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EFFECT OF WHEEL/RAIL LOADS ON CONCRETE TIE STRESSES AND RAIL ROLLOVER

Brian P. Marquis
Michelle Muhlanger
David Y. Jeong
U.S. Department of Transportation
Research and Innovative Technology Administration
Volpe National Transportation Systems Center
Cambridge, Massachusetts, United States

ABSTRACT

As a result of vertical and lateral wheel/rail forces, high contact stresses can develop at the interface between the rail base and tie. Under certain conditions, these stresses can exceed the strength of the concrete tie and result in deterioration of the tie and ultimately derailment due to rail rollover. This failure mode has been determined to be the probable cause of at least two derailments where the ties were found to have a triangular wear pattern. Following these derailments, a field investigation revealed this pattern of failure present in an appreciable portion of concrete ties [1]. Closed-form analyses have been conducted to examine combinations of wheel/rail loads and contact conditions that produce concrete tie rail seat deterioration or rail rollover. These results indicate that under certain circumstances truck-side L/V permitted by the Federal Railroad Administration (FRA) Safety Criterion on Wheel/Rail Loads can result in stresses above the AREMA specified minimum design compressive strength of concrete used in concrete ties. Furthermore the analysis indicated that under certain circumstances truck-side L/V permitted by the FRA Safety Criterion can result in rail rollover. The analyses show that rail rollover can be a problem for new concrete ties, but is more of a problem in the presence of rail seat deterioration described above.

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INTRODUCTION

Damage of concrete ties at the rail seat (often referred to as rail seat deterioration or RSD) can cause loss of rail fastener toeload and increase the likelihood of rail rollover derailment. In two independent Amtrak derailments in curve track, excessive RSD occurred on a sufficient number of consecutive ties that resulted in wide gage and ultimately rail rollover, Figure 1. In both of these derailments, the tie damage appeared triangular in shape, Figure 2, with a deeper void on the field side of the rail seat, that allowed the rail to tilt or roll outward under load, increasing track gage, and permitting the wheels to drop on the ties causing a derailment.

Figure 1: Rail Rollover in Curve Track due to Consecutive Ties having Damage at Rail Seat

Previous research of these derailments, sponsored by the FRA Office of Research and Development and conducted by the Volpe National Transportation Systems Center (Volpe Center), attributed the triangular shape of the deterioration to rail seat pressures that are greater than the minimum specified compressive strength of the concrete tie at the rail seat field side. In normal operation, compressive overloading (crushing) and repeated wheel loading produced stresses that initiated breakdown at the tie surface **[**2**,**3**]**. NUCARS simulations were conducted using measured track geometry taken prior to derailments to estimate the dynamic wheel loads. The rail seat pressure distributions calculated from these loads was triangular in shape (similar to the observed tie damage pattern) and on the field side exceeded the AREMA specified minimum 28-day-design compressive strength of concrete used for concrete ties of 7,000 psi [4].

Figure 2: Concrete Tie with Triangular Pattern of Damage at Rail Seat, Damage Deeper on Field Side.

During investigation of these derailments, comparisons were also made to the safety criterion used by FRA for rail rollover (truck-side L/V criterion in Table 1) [5]. Rail rollover is a sudden failure of the rail to maintain its proper vertical orientation under load, and the safety criterion used to prevent rail rollover is a truck-side lateral to vertical (L/V) force ratio. This ratio assumes that a rail has zero cant (rails are commonly installed with a 1:40 cant inward toward the track center) and that the wheel rail contact is fixed at a nominal position on the gage corner of the rail. The ratio will indicate if the resultant load on the rail falls outside the edge of the rail base, and the roll moment about the rail section corner has changed sign. Although this criterion is generally considered conservative because it ignores the effect of rail restraint forces from the fastener system and the rail torsional resistance (i.e. assumes tipping of an unrestrained rail), it is generally recognized that any overturning moment is undesirable.

Table 1: Wheel/Rail Force Safety Criterion used by FRA for Prevention of Derailment

Parameter	Safety Limit	Filter/Window
Single Wheel Vertical Load Ratio	≥0.15	5 foot window
Single Wheel L/V	$\le \frac{\tan(\delta) - 0.5}{1 + 0.5\tan(\delta)}$ [1]	5 foot window
Net Axle L/V	$\le 0.4 + \frac{5.0}{Va}$ [2]	5 foot window
Truck-side L/V	≤0.60	5 foot window

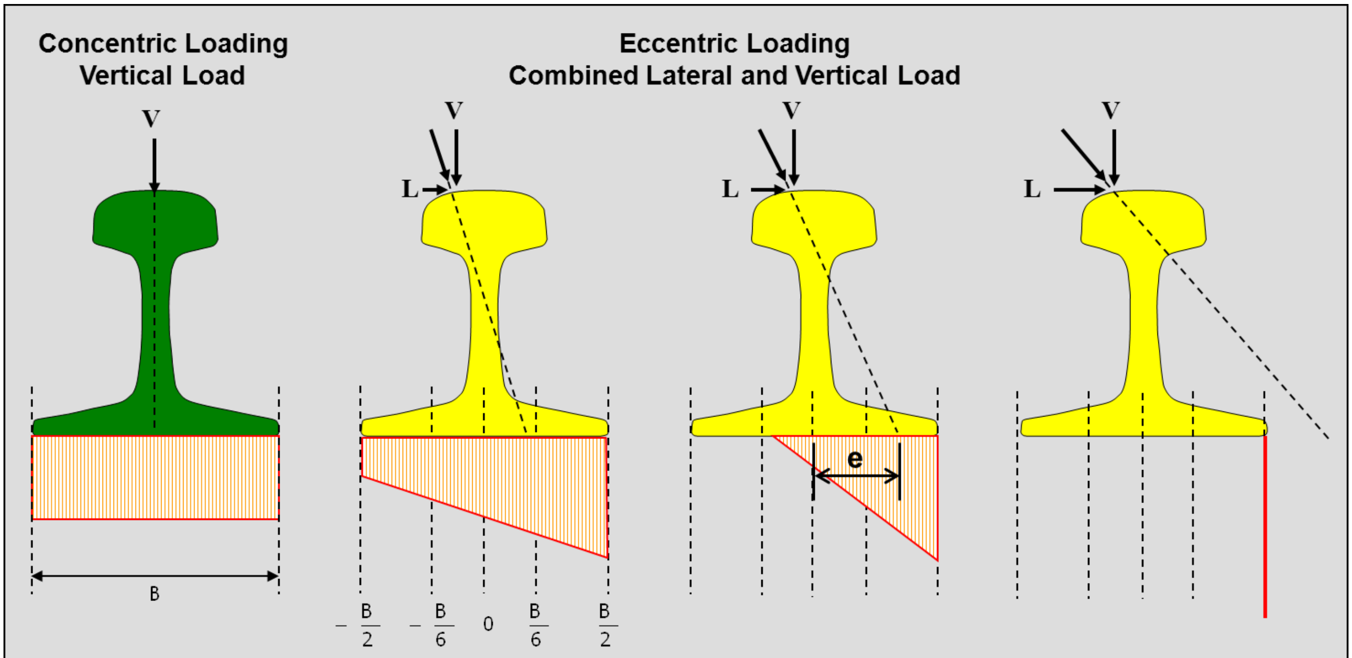
[1] δ – Flange angle in radians
[2] Va – Vertical axle load in kips

For many standard rail sections, the typical contact location is such that this ratio is on the order of 0.6 in flanging conditions. This ratio is computed on a truck side basis since it can be exceeded at a single wheel without the occurrence of rollover because adjacent wheels may hold the rail down. The wheel loads calculated from the results of NUCARS simulations indicated that truck-side L/Vs below the FRA 0.6 safety criteria were present at the time of these two rail rollover derailments, an indication that under certain conditions this criterion may not be conservative enough.

This paper describes closed-form analysis that have been conducted to examine combinations of wheel/rail forces, rail cant, and contact conditions that produce concrete tie rail seat deterioration and rail rollover. These results indicate that under certain circumstances truck-side L/V below the FRA Safety Criterion can result in rail seat pressures that are greater than the minimum specified compressive strength of concrete ties. Identification of critical truck-side L/V loads can provide the technical basis for redesigning the tie structure. Furthermore the analysis indicated that under certain circumstances truck-side L/V below the FRA Safety Criterion can result in rail rollover.

ESTIMATATION OF RAIL SEAT PRESSURE AND RAIL ROLLOVER DUE TO ECCENTRIC WHEEL FORCES

Figure 3 shows schematically the rail seat pressure distribution due to four possible cases of forces imposed on the rail by the vehicle. The concentric loading case, Case 1, which occurs from a vertical force applied at the rail center, creates a pressure distribution on the concrete tie that is for practical purposes uniform throughout the rail seat and its intensity is equal to the total applied load divided by the total area. In this case there is no concern for overturning or crushing of concrete due to compressive overloading.



Case 1: e = 0	Case 2: 0 ≤ e < B/6	Case 3: B/6 ≤ e ≤ B/2	Case 4: B/2 ≤ e
$p = \frac{V}{B}$	$p = \frac{V}{B}\left(1 + \frac{6e}{B}\right)$	$p = \frac{V}{B}\frac{4B}{3(B-2e)}$	$p = \infty$

Figure 3: Rail Seat Pressure and Rail Rollover from Eccentric Lateral and Vertical Wheel/Rail Loads

When a rail is subjected to forces (vertical forces, lateral forces, or both) such that the point of application of the resultant of all the forces would lie outside the geometric center of the rail base, eccentricity in loading results. The resultant eccentric force induces an overturning moment to the rail and the pressure on the tie is not uniformly spread. In this case, both stability against overturning and the pressure distribution under the rail base should be assessed to ensure that the rail does not roll and the maximum pressure does not exceed the compressive strength of concrete used in concrete ties when subjected to permissible but extreme wheel loads. The rail seat pressure varies from a maximum on the side of the eccentricity to a minimum at the opposite side, or to zero at some intermediate point depending on the magnitude of the eccentricity. When the maximum pressure exceeds the compressive strength of concrete used in concrete ties, local crushing of the supporting tie at the tie surface on the side of eccentricity is presumed to occur. In this paper, the approximate maximum pressure for a given eccentric loading is determined using the formulae in Figure 3 which are commonly used to evaluate the pressure at the base of a footing subjected to a direct load P and a moment M [6]. These formulae assume that the variation of rail seat pressure between the two extremes is linear, the rail acts as a rigid structure, and that the bodies in contact are uniform. These assumptions are not strictly valid, but are considered sufficiently accurate and useful in estimating rail seat pressures.

The three eccentric loading cases shown schematically in Figure 3 result from progressively larger truck-side L/V ratios:

1) If the truck-side L/V ratio is low, the resultant will fall in the middle third of the rail and give a trapezoidal pressure distribution, Case 2.
2) As the truck-side L/V ratio increases, the resultant will fall in the outer third of the rail and give a triangular pressure distribution, Case 3. In this case the gage side of the rail begins to unload and the maximum stress can exceed the bearing strength of the tie.
3) At an extreme truck-side L/V ratio, the resultant will point outside the rail base, Case 4, and the roll moment about the center of rotation changes sign and the rail begins to roll.

For the analysis conducted in this paper the following dimensions were assumed: rail base B = 6 inches, and concrete tie width = 11 inches. There are two key values of eccentricity, e (the position of the resultant relative to the center of the rail base), for a 6 inch rail seat. At greater than or equal to 1 inch of eccentricity, the pressure is no longer distributed along the entire base of the rail and at greater than 3 inches of eccentricity, the pressure is concentrated on the outside edge of the rail and there is a high risk of rollover depending on the condition of the fasteners.

Condition 1: Zero Rail Cant Assumed

The location of the point of wheel and rail contact is described using the ratio, D/H, where D is the horizontal distance from the outside of the rail base, and H is the height from the bottom of the rail base, H. Figure 4 shows the eccentricity for different values of truck-side L/V when the rail has zero cant and the forces are applied at a fixed contact point location where the ratio D/H = 0.6 (this corresponds to a nominal gage contact location in flanging condition). The wheel load, which is used in these calculations (and all of the calculations in this paper) to compute vertical load, is held constant at 30 kips (a value of 30 kips was chosen to represent the wheel load of the locomotive in the Amtrak derailments). In addition, the rail was assumed to be discretely supported on ties, with each tie supporting a portion of the total applied lateral and vertical forces. In these examples, the tie directly under the load was examined and it supported 40% of the total vertical load and 45% of the total lateral load.

In general, eccentricity, e, is a function of both L and V (and in particular the L/V ratio), however, in this example V is held constant. As L/V is increased, the resultant load transitions from pointing straight down to shifting outward on the rail seat, as shown schematically in Figure 3. Truck-side L/V ratios greater than 0.6, the FRA safety limit, are shaded tan to indicate these are generally not expected to occur in service for well-maintained track and equipment. The two horizontal black lines separate the three different eccentric loading cases described above and shown in Figure 3. Since a rail base of 6 inches is used, an eccentricity of 3 in indicates when the resultant lies outside the base. An eccentricity of 3 in occurs at a truck side L/V of 0.6. An L/V value of 0.6 or higher corresponds to $p = \infty$ and rollover of an unrestrained rail.

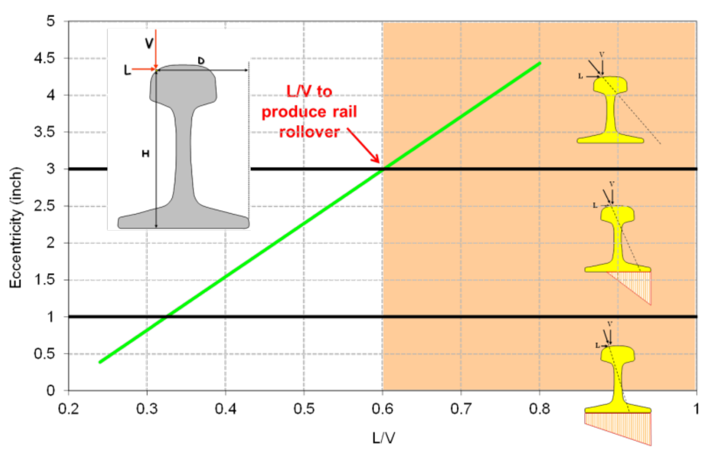


Figure 4: Eccentricity, e, due to an Eccentric Loading L/V, Contact Point at D/H = 0.6

Using the pressure distribution equations shown in Figure 3, the maximum stress is plotted for different values of lateral load and vertical load in Figure 5. For these calculations, the contact point location is held fixed at D/H equal to 0.6. A higher axle load would shift the green curve to the left. The horizontal black line in Figure 5 highlights the AREMA specified minimum design compressive strength of concrete used for concrete ties of 7,000 psi. Figure 5 shows that the maximum stress on the concrete increases rapidly for small increases in L/V for truck-side L/Vs above 0.5. The truck-side L/V required to produce 7,000 psi is approximately 0.51 and there is no margin of safety for truck-side L/V ratios approaching 0.6 which are permitted by the FRA Safety Criterion on Wheel/Rail Loads. As a result, for this case with zero rail cant, the compressive strength of the concrete could not be practically increased to prevent overloading the tie structure and maintain a safe condition for all truck-side L/V values up to the limit of 0.6.

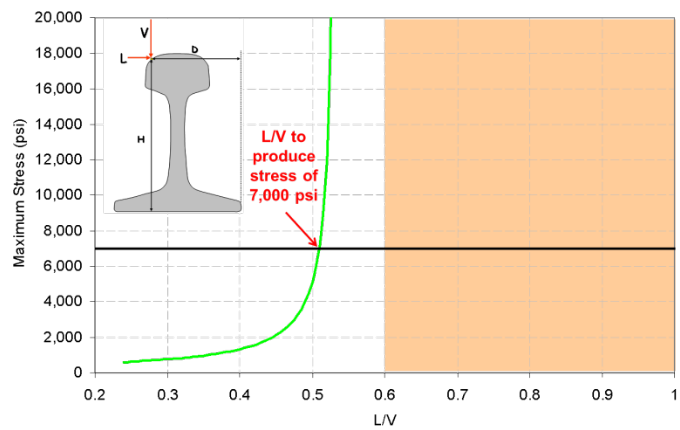


Figure 5: Maximum Rail Seat Pressure (stress) on Field Side due to Eccentric Loading L/V, Contact Point at D/H=0.6, 60 kip axle load

Condition 2: Effect of Rail Cant Included

Figure 5 shows the overstressed conditions that can occur for a rail with zero cant. When the rail is canted outward, the undesirable effects of the eccentric loading becomes more severe, thus reducing critical truck-side L/V required to cause rail rollover and overload. The next analyses examine the effect of rail cant on critical truck-side L/V to produce rail rollover and pressures exceeding the bearing capacity of the tie. Figure 6 shows the convention for a right rail with inward cant ($-\theta$), zero cant, and outward cant ($+\theta$), where θ is the angle between the rail and the ground. The contact point is referenced in the rail coordinate by the dimensions D and H. However, the forces L and V are defined in the track coordinates.

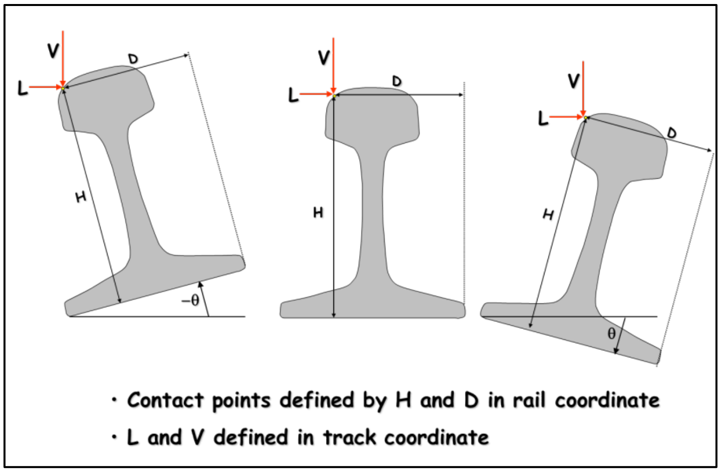


Figure 6: Convention for Designation of Contact Point (D/H), Wheel/Rail Load (L/V), and Rail Cant (θ)

When taking into account the effect of rail cant, eccentricity, e, (defined in the rail coordinate) is generally a function of L, V, and θ, however, in this example, V is held constant. As L/V is increased, the resultant load transitions from pointing straight down to shifting outward on the rail seat. Figure 7 shows the eccentricity as a function of truck-side L/V for three values of rail cant. An angle of 1.43 degrees corresponds to a rise over run of 1/40 for the rail. For a rail with an inward cant of -1.43 degrees, the L/V required to roll the rail is approximately 0.65. For an outward canted rail, the truck-side L/V required to roll the rail is approximately 0.56, less than the 0.6 truck-side L/V ratio permitted by the FRA Safety Criterion on Wheel/Rail Loads.

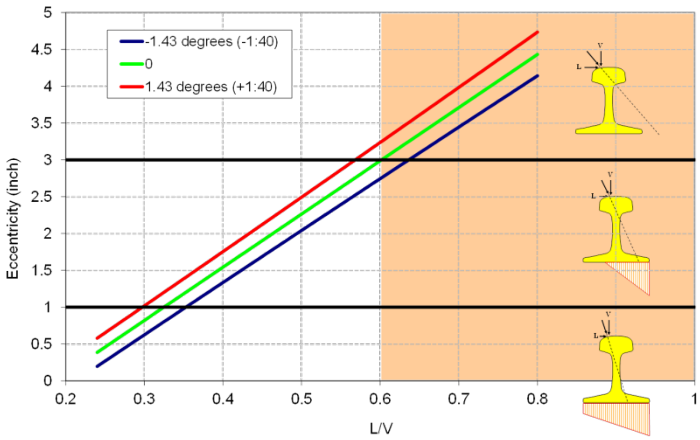


Figure 7: Effect of Cant Angle on Eccentricity e, Contact Point at D/H = 0.6

The cant of the rail also affects the stress distribution along the rail seat. In Figure 8, the maximum stress on the rail tie is shown as a function of truck-side L/V ratio for three values of rail cant. The horizontal black line in Figure 8 highlights the AREMA specified minimum design compressive strength of concrete used for concrete ties of 7,000 psi. L/V ratios above 0.6 are shaded as they are not permitted by the truck-side L/V safety criteria. For a rail with an outward cant of -1.43 degree, the truck-side L/V that creates a maximum stress above 7,000 psi is approximately 0.54. All of these rail cant orientations exceed 7,000 psi well before the maximum 0.6 truck-side L/V ratio permitted by the FRA Safety Criterion on Wheel/Rail Loads are reached. This creates a potential for rail seat deterioration, and eventually rail rollover. Also, if the rail seat starts to deteriorate, the rail will be moving towards a more vertical, and eventually an outward cant position. As the rail is allowed to roll outward, the truck-side L/V ratio required to exceed the compressive strength of the concrete is lowered. This could lead to a rapidly deteriorating situation that ultimately results in derailment.

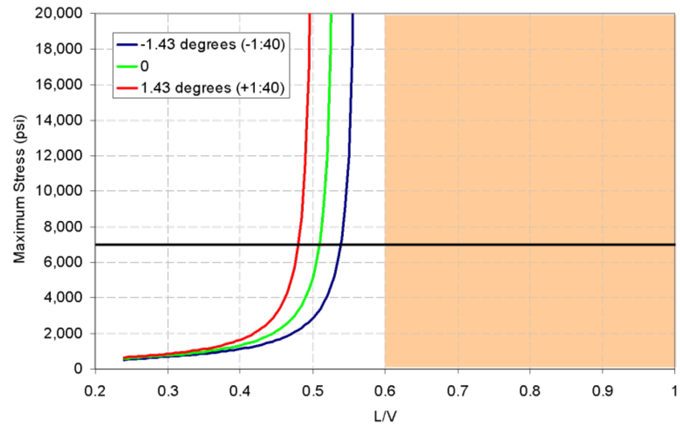


Figure 8: Effect of Cant Angle on Maximum Rail Seat Pressure, Contact Point at D/H=0.6, 60 kip axle load

Prevention of rail rollover and rail seat deterioration (which leads to wide gage and rail rollover derailments) are both important in maintaining safe operation. Figure 9 shows both the truck-side L/V required to roll the rail and the truck-side L/V required to reach the compressive strength of 7000 psi as a function of cant angle. Figure 9 shows that the L/V values that cause stress levels exceeding the compressive strength of the concrete in concrete ties are less than the L/V required to cause rail rollover. Furthermore, pressures increase rapidly for small increases in truck-side L/V, as shown in Figure 5 and Figure 8. Inward cant is desirable since it helps to orient the resultant eccentric force closer to the midpoint of the rail base thus reducing the moment that tends to roll the rail outward. However, a rail cant of -1.43 degrees, which is used in typical applications, highlighted by the dashed vertical line, is insufficient to prevent overloading of the concrete for all permissible truck-side L/V values. Outward cant is undesirable because it causes the pressure under the rail seat to increase further and it decreases the truck-side L/V necessary to produce wide gage and rail rollover derailments.

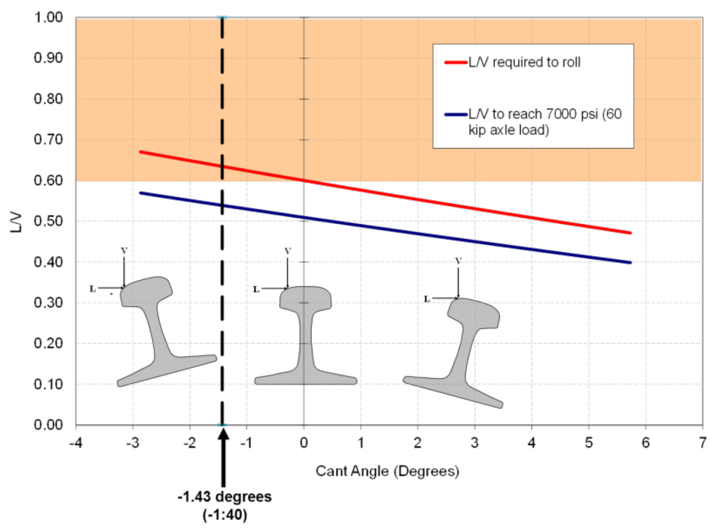


Figure 9: Effect of Cant Angle on L/V Required to Produce 7,000 psi and Rail Rollover, Contact Point at D/H=0.6, 60 kip axle load

EFFECT OF RAIL CANT, CONTACT LOCATION (D/H), AND CLIP FORCE ON RAIL ROLLOVER CRITERIA

In the previous section, the wheel rail contact is assumed to be fixed at the gage corner of the rail corresponding to a typical flanging condition for new rails and wheels of D/H = 0.6, i.e. at the location corresponding to the L and V forces shown in Figure 10. This is not generally the most harmful condition in terms of rail rollover (or maximum pressure on the rail seat field side). Under certain circumstances, such as a worn wheel and/or worn rail (Figure 11), the contact point is likely to be near the rail center and perhaps even closer to the field side. This reduces the moment arm, D, from the pivot corner to the line of action of the vertical load and may make the rail more likely to roll. For the next discussion, a set of contact locations, shown in Figure 10, with D/H ranging from 0.65 to 0.4 are chosen to examine the effect on rail rollover.

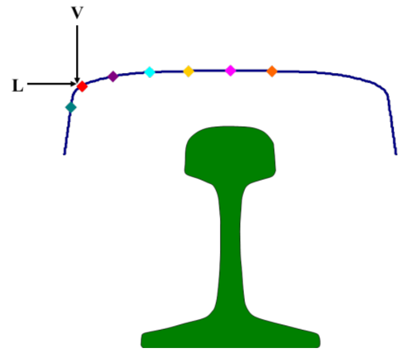


Figure 10: Variation in Contact Point along Rail Surface Required to Achieve Various D/H, (from left to right D/H=0.65, 0.6, 0.55, 0.5, 0.45, 0.4)

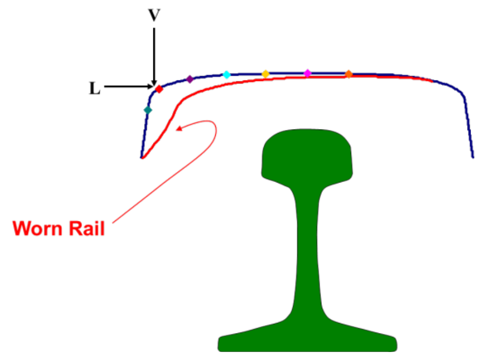


Figure 11: Variation in Contact Point along Rail Surface, D/H=0.65, 0.6, 0.55, 0.5, 0.45, 0.4, with worn rail superimposed for reference

There are several different methods to evaluate the effect of eccentric forces applied to a rail and rail rollover. The previous results (shown in Figure 4, Figure 7, and Figure **9**) determined when the resultant load on the rail falls outside the edge of the rail base, i.e. the eccentricity e was greater than 3. This was convenient because calculation of eccentricity was needed for calculation of rail seat pressure. When determining the effect of clip force on rail rollover, it is more convenient to determine when the roll moment about the rail section corner changes sign. To determine the L/V needed to produce an overturning moment, a sum of moments about the corner of the rail is done with the equations shown in Figure 12. If the rail is assumed to be unrestrained then no clip force is included in the moment calculation, left side of Figure 12, and the L/V required to produce rail rollover is simply a function of the contact location (D/H). Inclusion of the clip force C on the gage side will help to reduce rail rollover. In this case the L/V required to produce rail rollover will be a function of the contact location (D/H) and the axle load V.

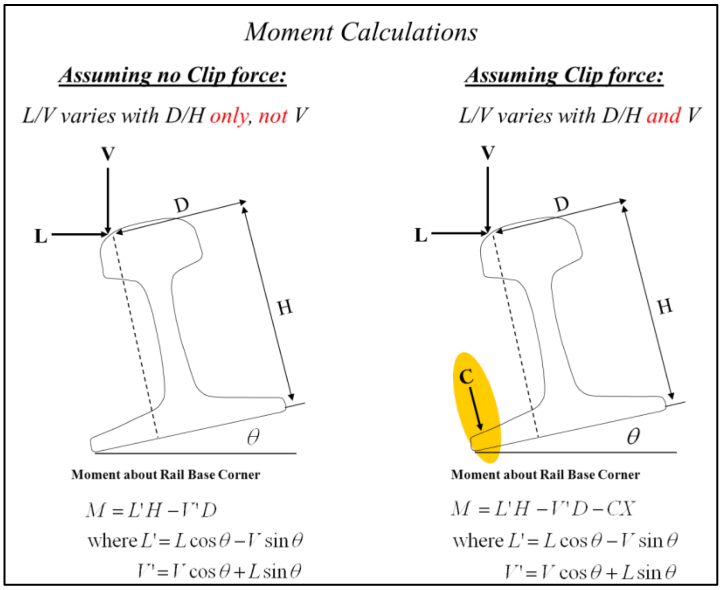


Figure 12: Calculation of Overturning Moment with and without Clip Force (C)

Figure 13 shows the effect of the contact location and cant angle on the L/V required to produce rail rollover. The clip force is not included in these calculations. The arrows point to the D/H of 0.6, which was shown in Figure **9**. The lower lines correspond to a contact point closer to the field side and center of the rail. As the contact point is shifted closer to the center of the rail, the L/V required to produce rail rollover decreases significantly. For almost all the locations with a worn rail, a truck-side L/V much less than 0.6 would roll the rail and cause compression failure of concrete.

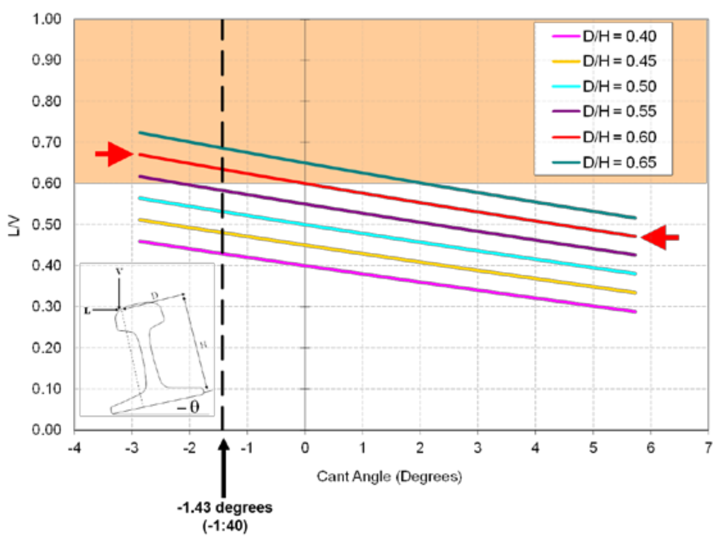


Figure 13, Effect of Contact Location on Rail Rollover Criteria, assuming no clip force

Figure 14 shows the effect of rail cant, contact location, and clip force on the L/V required to produce rail rollover. Including the clip force slightly increases the L/V values necessary to roll the rail. With a clip force of 4,000 lb and an inward cant of -1.43 degrees a D/H value as low as 0.55 will not roll at an applied L/V of 0.6. Without the clip force, the rail is predicted to roll at this value.

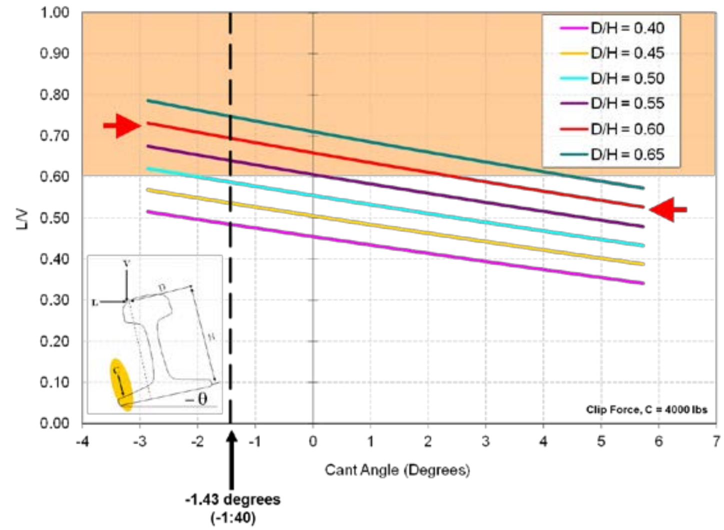


Figure 14: Effect of Contact Location on Rail Rollover Criteria, assuming 4,000 lb clip force

DISCUSSION

The results shown above indicate that combinations of vertical and lateral wheel forces resulting from track geometry irregularities or poorly maintained trucks can explain a newly observed type of concrete tie rail seat deterioration characterized by a loss of material under the field side of the rail. This failure mode has been found wide spread on certain sections of track during surveys sponsored by FRA, and has been the cause of at least two Amtrak derailments. This failure mode results from resultant eccentric force that produce field side rail seat pressures that exceed the compressive strength of the concrete in concrete ties. It develops over time with repeated loading. Progressive crushing of the tie beneath the rail seat may increase the outward cant over time. The increased outward cant causes the pressure under the rail seat to increase further until finally derailment occurs by rail overturning or wide gage. Truck-side L/Vs less than the FRA criteria of 0.6 are sufficient to cause this rail seat deterioration pattern for many different combinations of rail cant and contact location. These results were for an assumed axle load of 60 kips and would be more severe for higher axle loads. Beyond a certain truck-side L/V, for example a value of 0.5 for the case shown in Figure 5, pressures increase rapidly for small increases in L/V and when rail is canted outward. Ideally ties should be designed in such a way that the point of application of the resultant eccentric load is located close to the midpoint of the base as possible. However this is difficult given the range of possible contact locations and rail cant. Inward rail cant helps to orient the resultant eccentric force closer to the midpoint of the rail base thus reducing the moment that tends to roll the rail outward, but is not sufficient to maintain an eccentric load within the base depending on the contact point location, such as those see with worn profiles, and the magnitude of truck-side L/V.

The results also show that truck-side L/Vs less than the FRA criteria of 0.6 are sufficient to cause rail rollover under many different combinations of rail cant and contact location. The truck-side L/V required to cause rail rollover (if rail assumed unrestrained) is a function of contact location (D/H) and cant angle (not axle load). However, rail rollover will also be a function of axle load if the rail is assumed to be restrained by a clip force C.

Potential approaches to mitigating safety concerns over rail seat deterioration include but are not limited to:

- reduce the allowable truck-side L/V loads
- redesign the tie structure taking into account critical truck-side L/V loads
- redesign the rail-tie interface – establish a larger contact area to spread the load
- set tolerances on unacceptable amount of rail seat deterioration and rail cant.

In order to address concerns over rail rollover, revisions to the FRA truck-side L/V criterion should be considered. The factor of safety inherent in this "conservative" criterion is unknown and, as demonstrated in the analyses here, at times not present. Either a new lower limit could be established to account for additional situations beyond the case of rail with zero cant and contact at D/H = 0.6, or a new criterion could be developed that takes into to account different contact locations and rail cant to provide a margin of safety in these conditions. Improvements to the truck-side L/V criterion will also help to address safety concerns over rail seat deterioration.

Ongoing work is developing a FEM model to confirm results shown in paper using closed form expressions. In addition, to understand the mechanism of rail seat deterioration and rail rollover, as well as to validate or develop new criteria, future work will involve testing to investigate compression failure (crushing) for a variety of vertical and lateral force combinations up to and including critical levels. This testing will load sections to failure under the conditions representative of the failure modes in question. Finally, ongoing work is examining, through VTI modeling, what conditions produce critical truck-side L/Vs and how to mitigate these conditions.

ACKNOWLEDGEMENTS

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