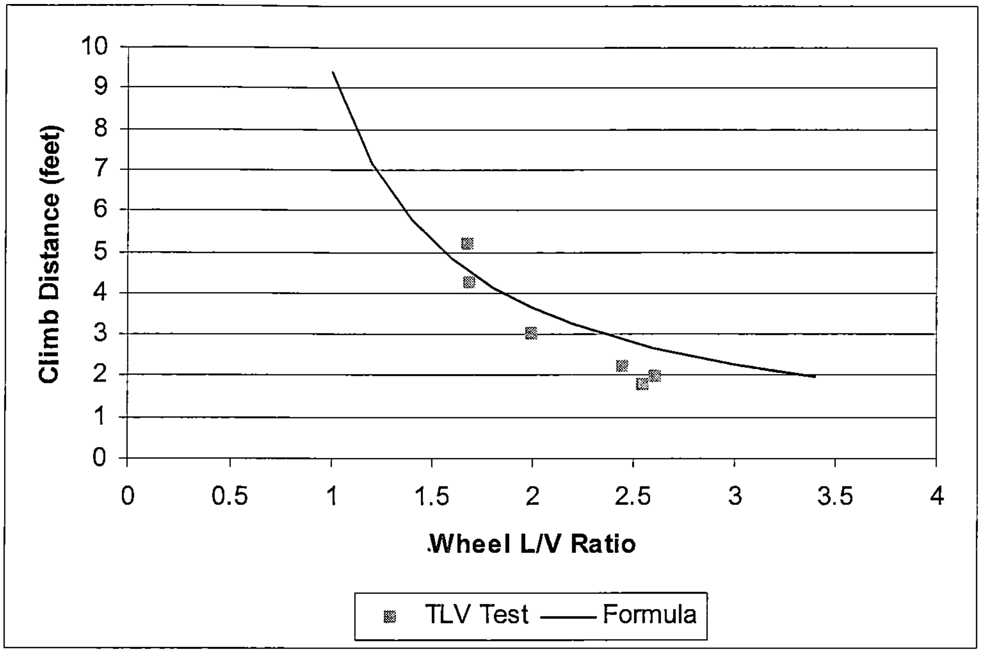

Figure 22. Comparison between the TLV Test and Equation 15, AOA = 4.4 mrad

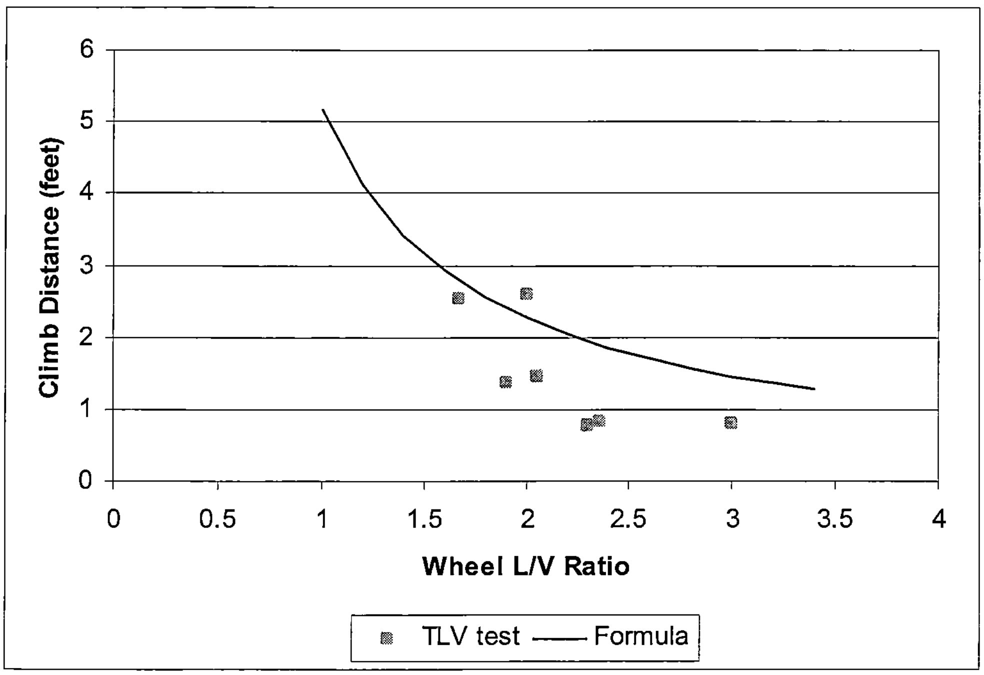

Figure 23. Comparison between the TLV Test and Equation 15, AOA = 11 mrad

The difference between the TLV test and Equation 15 shown in Figures 21 to 24 is due to two main factors: the wheel/rail friction coefficient and the vehicle's speed. Equation 15 was derived based on simulations of a single wheelset with 0.5 friction coefficient at 5 mile/hour running speed. The TLV test was conducted at an average speed of 0.25 mile/hour, and the friction coefficient during the test varied from 0.29 to 0.54 for the dry flange face of the new rail [6].

To demonstrate these differences, three TLV test cases at 32 mrad AOA were simulated by using the single-wheelset flange climbing model. The friction coefficients in these simulations were derived from the instrumented wheelset L/V ratios. Simulation results show the L/V ratio converges to Nadal's climbing value when AOA is larger than 10 mrad. For these runs (runs 30, 31, and 32), the L/V ratio just before the wheel climbs is 1.57. The instrumented wheel profile is the 75-degree AAR-1B wheel profile. The friction coefficient between wheel and rail calculated from Nadal's formula is 0.32. As can be seen in Figure 24, the simulations with 0.32 friction coefficient and 0.25 mile/hour vehicle speed show good agreement with the test data.

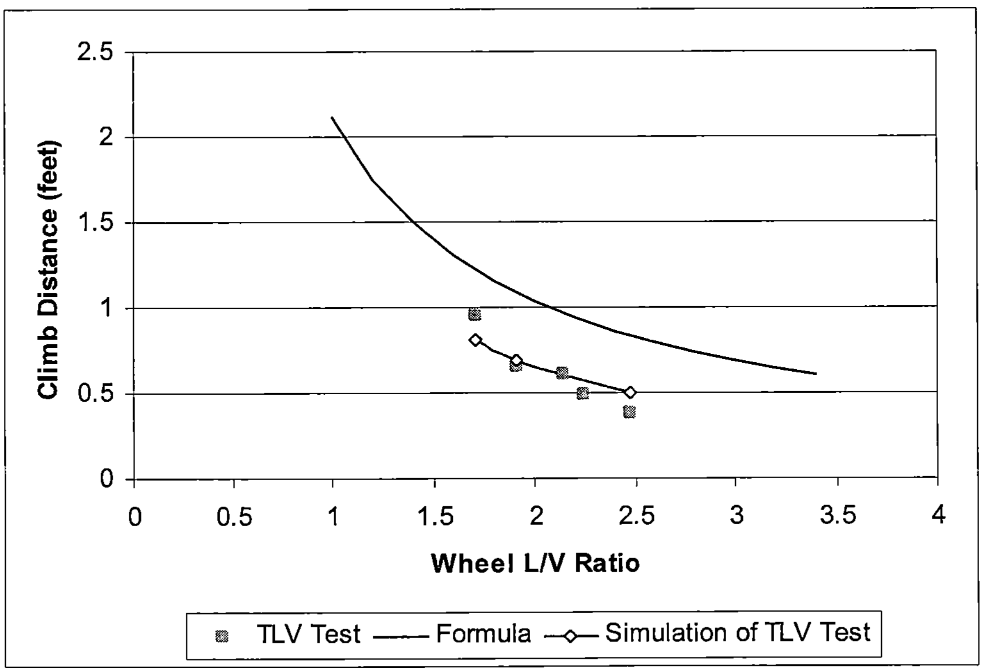

Figure 24. Comparison between the TLV Test and Equation 15, AOA = 32 mrad

Considering the operating speeds of vehicles in practice, it is reasonable to use 5 mph rather than 0.25 mph for developing flange climbing criteria.

The speed effect on the flange climbing distance is further investigated through the single wheelset flange climbing simulation at higher speed. As shown in Figure 25, the distance to climb increases slightly with increasing running speed.

The dynamic behavior of wheelset becomes very complicated at high running speed (above 80 mph for 5 mrad AOA and 50 mph for 10 mrad AOA). However, the distance limit derived from the speed of 5 mph should be conservative for higher operating speeds.

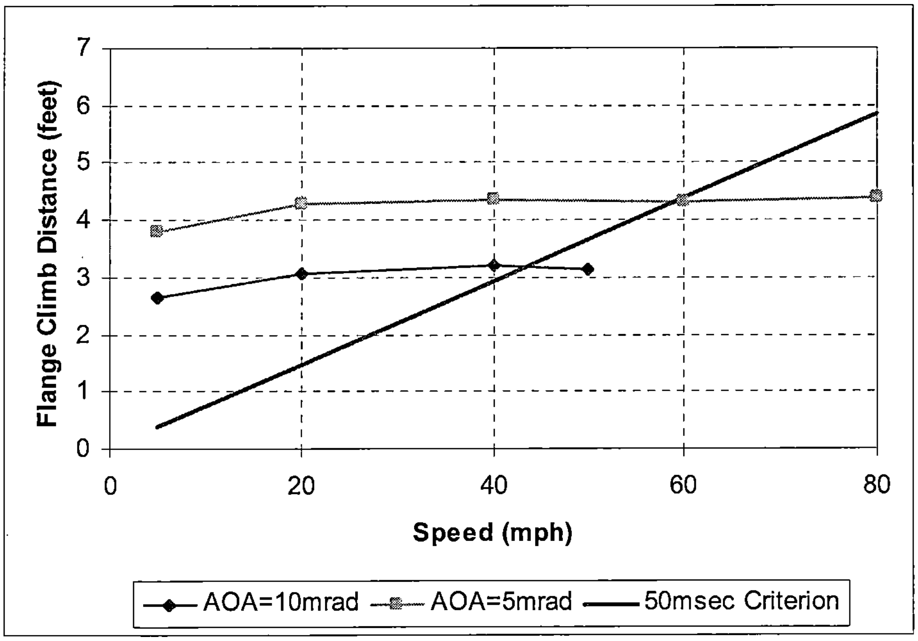

Figure 25. Effect of Speed on Distance to Wheel Climb
L/V Ratio = 1.99, AAR-1B Wheel (75-degree flange angle) and 136 RE Rail

The 50 msec criterion, in which flange climbing distance varies linearly with speed, is also plotted on Figure 25. It can be seen that the time based criterion is too conservative at low speeds. At higher speeds (42 mph for 10 mrad AOA, and 60 mph for 5 mrad AOA) it is not conservative and may be unsafe.

The effect of the flanging friction coefficient μ at different AOA on the climbing distance was investigated in the study for TCRP program [9].

5.0 ESTIMATION OF AOA

In the single-wheelset flange climbing simulations and the TLV test the AOA was held constant to investigate its effect on flange climbing. Both the single-wheelset simulations and the TLV test have shown that the flange climbing distance is sensitive to AOA. However, in practice the AOA will vary during the climb, as shown in the full vehicle simulations.

In most practical applications, measurement of instantaneous AOA is not possible. Therefore, to evaluate flange climbing potential with the bi-parameter distance criterion an equivalent AOA (AOAe) has to be estimated using available information (for example, vehicle type, track geometry, perturbation, suspension parameters).

Four kinds of representative vehicles, corresponding to the light rail vehicle Model 1 (LRV1), Model 2 (LRV2), and heavy rail vehicle (HRV) for transit systems [9] and one freight car with three pieces trucks, were simulated running on a 10-degree curve, with 4 inches superelevation, and with the AAR Chapter XI dynamic curve perturbation. Simulation results were used to estimate the AOAe during wheelset flange climb.

Five running speeds of 12, 19, 24, 28, and 32 mph – corresponding to a 3 and 1.5 inch underbalance, balance, and a 1.5 and 3 inch overbalance speed – were simulated to find the worst flange climbing cases with the longest climbing distances.

Longitudinal primary suspension stiffness of the passenger trucks can have a significant effect on axle steering and axle AOA. Therefore, for each of the vehicles two stiffness variations, which were 50 percent lower and 150 percent higher than that of the designed longitudinal primary stiffness, were used to investigate the effect of suspension parameters on flange climb.

Figure 26 shows the effect of longitudinal primary suspension stiffness on AOAe, which was calculated as the average AOA during the flange climb.

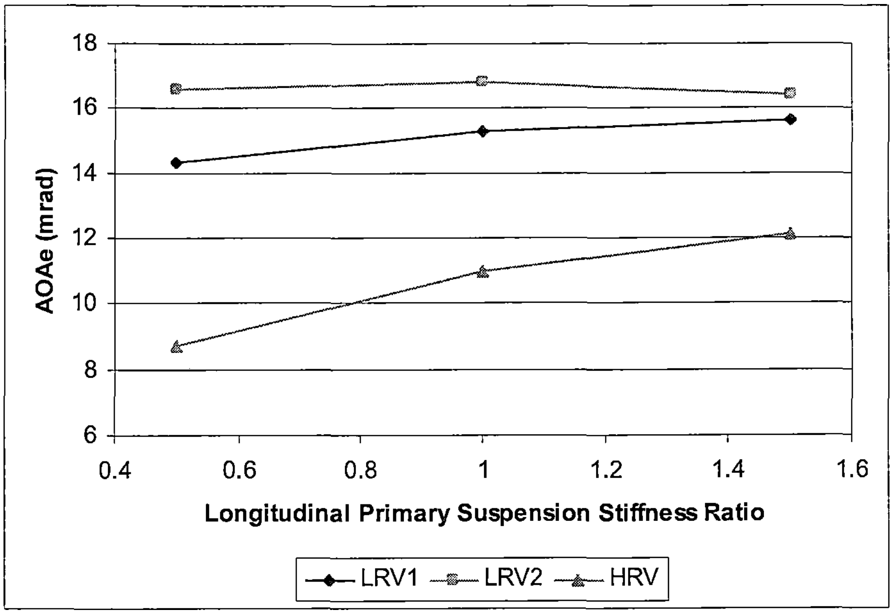

Figure 26. Effect of Longitudinal Suspension Stiffness on AOAe

The warp stiffness of three-piece bogies has an important influence on the AOAe. Three values of warp stiffness were modeled corresponding to a worn truck, a new truck, and a stiff H-frame truck. As shown in Figure 27, for the AAR-1B wheel and 136 RE rail profiles, the average AOA during climbing decreased with increasing warp stiffness. For the new wheel and rail profile, the wheel did not climb on the rail due to improved steering resulting from the new profile having a larger rolling radius difference on the tread than that of the worn profile.

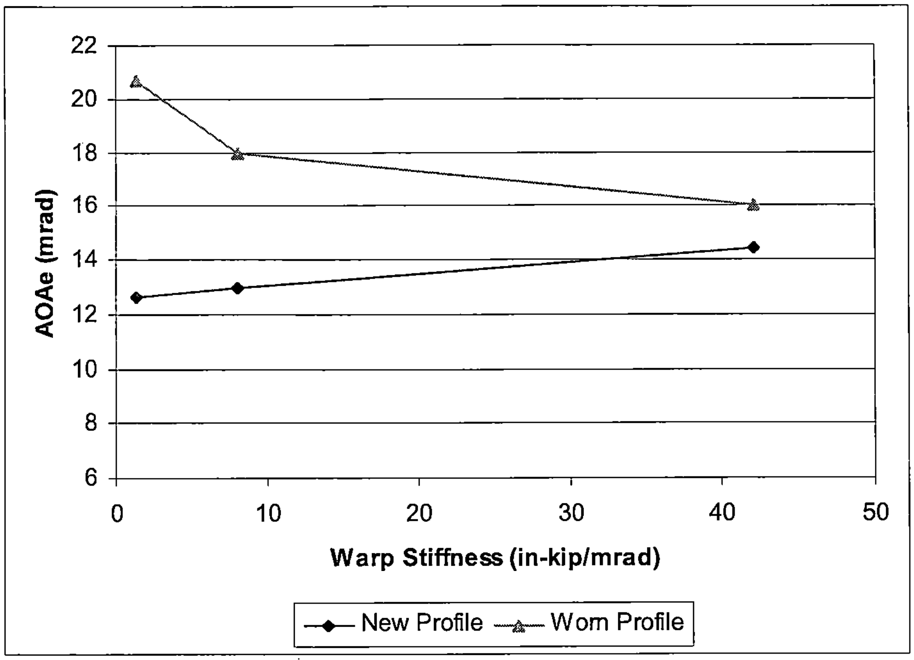

Figure 27. Effect of 3-Piece Truck Warp Stiffness on AOAe

When wheelset AOA is not available, an equivalent index AOAe (in mrad) of the leading axle of a two-axle truck can be obtained through a geometric analysis of truck geometry on a curve, Figure 18:

$$\text{AOAe} = 0.007272clC \qquad (18)$$

where c is a constant for different truck types, l (inch) is the axle spacing, and C (degree) is the curvature.

Table 3 lists the constant c in Equation 18 for five kinds of representative vehicles (LRV1, LRV2, HRV, and Freight Car equipped with 3-piece Truck (new and worn)) based on simulation results of the maximum AOAe and axle spacing distance for each of them.

Table 3. Estimation of AOAe

Vehicle type	Maximum AOAe (mrad)	Axle Spacing Distance (inches)	Constant c
LRV1	16.8	74.8	3.08
LRV2	15.6	75.0	2.86
HRV	12.1	82.0	2.04
Freight Car with New Three Pieces Bogies	12.7	70.0	2.50
Freight Car with Worn Three Pieces Bogies	20.7	70.0	4.00

Due to the effect track perturbations have on degrading a wheelset's steering capability, equivalent AOAs in practice could be higher than the value calculated by Equation (18). Table 4 shows a recommended, conservative correction to Equation 18.

Table 4. Conservative AOAe (mrad) for Practical Use

Vehicle and Truck Type	AOAe (mrad)
Vehicle with IRW and Worn Three Piece Trucks	Equation (11) +10
Others	Equation (11) +5

It is also recommended that AOA statistical data from wayside monitoring systems be used in the criterion to take into account the many factors affecting AOAe, if such systems are available.

6.0 APPLICATIONS TO AAR CHAPTER XI PERFORMANCE ACCEPTANCE TESTS

6.1 Application to a Passenger Car Test

The bi-parameter criterion was applied to a passenger car with an H frame truck undergoing Chapter XI tests at the Transportation Technology Center, Pueblo, Colorado, on July 28 1997. The car was running at 20 mph through a 5 degree curve with 2 inch vertical dips on the outside rail of the curve. The rails during the tests were dry, with an estimated friction coefficient of 0.6. The wheel flange angle was 75 degrees, resulting in a corresponding Nadal limiting value, L/V ratio of 1.0.

The L/V ratios were calculated from vertical and lateral forces measured from instrumented wheelsets on the car. Table 5 lists the five runs with L/V ratios higher than 1.0, exceeding the AAR Chapter XI flange climbing safety criterion. The climbing distance and average L/V ratio (L/V ave) in Table 5 were calculated for each run from the point where the L/V ratio exceeded 1.0.

Table 5. Passenger Car Test Results
Distance Measured from the L/V Ratio Higher than 1.0 for Friction Coefficient of 0.6

Runs	Speed (mph)	L/V Maximum	Average L/V	Climb Distance (feet)
rn023	20.39	1.79	1.37	6.2
rn025	19.83	2.00	1.43	7.0
rn045	19.27	1.32	1.10	4.0
rn046	20.07	1.06	1.01	2.0
rn047	21.45	1.85	1.47	5.7

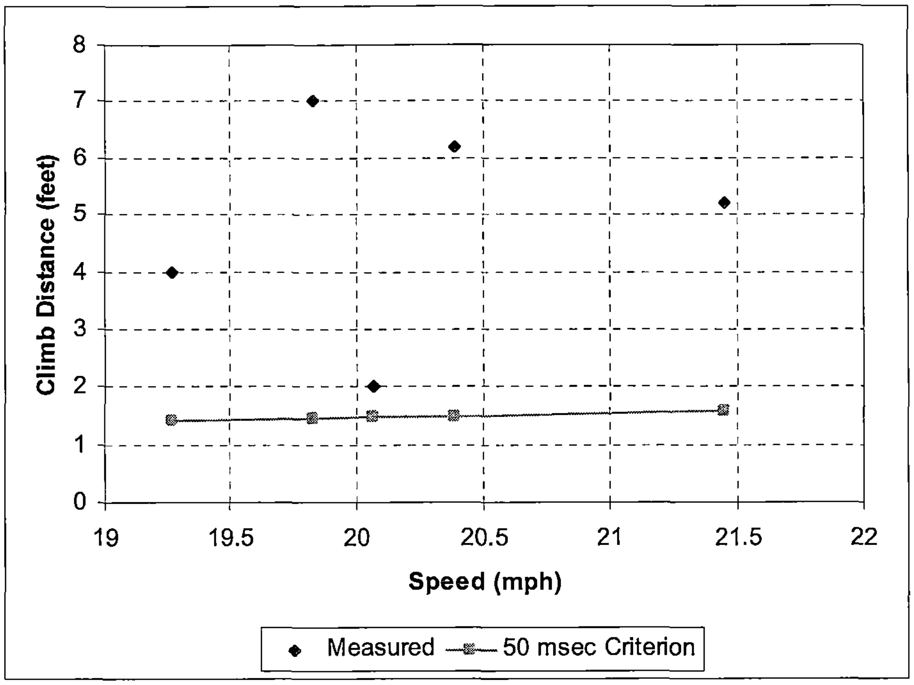

Figure 28. Application of 50 msec Climbing Distance Criterion

Figure 28 compares the climbing distances to the corresponding distances that are equivalent to a 50 msec time duration. As can be seen, all the climbing distances exceeded the 50-msec duration. However, there does not appear to be a direct correlation between test speed and duration of the climb.

Equation 15 was used to calculate a climbing distance for each run, based on the measured L/V ratios. As AOA was not measured during the test, Equation 15 was used with several values of AOA. The results are compared to the 50 msec duration in Figure 29.

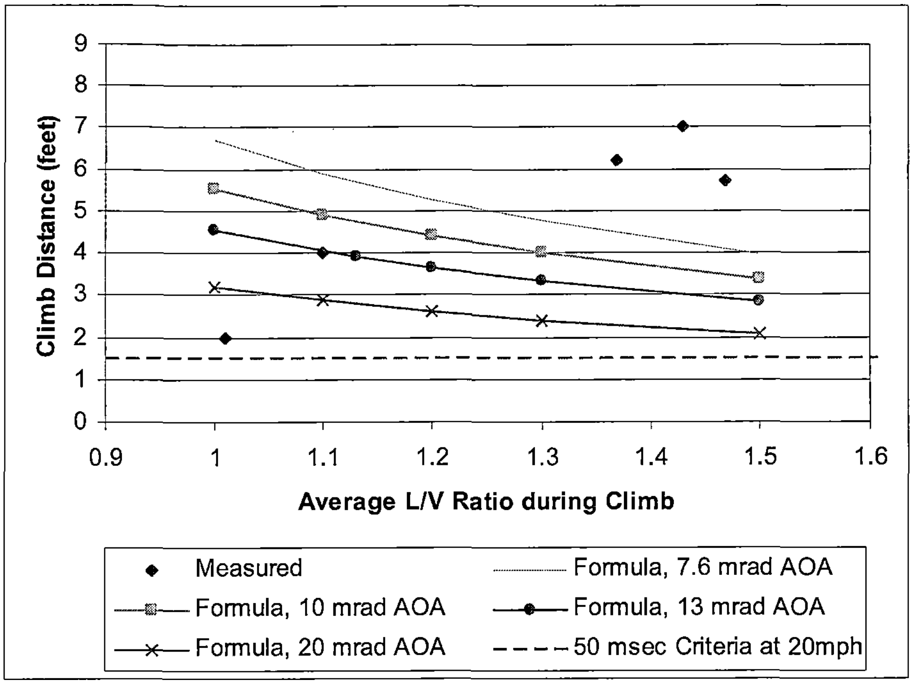

Figure 29. Comparison between New Criterion (Equation 15) and 50 msec Criterion

According to the bi-parameter distance criterion, the run with 1.01 average L/V ratio (maximum L/V ratio 1.06) was acceptable even for the 20 mrad average AOA, which is an unlikely occurrence for an H-frame truck in a 5 degree curve.

The run with a 1.1 average L/V ratio (maximum L/V ratio 1.32) was acceptable according to the new criterion as shown in Figure 29 unless the AOAe was greater than 13 mrad. This result also means the bi-parameter distance criterion is less conservative than the general flange climbing distance criterion.

The other three test runs were unacceptable since the measured climbing distance exceeded the new criterion for AOA greater than 7.6 mrad. The same conclusion can also be drawn by applying the new criterion with a conservative 12.6 mrad AOA, according to Table 3. As noted before, all the test runs exceed the 50 msec criterion.

If a friction coefficient of 0.5 is assumed instead of 0.6, the corresponding climbing distances, measured at an L/V ratio higher than Nadal's limiting value of 1.13, are listed in Table 6.

Table 6. Passenger Car Test Results
Distance Measured from the L/V Ratio Higher than 1.13 for Friction Coefficient of 0.5

Runs	Speed (mph)	L/V Maximum	Average L/V Ratio	Climb Distance (feet)
rn023	20.39	1.79	1.39	5.8
rn025	19.83	2.00	1.45	6.3
rn045	19.27	1.32	1.23	0.7
rn047	21.45	1.85	1.52	5.0

The run with the maximum L/V ratio 1.06 would then be acceptable because no climbing was calculated when the L/V ratio was lower than Nadal's limiting value. The run with the maximum 1.32 L/V ratio would be acceptable since the climbing distance was well below the 20 mrad AOAe criterion, as shown in Figure 30. The other three runs would be considered unacceptable because their climbing distances exceeded the 7.6 mrad AOAe criterion line.

The same conclusion can also be drawn if the conservative adjustment to AOAe is made as shown in Table 4. The conservative AOAe would be 12.6 mrad.

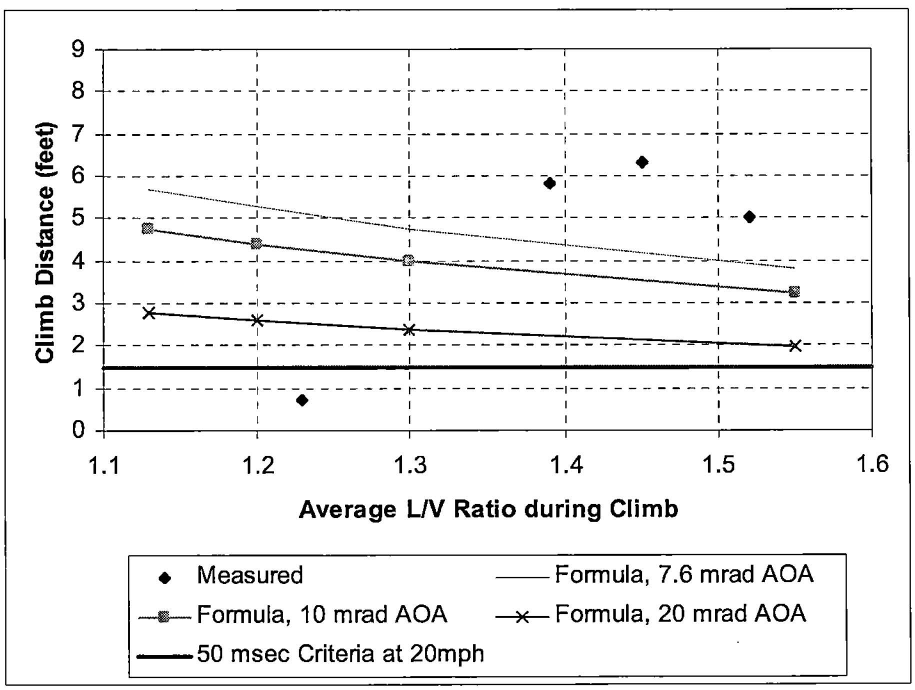

Figure 30. Comparison between New Criterion (Equation 15) and 50 msec Criterion

This passenger car test shows that Nadal's limiting L/V ratio value, the AAR Chapter XI criterion, and the 50-msec time-based criterion are more conservative than the new distance-based criterion for speeds around 20 mph. This means that critical L/V values would be permitted for longer distances under the new distance-based criterion at low speeds.

6.2 Application to an Empty Tank Car Derailment Test

The bi-parameter distance criterion was applied to an empty tank car flange climbing derailment that occurred during dynamic performance testing at TTC on September 29, 1998. The car was running at 15 mph through the exit spiral of a 12 degree curve. The L/V ratios and wheel/rail contact positions on the tread, measured from the instrumented wheelsets on the car are shown in Figures 31 through 34. Positive contact positions indicate contact on the outside of the wheel tape line, while negative values indicate contact on the flange side of the tape line. Negative values approaching -2.0 indicate hard flange contact. This is shown in Figure 33 for Wheel B, which is the wheel that derailed.

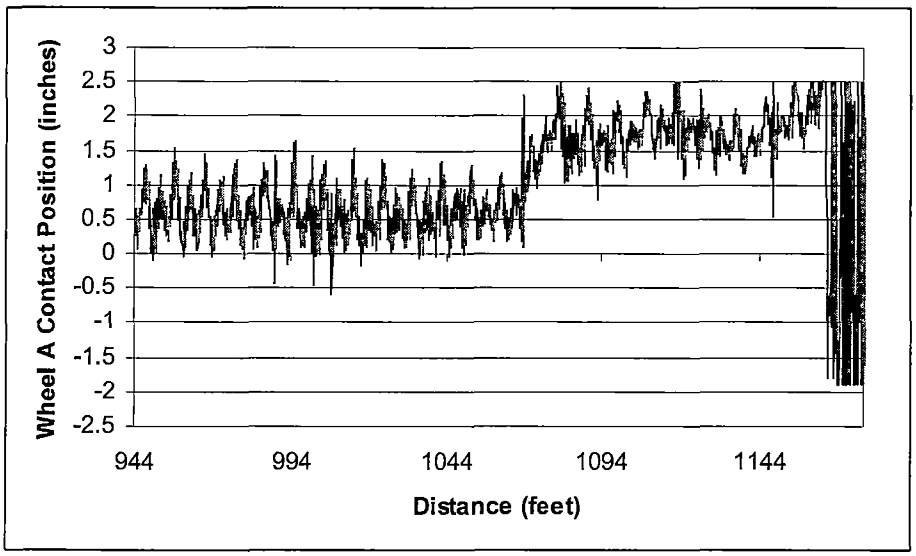

Figure 31. The Contact Position on Tread of Wheel A

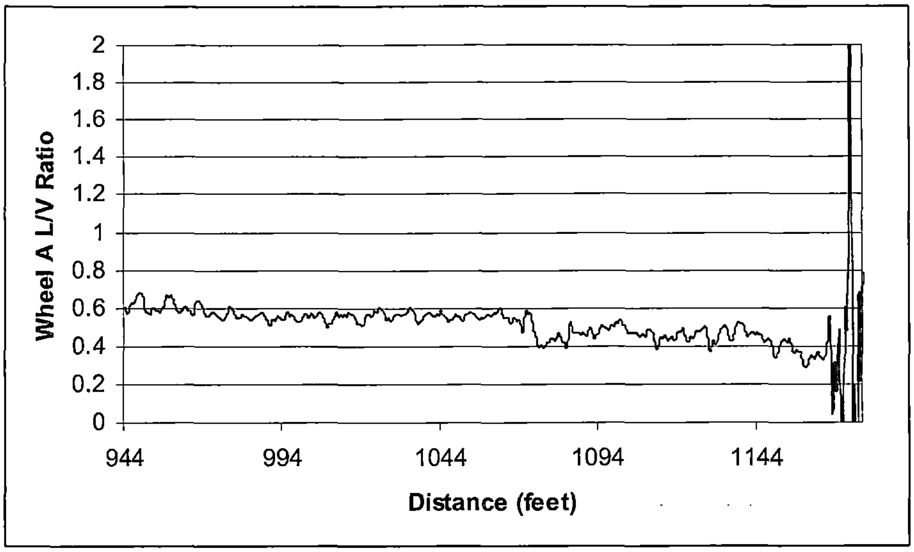

Figure 32. L/V Ratio of Wheel A

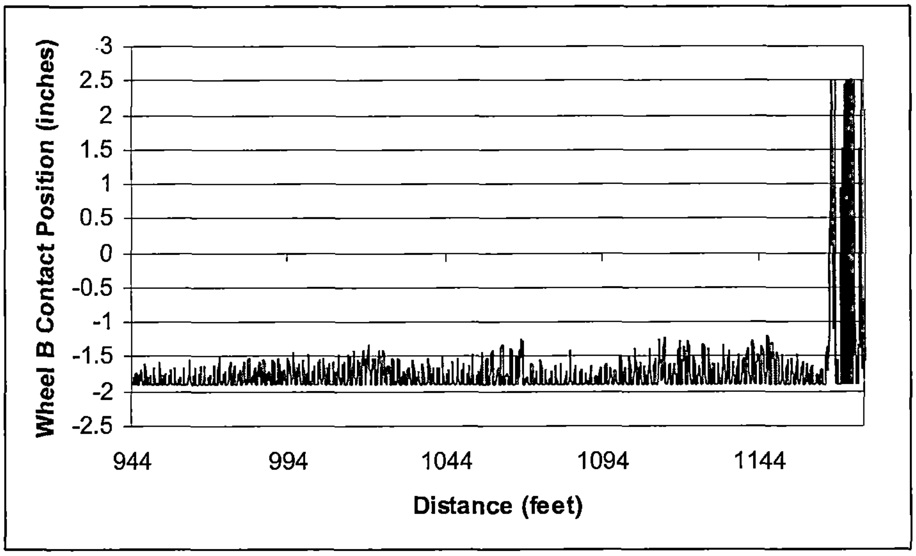

Figure 33. The Contact Position on Tread of Wheel B

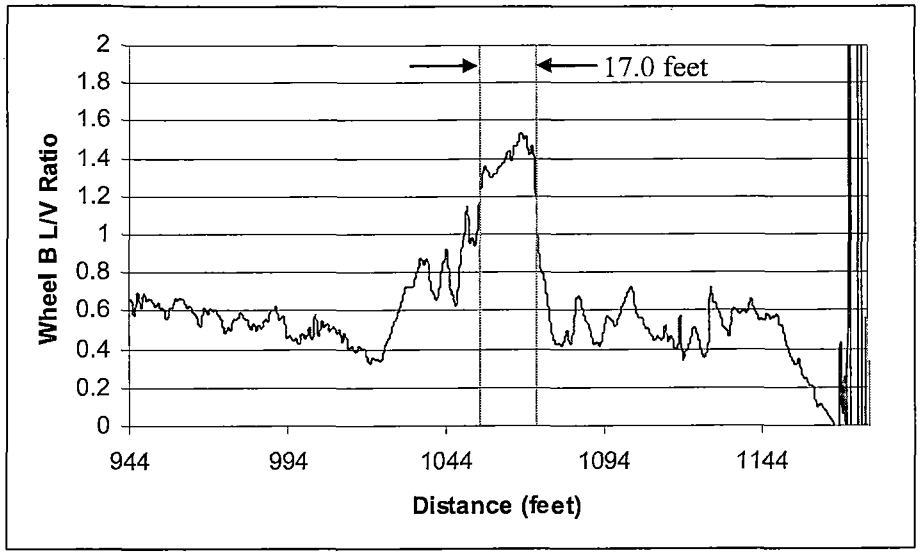

Figure 34. L/V Ratio of Wheel B

The climbing distance measured when the L/V ratio was greater than 1.13 (Nadal's limiting value for 75 degree flange angle and a 0.5 friction coefficient) is 17.9 feet, as shown in Figure 34. The average L/V ratio is 1.43 during the 17.9 foot climbing distance.

The data shown is for an instrumented wheelset that was in the leading position of the truck. The curvature of the spiral during the climb is about 9 degrees. The axle spacing distance for this tank car is 70 inches. The constant c was taken as 2.5, which represents a new bogie in Table 2. According to Equation 18, the AOAe should be approximately 11 mrad for the three-piece bogie at this location in the spiral curve.

According to Equation 15, for an 11 mrad AOAe the climbing distance is 3.3 feet. Since the measured climbing distance has exceeded the value of the bi-parameter distance criterion, the vehicle was running unsafely at that moment.

Wheel B started climbing at 1,054.6 feet and derailed at 1,164 feet. Therefore, the actual flange climbing distance is longer than 17.9 feet. As shown in Figure 34, the wheel climbed a longer distance on the flange tip, and the L/V ratio decreased due to the lower flange angle on the flange tip.

The empty tank car derailment test results show that the bi-parameter distance criterion could have been used as a criterion for the safety evaluation of wheel flange climbing derailment in this case.

7.0 SIMPLIFIED FLANGE CLIMBING DISTANCE CRITERION

According to the test results in Section 6.0, the maximum L/V ratio of 2.1 with and an average value of 1.6 represents the worst case for flange climbing. Using this average value and the worst estimation of AOA from Table 4, the flange climbing distance criterion can be simplified as shown in Table 7.

Table 7. Simplified Climbing Distance Criterion, for Average L/V Ratio Lower than 1.6, and Curvature Less than 20 degree

Curvature (degrees)		0	5	10	20
Flange Climb Distance Limit (feet)	Vehicles with IRW and Worn Three Piece Trucks	3	2	1.5	1
	Other Vehicles	4.5	3	2	1.5

This table could be used as a practical simplification of the bi-parameter criterion for flange climbing.

8.0 CONCLUSIONS

Based on the analysis of flange climbing simulations and test data, the following conclusions are drawn:

- A bi-parameter flange climbing distance criterion that uses the AOA and the L/V ratio as parameters is proposed for vehicles with AAR-1B wheel operating on AREMA 136 RE rail profiles, Equation 15:

$$\text{L/V Distance(feet)} < \frac{1}{0.001411 \times \text{AOA} + (0.0118 \times \text{AOA} + 0.1155) \times \text{L/V} - 0.0671} \qquad (15)$$

  where, AOA is in mrad. L/V is the average value of L/V ratio during the flange climbing distance.

- The L/V ratio in the criterion must be higher than the L/V limiting ratio that corresponds to the AOA and the friction coefficient as shown in Reference 8. The L/V limiting ratio equals to the Nadal's limiting value when the AOA is larger than 10 mrad. No flange climb occurs when the L/V ratio is lower than the L/V limiting ratio.

- The flange climbing distance increases with increasing vehicle speed and converges to a value. The bi-parameter flange climbing distance criterion derived from the speed of 5 mph is conservative for higher operating speeds.

- The bi-parameter flange climb distance criterion was partially validated using TLV test data. Since the vehicle speed in TLV tests was only 0.25 mph, the validation of the bi-parameter flange climbing distance criterion is limited. A full-scale validation test is recommended.

- Application of the bi-parameter flange climbing distance criterion to an H-frame truck undergoing AAR Chapter XI tests shows that the bi-parameter distance criterion is less conservative than the Chapter XI criteria and the 50 msec duration limit.

- Application of the bi-parameter flange climbing distance criterion to empty tank car derailment test results shows that the bi-parameter distance criterion can be used effectively for wheel flange climbing derailment analysis.

- The following simplified flange climbing distance criterion is proposed according to the track curve curvatures for the situation when the average L/V ratio is higher than 1.13 and lower than 1.6. It is considered rare that the L/V ratio would be higher than this range in practice, Table 7.

The following are some limitations for applying the bi-parameter flange climbing distance criterion:

- The bi-parameter flange climbing distance criterion is obtained by fitting the bi-linear in the data range where the AOA is larger than 5 mrad. It is conservative at lower angles of attack (<5 mrad) due to its nonlinear characteristic.

- The criterion is based on the simulation results for an AAR-1B wheel profile operating on a 136 RE rail. It is only valid for vehicles with this combination of wheel and rail profiles. For different wheel and rail profile combinations, the bi-parameter flange climbing distance criterion needs to be derived based on further simulations.

- The criterion can not be used directly where there is a guard rail.

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