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EFFECT OF DESIGN RAIL CANT ON CONCRETE CROSSTIE RAIL SEAT PRESSURE DISTRIBUTION

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ABSTRACT

Previous research has focused on the effect of rail cant on rail wear and wheel/rail interaction, indicating that a steeper rail cant results in increased wear on rails and wheels. However, no research has investigated the effect of rail cant on the crosstie rail seat pressure distribution. Past research at the University of Illinois at Urbana-Champaign (UIUC) looked into the effect of negative (reverse) rail cant on pressure distribution across the rail seat utilizing matrix-based tactile surface sensors (MBTSS) on artificially created rail seat wear profile at TTC, Pueblo. These results showed that the pressure distribution became more non uniform with increasing negative rail cant. This paper looks into the effect of 'design' rail cant on pressure distribution across the rail seat. Static tests were carried out on 1:30 and 1:40 cant crossties imparting a predefined sequence of vertical and lateral load combinations. MBTSS and potentiometers were used to measure pressure distribution and rail rotation respectively. The 1:30 cant distributed load more evenly than 1:40 cant at lateral to vertical force ratios greater than 0.4. The two rail cants did not show significant differences in the values of average pressure, contact area, or rail rotation.

INTRODUCTION

North America freight railroad infrastructure is being subjected to heavier freight car axle loads and increased tonnages due to increases in rail car maximum gross rail loads and growing freight traffic volumes. As a result of these developments, the use of concrete crossties and fastening systems has increased [1]. However, several heavy haul freight railroads in North America have encountered rail seat deterioration (RSD), which has prevented concrete crossties from achieving their intended life cycles. RSD is the degradation of the concrete at the rail seat and may also be referred to as rail seat abrasion (RSA). North American industry experts ranked RSD as the most critical problem facing concrete crossties and fastening systems in a North American rail industry survey conducted by Zeman in 2009 [2] at the University of Illinois at Urbana-Champaign (UIUC) and an international survey conducted in 2012 by Van Dyk [3]. Furthermore, the international survey performed by Van Dyk reported that RSD was a problem that was specific to North America and was in fact considered the least critical problem internationally [3]. Zeman's survey helped identify as many as six potential mechanisms of RSD [2]. He determined that cavitation erosion was not a feasible failure mechanism in field conditions [2] and that as many as four of the five feasible mechanisms were influenced by the pressure distribution across the rail seat [2]. As a result, considerable research has been undertaken to better understand the distribution of the rail seat load, and its effect on rail seat deterioration. Previous research at UIUC has highlighted the effect of rail pad modulus, fastening system type, loading environment, and negative rail cant on the rail seat load distribution [1, 4, 5].

Rail cant is one of several factors that is believed to affect the pressure distribution across the rail seat. Rail cant has been commonly defined as the amount of rail rotation relative to horizontal, typically inward toward the gauge side [6]. It is a common design feature of concrete crossties as shown in Figure 1. A literature review has shown that most of the rail cant research conducted thus far has focused on the effect of rail cant on wheel and rail interaction, specifically the wear of these components. The standard value of rail cant differs throughout the international railway community, and the most common values of rail cant are 1:20, 1:30 and 1:40 [7]. In order to optimize the amount of wear at the wheel and rail, some railroads have opted for 1:40 rail cant.

This paper aims to quantify the effect of the 'design' rail cant on the pressure distribution across the rail seat of a concrete crosstie.

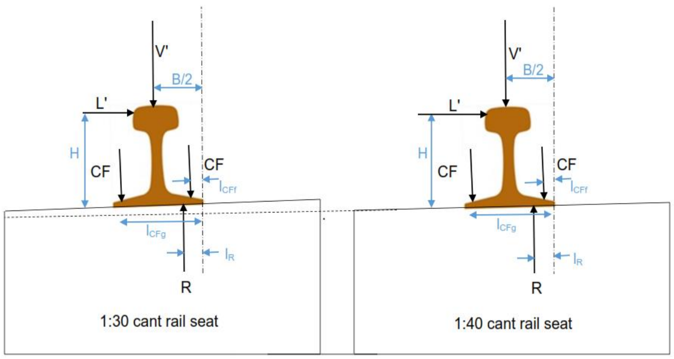


Figure 1: Free Body Diagrams of 1:30 and 1:40 Cant Rail Seats.

The rail cant values selected for the analysis are 1:40 and 1:30, two designs that are used within North America. To quantify the effect of this change in rail cant, the induced moment about the field side base of rail was calculated using Equations 1, 2, and 3. Figure 1 aids in illustrating the symbols used in Equations 1, 2, and 3.

$$M_L = (V' \times B/2) - (L' \times H) + CF \times (l_{CFg} + l_{CFf}) - R \times l_R \quad (1)$$

where,

M_L: Induced Moment from actuator loads
V: Applied vertical load
V' : Vertical wheel load relative to rail seat
L: Applied lateral load
L': Lateral wheel load relative to rail seat
B: Width of base of rail
H: Height of rail
θ: Respective rail cant angle
CF: Clamping force applied by fastening system clip
l_{CFg} : Moment arm to gauge side clamping force from rail base field
l_{CFf} : Moment arm to field side clamping force from rail base field
R: Rail seat reaction
l_R : Moment arm to reaction from rail bas field
where,

$$L' = V \sin\theta + L \cos\theta \quad (2)$$

$$V' = V \cos\theta + L \sin\theta \quad (3)$$

To quantify what was expected to cause the greatest change in induced moment the following was assumed: a 30 kip (134 kN) vertical load and 18 kip (80 kN) lateral load were applied to 136RE rail with a 6” (152.4 mm) base and height of 7.1325” (181.2 mm), and 2.5 kip (11.1 kN) clamping force acting 0.25” (6.4 mm) from the edge of each side of the base of rail, and the rail seat reaction being triangular increasing from 1” (25.4 mm) towards the gauge-side of center of the rail base and reaching a maximum at the field-side rail base edge [1]. The 1:30 cant crosstie only exhibited a 1% reduction in moment when compared to the 1:40 cant rail seats. Therefore, based on preliminary calculations it was hypothesized that 1:30 cant and 1:40 cant crossties will not display significant changes in rail rotation or rail seat contact area.

Previous research at UIUC carried out by Greve looked into the effect of negative rail cant on pressure distribution on the rail seat [1]. The rail cant was created by way of artificial triangular wear profiles with zero wear on the gauge side and a certain wear depth on the field side, resulting in a negative rail cant. Although the rail cants examined are not standard cant profiles, they provided valuable insights. These data indicated a trend of increasing maximum pressure with decreasing rail cant. This agrees with previous research that found that increased negative rail cant indicates greater rotation of the rail towards the field side, which decreases rail seat contact area [1]. However, it must be noted that the field experiments carried out on negative rail cant utilized worn fastener rail clips, which may have contributed to the rail rotation.

Instrumentation Technology

Matrix-based tactile surface sensors (MBTSS) have been extensively used by UIUC researchers to measures the pressure distribution across the rail seat [1, 4, 8, 9]. The MBTSS systems used by UIUC are manufactured by Tekscan® Inc. and consists of rows and columns of pressure sensors which can detect the pressure and relay that information to the data acquisition system.

The data acquisition handle is used to collect data from the MBTSS. It is connected using a USB connection to a computer system which has the requisite software installed. Along with collecting information on the magnitude of pressure, data on contact area are easily obtained based on the number of sensors that detect load and the fact that their area is known [1]. MBTSS are a sensitive instrumentation type and are susceptible to shear damage and puncture. To provide protection, polyethylene terephthalate (BoPET) and polytetrafluoroethylene (PTFE) are used as shown in Figure 2.

It can be seen that the experimental matrix (Table 1) was designed to gradually increase the vertical and lateral forces until an L/V force ratio of 0.6 was obtained for a vertical force of 30 kips (134 kN). The AREMA Manual for Railway Engineering, Chapter 30 (Ties), shows that for a concrete crosstie spacing of 24 inches (609 mm), the average value for the rail seat load directly below point of loading is 50% of the total vertical wheel load [10]. However, there can be significant variation in this load distribution due to support conditions in field [11]. To account for this variability, the run matrix was designed to investigate the pressure distribution at vertical loads of 10 kips (44.5 kN), 20 kips (89 kN), and 30 kips (134 kN) as they correspond to the 25%, 50%, and 75% of 40 kips (178 kN) respectively. 40 kips (178 kN) represents a 95 percentile nominal vertical wheel load in North American heavy haul freight service [11].

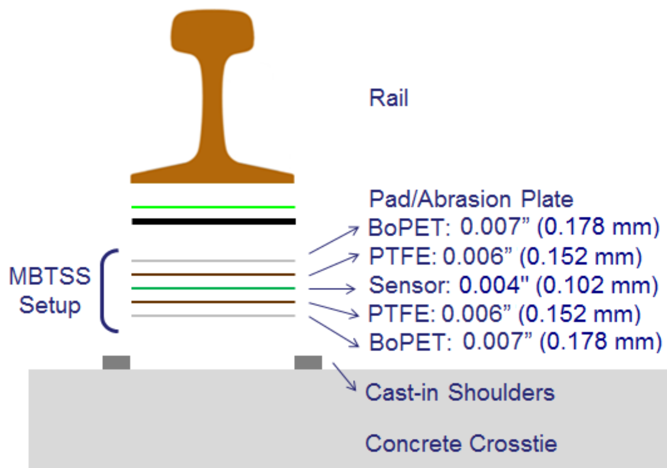


Figure 2: MBTSS Setup with Layers and Thicknesses (1).

Table 1: Run Matrix of Static Test

Sequence	Vertical Load	Lateral Load	L/V	Sequence	Vertical Load	Lateral Load	L/V
1	0	0	-	16	20	6	0.3
2	1	0	0	17	20	8	0.4
3	5	0	0	18	20	10	0.5
4	10	0	0	19	20	12	0.6
5	10	1	0.1	20	20	0	0
6	10	2	0.2	21	25	0	0
7	10	3	0.3	22	30	0	0
8	10	4	0.4	23	30	3	0.1
9	10	5	0.5	24	30	6	0.2
10	10	6	0.6	25	30	9	0.3
11	10	0	0	26	30	12	0.4
12	15	0	0	27	30	15	0.5
13	20	0	0	28	30	18	0.6
14	20	2	0.1	29	30	0	0
15	20	4	0.2	30	0	0	-

1 kip = 4.45 kN; - = not applicable

Experimentation Plan

Experiments on both 1:40 and 1:30 cant crossties were carried out on the Pulsating Load Test Machine (PLTM), a biaxial loading frame. The PLTM is located in the Rail Transportation and Engineering Center's (RailTEC) Research and Innovation Lab (RAIL) at UIUC and has a 55,000 lb (222 kN) vertical actuator and a 35,000 lb (156 kN) lateral actuator. It has the ability to simulate various lateral/vertical (L/V) force ratios that are present in revenue service track [10].

The experimental setup used one 18 inch (457 mm) piece of 136 RE rail fastened to a crosstie. New fastener clips, capable of imparting sufficient clamping force to restrain rotation were used on both 1:40 and 1:30 cant crossties. The same two-part pad assembly and insulators were used for all experiments in order to reduce variability among the experiments.

The loading in the tests were applied in a static manner. A predetermined sequence of vertical and lateral loads were applied on the rail head to simulate conditions of trains on tangent and curved tracks. The experimental testing matrix, which was repeated for both rail cants, consisted of three replicate tests to check for variability in the measurements. No two replicates were carried out on the same rail seat.

In addition to the data collected from MBTSS, potentiometers were also set up to record displacements (Figure 3). The displacements were recorded at various locations at the rail head and the rail base to calculate the rail rotation resulting from the applied load. The measurement points were set 5 inches (127 mm) on each side of the center line of the fastening system.

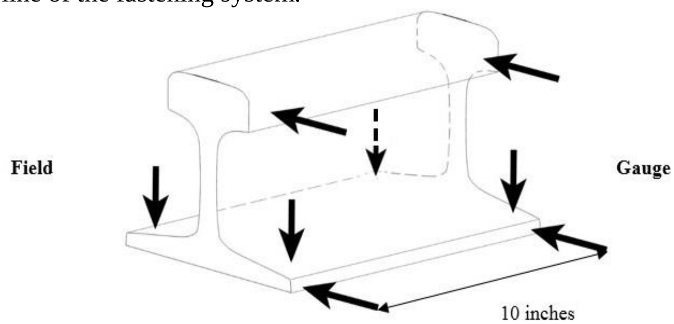


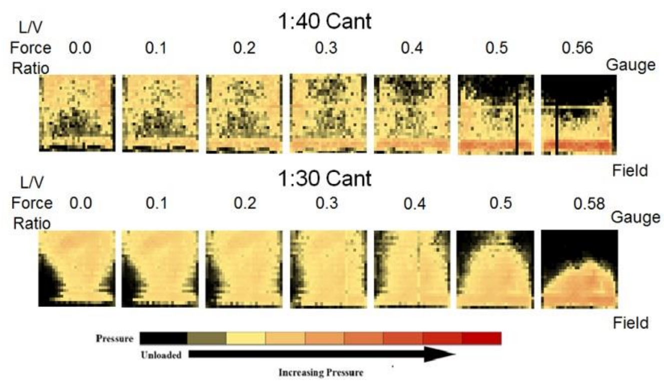
Figure 3: Potentiometer Locations for Tests

RESULTS OF EXPERIMENTATION

The effect of rail cant was investigated both qualitatively and quantitatively. To quantify the effect of rail cant, contact area, average pressure, maximum pressure, and rail rotation, were analyzed. Based upon the calculations above, the 1:30 cant and 1:40 cant crossties were not expected to display significant differences.

Qualitative Effect of Design Rail Cant

Figure 4 shows the qualitative effect of rail cant on the rail seat load distribution.



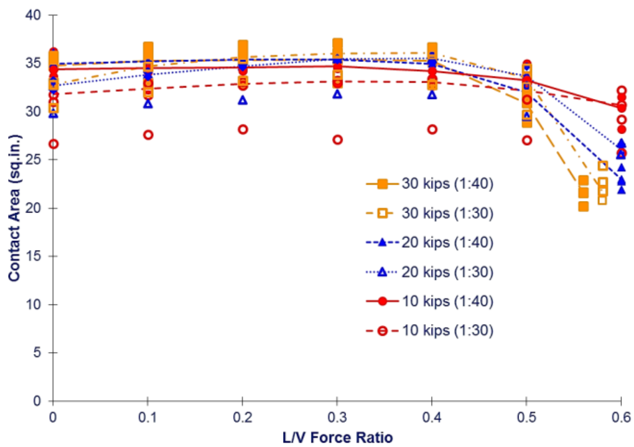
1 psi = 6894.76 × 10^{-6} Mpa, 1 kip = 4.45 kN
Figure 4: Rail Seat Pressure Distribution - 1:40 & 1:30 Cant.

In the figure, all rail seats are oriented such that the gauge side of the rail seat is towards the top of the page. The 1:30 and 1:40 cant crossties display a similar trend of unloading from the gauge side with increasing L/V force ratio applied. The 1:40 cant crossties show a distinct patch of high pressure on the field side for higher L/V force ratios while the 1:30 cant crossties do not show as distinct patch of high pressure on the field side. At low L/V force ratios, 0.0 and 0.1, the 1:30 cant crossties appear to lose contact on the field side of the rail seat.

For mid-range L/V values, 0.2, 0.3 and 0.4, the 1:30 cant crossties no longer display unloading from the field side, but distribute load across the entire rail seat. For these L/V force ratios and higher values, 0.5 through 0.6, it is difficult to qualitatively distinguish between the results beyond the distinct patch of high pressures. It is to be noted that no test was run to the 0.6 L/V force ratio for 30 kips (134 kN) as was planned due to experimental safety limits. The maximum L/V force ratios realized for vertical load of 30 kips (134 kN) on 1:40 cant and 1:30 cant were 0.56 and 0.58 respectively.

Contact Area

The contact area obtained for both 1:30 and 1:40 cant crossties is shown via scatter points denoting the actual values from the three replicate tests and the straight lines denoting the averages (Figure 5).



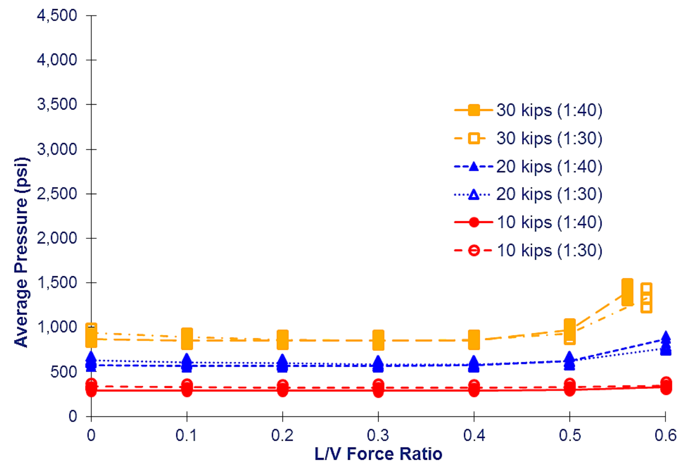
1 sq.in. = 6.452 sq.cm, 1 kip = 4.45 kN

Figure 5: Effect of Rail Cant on Contact Area.

The general trend from the average data is that 1:30 cant crossties have lower contact area at low L/V force ratios but greater contact area as the L/V force ratio increases. For example, the average value of contact area at 20 kips (89 kN) for zero L/V force ratio for 1:30 rail cant is approximately 33 square inches (213 square centimeters) while the corresponding value for 1:40 rail cant is 35.5 square inches (229 square centimeters). However, at an L/V force ratio of 0.6, the 1:30 rail cant average value of contact area is reduced to approximately 25.5 square inches (164.5 square centimeters) while the 1:40 rail cant exhibits a greater reduction to approximately 24 square inches (155 square centimeters). However, given the overlap in the data scatter, it is hard to determine a significant difference. Furthermore, the maximum difference between the two rail cants tests is only 6% and occurs for the highest values of loads applied.

Average Pressure

As mentioned, the average pressure was obtained by dividing the vertical actuator load applied by the contact area and the contact area was determined directly from the MBTSS data collected. The average pressure calculated for both 1:30 and 1:40 cant crossties is shown via scatter points denoting the actual values from the three replicate tests and the straight lines denoting the averages (Figure 6). There again appears to be no significant difference in the magnitudes of average pressure for 1:30 and 1:40 rail cant crossties. The values show enough variation to make it difficult to make any conclusions. It should be noted however that there is a considerable increase in average pressure when the L/V force ratio increases beyond 0.5 for vertical actuator loads of 20 (89 kN) and 30 kips (134 kN) for both 1:30 and 1:40 cant crossties, indicating potentially a greater rail rotation beyond these lateral load magnitudes.



1 psi = 6894.76 × 10^{-6} Mpa, 1 kip = 4.45 kN

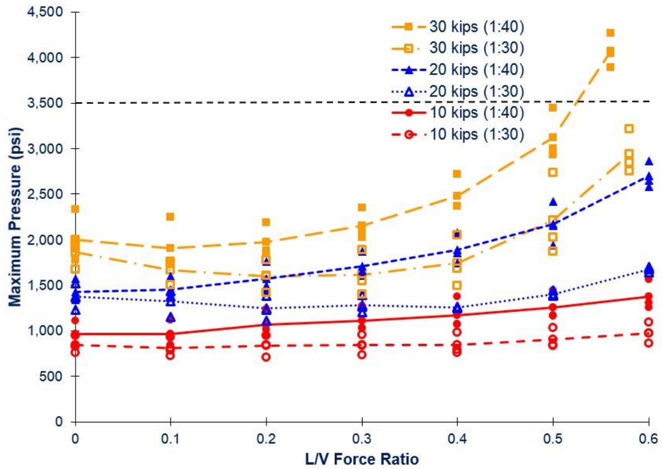
Figure 6: Effect of Rail Cant on Average Pressure.

Maximum Pressure

The maximum pressure is the maximum value of pressure recorded by any of the MBTSS sensors. MBTSS are made up of rows and columns of sensing locations. 676 locations (26 rows×26 columns) in the MBTSS were utilized for recording pressure values during experimentation. The maximum pressure calculated for both 1:30 and 1:40 cant crossties is shown via scatter points denoting the actual values from the three replicate tests and the straight lines denoting the averages (Figure7).

There is overlap in the data at low L/V force ratios, 0.0 through 0.2, when 10 kips (44.5 kN) vertical load is applied to the rail seat. As the vertical load is increased to 20 and 30 kips (89 and 134kN) the overlap in data is seen only between L/V force ratios of 0.0 and 0.1. Given there is overlap at low L/V force ratios and low vertical forces indicates that there is little-to-no effect of rail cant on pressure distribution at the rail seat under these conditions. However, there does appear to be an effect of rail cant on maximum pressure distribution at higher L/V force ratios, especially when higher vertical forces are applied to the rail seat. This is evident, given there is no overlap at higher L/V force ratios and that the average trends for all vertical forces show that 1:30 rail cant crossties produce lower maximum pressures compared to 1:40 rail cant crossties (Figure 7). The average maximum pressure recorded under a

30 kip (134 kN) vertical load and 0.56 L/V force ratio for the 1:40 rail cant crosstie was 4,040 psi (28 Mpa), while the corresponding value for the 1:30 rail cant crosstie was only 2,940 psi (20 Mpa), a 29% reduction. The corresponding reductions when vertical loads of 20 kips (89 kN) and 10 kips (44 kN) were applied were 36% and 30% respectively.

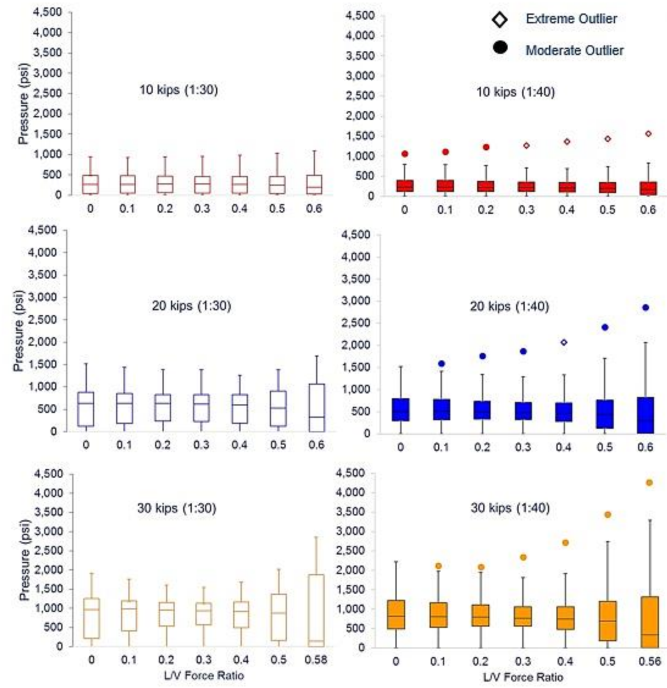


1 psi = 6894.76 × 10^{-6} Mpa, 1 kip = 4.45 kN

Figure 7: Effect of Rail Cant on Maximum Pressure.

While the tests on the 1:40 rail cant crossties did not result in pressures exceeding the conservative estimates of the compressive strength of concrete (7,000 psi, 48 Mpa), each replicate exceeded the fatigue strength, generally regarded as 50% (3,500 psi, 24 Mpa) of the compressive strength [12]. No replicate performed on the 1:30 rail cant crossties exceeded this value. Therefore, based on these data, it appears that under demanding conditions (high vertical loads and L/V force ratios), 1:40 cant crossties are more susceptible to concrete crushing fatigue failure when compared to 1:30 cant crossties.

Because this trend was not expected based upon the calculations performed above, the load distribution was analyzed further using box and whisker plots (Figure 8). Data from all three rail seats, 2,028 data points (676×3), were considered. The box plots denote the first (Q1), second (Q2) and third quartile (Q3) values while the whiskers denote the maximum pressure value less than Q3 added to 1.5 times the Inter Quartile Range (IQR) i.e. Q3 + 1.5 × (Q3 – Q1). The scatter points denote data which are moderate or extreme outliers. It is worth discussing whether the outlier values are actual pressures or ‘instrumentation errors’ from MBTSS. Qualitative analysis of pressure maps, such as shown in Figure 4, showed that there were a few cases with isolated sensing locations showing a pressure spike surrounded by lower pressure values. This was believed to be caused by instrumentation errors of MBTSS since all the rail seats tested were in good condition and there was no deliberate intrusion of particles. Hence, the outliers were excluded from the analysis.



1 psi = 6894.76 × 10^{-6} Mpa, 1 kip = 4.45 kN

Figure 8: Box and Whisker Plots of Pressures Obtained from All Three (3) Rail Seats.

As is evident from the box and whisker plots in Figure 8, data from all the loading cases for both 1:30 and 1:40 cant crossties have MBTSS sensors that record zero pressure. However, as the L/V force ratio is increased, it can be observed that even the first quartile value of pressure approaches zero, particularly for vertical actuator loads of 20 kips (89 kN) and 30 kips (134 kN). As expected, lower values of first quartile pressure correspond to greater third quartile and maximum pressure values. This simply shows that an unloading from the gauge side is accompanied by a concentration of pressure on the field side. It is also to be noted that the maximum and the third quartile pressure values decrease as L/V ratios increase from 0.0 to approximately 0.35, after which these pressure values increase again as the applied L/V increases. This trend is more prominent for loads of 20 kips (89 kN) and 30 kips (134 kN) on both cants. This suggests that the steeper 1:30 cant has a non-zero ‘optimum’ L/V force ratio for which the pressure distribution is the most uniform. The maximum pressure values for vertical load of 10 kips (44 kips) remains fairly constant across L/V force ratio for both cants.

The 1:40 cant crossties display outlier pressure values whereas 1:30 cant crossties do not. The outlier pressure values only occur in the positive direction and not negative. The moderate outlier values are those which exceed the value of Q3 + 1.5 IQR, but are less than Q3 + 3 IQR whereas the extreme outlier values denote values greater than Q3 + 3 IQR. The 1:40 cant crossties display extreme outliers for the vertical actuator load of 10 kips (44.5 kN), but mostly only moderate outliers for 20 (89 kN) and 30 kips (134 kN). Disregarding the outlier values, the 1:40 cant crossties actually result in lower pressure at 10 kips (44.5 kN) while 1:30 cant crossties still maintain lower pressure values at 20 (89 kN) and 30 kips (134 kN). At 20 kips (89 kN) and L/V force ratio of 0.6, the 1:40 cant crossties result in a pressure of 2,067 psi (14.25 Mpa) whereas the corresponding value for 1:30 cant crossties is 1,698 psi (11.71 Mpa), a reduction of 18 %. At 30 kips (134 kN) and the highest L/V achieved (0.56 for 1:40 and 0.58 for 1:30), the corresponding values for 1:40 and 1:30 cant crossties are 3,291 psi (22.7 Mpa) and 2,850 psi (19.65 Mpa), a 13 % reduction.

To confirm that the pressure values were indeed statistically different for the two cant values, t-tests were performed on pressures from both 1:30 and 1:40 rail cants for all the vertical and lateral load cases. The results are presented in Table 2.

Table 2: T-Test Results On 1:30 and 1:40 Cant Data

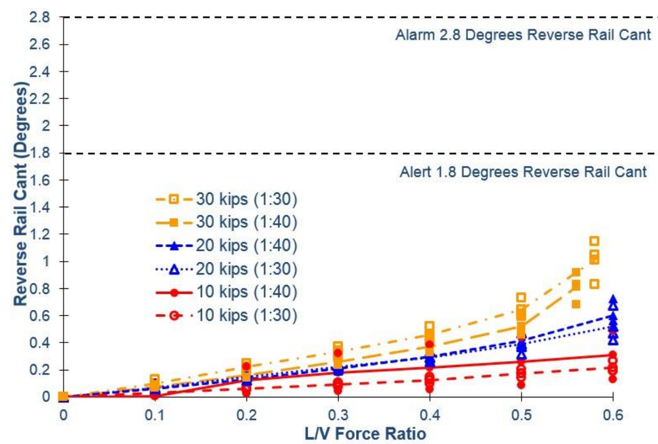
S. No.	Vertical (kips)	Lateral (kips)	Null Hypothesis Rejected
1		0	No
2		1	No
3		2	No
4	10	3	Yes
5		4	Yes
6		5	Yes
7		6	Yes
8		0	Yes
9		2	No
10		4	No
11	20	6	Yes
12		8	Yes
13		10	No
14		12	Yes
15		0	Yes
16		3	Yes
17		6	Yes
18	30	9	No
19		12	Yes
20		15	Yes
21		18	Yes

1 kip = 4.45 kN

The outlier pressure values were excluded from this t-test analysis. The null hypothesis was that pressure values from both 1:30 and 1:40 cant are independent random variables with the same mean and variance. The alternative hypothesis was that the pressure values have different means and variances. As is evident from Table 2, the null hypothesis tends to stand true when lower lateral loads are applied for vertical loads of 10 kips (44.5 kN) and 20 kips (89 kN), suggesting no significant differences in pressure distribution by 1:30 and 1:40 cant. In general, for L/V force ratios greater than 0.3, the hypotheses are rejected for vertical forces of 10 kips (44.5 kN), 20 kips (89 kN), and 30 kips (133 kN). This suggests that the pressure values on 1:30 and 1:40 cant differ significantly at higher lateral forces. Except for a couple cases, at higher lateral loads and for vertical of 30 kips (134 kN), the null hypothesis is rejected, suggesting at higher vertical and lateral loads, the pressure distributions are statistically different, with 1:30 cant pressure values being lower.

Rail Rotation

The rail rotation obtained for both 1:30 and 1:40 cant crossties is shown via scatter points denoting the actual values from the three replicate tests and the straight lines denoting the averages (Figure 9). The results indicate progressive rail rotation as the lateral load is increased for a fixed vertical load.



1 kip = 4.45 kN

Figure 9: Effect of Rail Cant on Rail Rotation

Reverse rail cant has been defined by some researchers as the amount of rail rotation towards the field side with reference to the original rail cant [13]. Based on maximum allowed rail head displacements by FRA, the alert and alarm levels of reverse rail cant are 1.8 and 2.8 degrees respectively [13]. Both the 1:30 and 1:40 rail cant crossties displayed rotation towards field side but did not exceed the alert level. One of the replicate tests on the 1:40 cant crossties displayed significant fluctuations for the case of 10 kips of vertical load and thus wasn't considered in the analysis. There again appears to be no significant difference in the magnitudes of rail rotation for 1:30 and 1:40 rail cant crossties. The values show enough variation to make it difficult to make any conclusions. For vertical loads of 20 kips (89 kN), the difference in rotation between 1:30 and 1:40 rail cant never exceeded 0.05 degrees while the difference did not exceed 0.2 degrees when subjected to 30 kips (134 kN) vertical load.

CONCLUSIONS AND FUTURE WORK

Based upon the data presented above, it can be determined that changing from 1:40 rail cant to 1:30 rail cant will not affect the contact area, average pressure, or rail rotation experienced by the crosstie. However, it was determined and confirmed from t-tests that even when discarding outlier data, there is an effect on maximum pressures at the rail seat when changing from 1:40 rail cant to 1:30; e.g. disregarding the outlier data, the pressure reductions achieved by 1:30 cant were as high as 18%. The disparity in the quartile values of pressures were also consistently found to be greater for 1:40 cant crossties, reinforcing this finding.

The maximum pressures recorded on 1:40 rail cant crossties exceeded the fatigue strength of the concrete while no pressure recorded on 1:30 rail cant crossties exceeded the fatigue strength. Therefore, it appears that 1:30 cant crossties could provide a better option in high degree curves which typically experience high lateral loads whereas 1:40 cant crossties should still continue to be a better option on tangent tracks. Having said this, the authors understand the logistical challenges of installing crossties with varying rail cants in track when also attempting to optimize the contact at the wheel rail interface. Further research may be required to determine the overall benefits derived from using either cant.

The analysis presented in this paper is from 3 replicate tests. The conclusions drawn would be more robust if more replicate tests were performed on both 1:40 and 1:30 cant. Furthermore, the 1:40 rail cant and the 1:30 rail cant crossties used were from different manufacturers and thus the results also account for potential manufacturing variability in the rail seat finishing, though there was no visual evidence to support this. Finally, a similar matrix could be performed on a concrete block, rather than a full crosstie, to provide greater flexibility in comparing additional rail cants (1:20) and eliminating the potential variable of variations in concrete finishing.

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REFERENCES

1. Greve M., M. S. Dersch, J. R. Edwards, Christopher P. L. Barkan, Hugh Thompson, Theodore Sussmann, and Michael McHenry. Examination of the Effect of Concrete Crosstie Rail Seat Deterioration on Rail Seat Load Distribution. In *Transportation Research Record: Journal of the Transportation Research Board, No. 1580*. 2015.
2. Zeman, J. C. Hydraulic Mechanisms of Concrete-Tie Rail Seat Deterioration. University of Illinois at Urbana-Champaign, Urbana, Illinois, M.S. Thesis 2010.
3. Van Dyk B., M. S. Dersch, and J. R. Edwards. International Concrete Crosstie and Fastening System Survey –Final Results. Railroad Transportation and Engineering Center (RailTEC), University of Illinois at Urbana-Champaign (UIUC). For United States Department of Transportation (US DOT) Federal Railroad Administration (FRA), Washington, D.C. 16 May 2012. pp. 3-8.
4. Rapp, C. T., M. S. Dersch, J. R. Edwards, C. P. L. Barkan, B. Wilson, and J. Mediavilla. Measuring Rail Seat Pressure Distribution In Concrete Crossties: Experiments with Matrix-Based Tactile Surface Sensors. In *Transportation Research Record: Journal of the Transportation Research Board, No. 2374*. 2014, pp. 190-200.
5. Greve, M., M. S. Dersch, J. R. Edwards, C. P. L. Barkan, J. Mediavilla, and B. Wilson. Analysis of the Relationship between Rail Seat Load Distribution and Rail Seat Deterioration in Concrete Crossties. In ASME Joint Rail Conference, Colorado Springs, Colorado, 2014.
6. Kerchof, Brad and Huimin Wu. Causes of Rail Cant and Controlling Cant through Wheel/Rail Interface Management. Presentation given at RailTEC, UIUC, Oct. 5, 2012.
7. Jabbar-Ali Zakeri, Masoud Fathali, and Nima Boloukian Roudsari. Effects of Rail Cant on Wheel-Rail Contact Forces in Slab Tracks. *International Journal of Mechanics and Applications*. 2011.
8. Gutierrez Romero, M. J., M. S. Dersch, J. R. Edwards, C. P. L. Barkan, B. Wilson and J. Mediavilla. Investigation of Concrete Sleeper Rail Seat Pressure Distributions for Varying Fastening Systems and Loading Conditions. In: Proceedings of the 2011 International Heavy Haul Association Conference, Calgary, Canada, June 2011.
9. Greve M., M. S. Dersch, J. R. Edwards, Christopher P. L. Barkan, Jose Mediavilla, and Brent Wilson. The Effect of Particle Intrusion on Rail Seat Load Distributions on Heavy Haul Freight Railroads. In *11th International Heavy Haul Association Conference*. Perth, Australia. June 2015.
10. M. S. Dersch and J. R. Edwards. RailTEC's Research and Innovation Laboratory (RAIL) Capabilities: General Briefing. Oct. 30, 2014.
11. "AREMA Manual for Railway Engineering." Ch. 30, Part 1. Maryland: American Railway Engineering and Maintenance of Way Association. 2014, pp. 30-1-5 to 30-1-6.
12. El Shahawi, M. and Batchelor, B.V. Fatigue of Partially Prestressed Concrete. *Journal of Structural Engineering* 112 (3): 524-537. 1986.
13. Clouse, A. Rail Cant Measurements of Concrete Crossties (Part 2 of 2). *Interface Journal - The Journal of Wheel/Rail Interaction*, 2008.