Causes of Rail Cant and Controlling Cant Through Wheel/Rail Interface Management

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ABSTRACT

Following a number of main-line derailments involving rail rollover in curves, Norfolk Southern (NS), working with Transportation Technology Center, Inc. (TTCI), established a rail test site in a 7.8-degree curve on a heavy-tonnage coal route to investigate the relationship among wheel/rail forces, track conditions and dynamic rail cant.

Wheel force measurements were collected over a 15-month period during 2011 and 2012 under a variety of track maintenance conditions, including tight, standard and wide gage; cut spike and elastic fastening systems; three rail grinding cycles; with and without top-of-rail friction modifier (TOR); and at two different super-elevations.

The following conclusions were made based on the lateral-force data associated with each of the track conditions:

• Very high lateral forces and significant rail cant (close to roll-over) can result from adverse wheel/rail contact.

• Track maintenance tasks that involve changing gage or rail orientation can have the unintended consequence of causing adverse wheel/rail contact, resulting in high lateral forces.
• Managing the wheel/rail interface by modifying track gage, rail profiles, elevation, fastening systems and TOR friction control can lower lateral forces.
• Cut spikes do not provide sufficient vertical rail restraint when subjected to high lateral forces.
• Elastic fasteners appear capable of handling high lateral forces.

INTRODUCTION

Understanding the causes and remedies of reverse rail cant has become increasingly important in recent years, due to several significant NS main-line derailments in curves where rail roll-over was identified as the primary contributing factor. The derailment sites had these two characteristics in common: curvature between 6 and 8 degrees, and a history of significant dynamic rail cant as measured by NS’s track geometry cars.

NS and TTCI have been conducting a joint investigation on reverse rail cant/rail rotation since early 2011. This investigation is co-funded by NS and the Association of American Railroads Strategic Research Initiative program.

DESCRIPTION OF RAIL CANT

In its normal position, the vertical axis of the rail is tilted slightly toward the gage side, due to the inward slope of the tie plate (designed to be 1:40 on most railroads). Any rotation of the rail is typically referenced from this orientation (Figure 1). Cant can be inward or outward, though it is outward cant that contributes to wide gage and rail instability.
Figure 1: Variation in rail cant is referenced to the rail’s design position on the tie plate (typically 1:40 inward)

Rail cant can have both a static and a dynamic component. Causes of static cant include tie plate cutting (Figure 2), uneven adzing (Figure 3), worn tie plate rail seat (Figure 4) or temperature (Figure 5). The first three conditions are likely to be reflected in the cant measurements of a geometry car, due to the rail orienting itself under wheel loading based on track support conditions. Cant caused by temperature, found only in cut-spike (non-elastic fastener) track, can disappear under load as the rail base is pressed back into its rail seat. The amount of temperature-induced cant is affected by two factors: the difference between rail neutral temperature and actual rail temperature, and the height to which the gage-side spikes are raised. In hot weather, the high rail will tend to roll toward the outside of the curve, while in cold weather, the low rail will tend to roll toward the inside of the curve.
Figure 2: Outward rail cant due to tie plate cutting

Figure 3: Outward rail cant due to uneven adzing. The field side (yellow arrow) is cut down further, resulting in the geometry car measuring 1.5° of outward cant
Figure 4: Outward rail cant due to a worn tie plate rail seat; on this plate, vertical wear on the field (left-hand) side measured 10/64”, resulting in about 2° of rail cant.

Figure 5: Cant due to hot weather (the gage side of the high rail is shown)

Dynamic outward cant is the rotation of the rail about the field-side edge of the base, and it occurs when the resultant of the vertical and lateral forces acting at the wheel/rail interface passes the outside of the rail base, creating an overturning moment. Lateral forces include both flanging and frictional creep (on the rail head). Figure 6 shows the how these forces combine into a resultant force that, if projected outside of the rail base, will tend to roll the rail. Opposite-hand moments applied by adjacent wheels, combined with the torsional stiffness of the rail and the hold-down strength of the fastening system, keep the rail from rolling over. Dynamic cant is affected by both track and vehicle condition, and is an indicator of how effective the trucks are steering. Figure 7 shows evidence of how far the rail is rotating outward under traffic – note the tell-tale contact marks on the gage-side base, indicating that the rail is rotating far enough to contact the underside of the spikes.
Figure 6: Horizontal and vertical forces generated at the wheel/rail interface combine into a resultant force (typically, the high rail experiences flange contact but not the low rail).

Figure 7: Dynamic cant: contact marks on the gage side of the rail base are evidence that the rail is rotating outward under traffic.

Tie plates that are significantly worn can give the appearance of dynamic cant: the rail appears to be seated on the field side, but is raised up on the gage side. Figure 8 shows the gage side of a rail seated on a worn tie plate; the field side of the base is actually sitting flush on a worn rail seat surface.
Figure 8: Worn tie plate: The gage side of the rail is raised, but the field side sits flush on a worn rail seat surface. Cant due to this worn plate measured 2°.

INSTRUMENTED TEST SITE

Fish Gage

Validation of the rail cant measurements reported by the geometry car was accomplished using a crude measurement tool called a fish gage (Figure 9). The concept was simple – a train pushed the rail head outward, which compressed the spring-loaded plunger and displaced white and black washers. After the train passed, the rail, plunger and white washer restored to their unloaded positions while the black washer remained displaced. The gap between the two washers indicated the maximum amount of dynamic rail movement caused by that train (Figure 10). There were two shortcomings with this measurement method: the measured displacement did not include static rail rotation, and it was not possible to distinguish the rail movement caused by individual cars.
Figure 9: Fish gage used to measure lateral displacement of the rail head

Figure 10: Separation between washers indicated lateral movement of the rail head under traffic

Instrumented Rail

To investigate the relationship between wheel/rail forces and rail cant, NS collaborated with TTCI to set up a rail cant test site at Wills, WV, on NS’s heavy-tonnage coal route between Bluefield, WV and Roanoke, VA. A curve was selected based on its geometry and history of rail cant. Characteristics included 7.8 degrees of curvature, 4” of elevation, 25 mph Timetable speed, hardwood ties, 8” x 18” tie plates with cut spikes, gage under load 57-3/8” and, most importantly, 3° of outward cant on both high and low rails. Train traffic includes loaded and empty coal trains, and mixed freight and double-stack intermodal trains.
Strain gages were installed mid-curve in two cribs to measure vertical and lateral forces, and string pots were installed to measure lateral displacement of rail head, rail base and tie plate (Figure 11).

Figure 11: Rail cant test site shown instrumented with strain gages and string pots

It quickly became apparent that displacement measurements made with the string pots were unreliable. While the string pots did distinguish rail movement caused by individual cars, their zero-reference point did not include static rail rotation, which varied with track conditions and rail temperature. The string pots were removed within the first two weeks of testing.

The objective of the test was evaluate how track conditions, such as gage, rail profile, rail cant, fastener type and lubrication, affected wheel/rail contact and influenced lateral forces and rail rollover. Loaded coal trains were selected for the data analysis because they had very similar vertical wheel loads, a characteristic that would make lateral force comparisons much more meaningful.

TRACK MAINTENANCE CONDITIONS

At the Wills test site, wheel forces were measured under nine different maintenance conditions, some of which were dictated by normal NS maintenance procedures and some by the researchers’ attempts to manipulate wheel/rail contact forces. The details of each track maintenance condition follow.
1. April 19, 2011, starting condition: 8” x 18” tie plates, cut spikes, gage 57-3/8”, 4” superelevation, 3° of cant on both high and low rails, and abundant gage-face lubrication but no TOR. The low rail showed significant rolling contact fatigue (Figure 12).

![Figure 12: Low rail during maintenance condition 1; note RCF, including false flange groove on field side of head](image-url)

2. April 26, grinding cycle 1: The low rail was given five passes that restored a normal-radius profile (Figure 13). The high rail also received five passes which unintentionally emphasized gage-side relief and maintained widely-spaced two-point contact. (During the pre-grind inspection, the grinding contractor applied a digital template to the rail profile. A grinding plan was created based on what relief was needed to reshape the rail like the template. The outward cant of the rail was not taken into account during the pre-grind inspection, which resulted in a programmed grinding pattern that took too much metal off the gage side, and not enough off the field side.)
Figure 13: Low rail after grinding cycle 1

3. June 6: Elastic fasteners were installed on the high rail, and track gage was tightened to 56-3/8”.

4. June 21: Elastic fasteners were installed on the low rail (Figure 14), gage was widened to 56-3/4”, and nearby TOR units were turned on for the first time during the test (Figure 15).

Figure 14: Rail cant test site after installation of elastic fasteners on both high and low rails
5. August 23, grinding cycle 2: The low rail was given five more passes, which restored a normal radius profile (following grinding cycle 1, the low rail surface deteriorated rapidly, degrading to its pre-cycle 1 condition within two months). The high rail was given two passes emphasizing field relief (Figure 16).

6. Sept 1: TOR units turned off; the objective was to determine what contribution TOR was making to the reduced lateral forces that were observed beginning on June 21st.

7. October 1, grinding cycle 3: Only the high rail was ground, with two passes emphasizing field side relief. The low rail was still in excellent shape and did not require any work. TOR units remained off, so that the effect of grinding could be isolated.

8. October 12: The TOR units turned back on.


TEST RESULTS
Over a period of 15 months (April 19, 2011 through June 18, 2012), 1295 loaded coal trains, with gross weight per car of 286,000 lbs., operated over the Wills test site. The graphs shown in Figure 17 display the lateral forces measured under the first 560 of those trains, covering the period between April 19 and October 30, 2011. The graphs are arranged with train number on the horizontal axis and lateral force (in kips) on the vertical axis. Each data point represents the average lateral force for an entire train. The top graph shows the average forces for the leading wheels of each train, the bottom graph the average forces for the trailing wheels. Blue indicates the low rail and pink indicates the high rail.

![Graph 1](image1.png)

**Figure 17: Average lateral force measurements for 560 loaded coal trains. Green and blue arrows indicate track maintenance changes.**

There are useful observations can be made regarding the forces measured during each maintenance condition:

1. At the beginning of the test, lateral forces generated by lead wheels were generally between 10 and 17 kips. False-flange contact was evident on the field side of the low rail due to wide gage (57-3/8”) and
a flat rail head. High rail contact was two-point, with some wheel tread contact on the field side of the
head.

2. Grinding cycle 1 had little effect on the lateral forces. Cycle 1 restored a desirable center-rail contact
pattern on the low rail, but retained a strong two-point contact on the high rail because of unintended
gage-side relief.

3. Elastic fasteners installed on the high rail only, combined with the track gaged to 56-3/8”, resulted in
dramatically higher lateral forces, with the both leading and trailing wheels generating 20 kips. The
forces under the trailing wheels are especially noteworthy. Throughout most of the test, the trailing
wheels generated much smaller lateral forces – on the order of 50% to 75% of the leading wheels.
Under this particular track condition, however, the trailing wheel forces equaled those of the leading
wheels. A video taken of the low rail recorded 7° of outward dynamic cant (Figure 18).

![Figure 18: Low rail cant of 7° was observed on video during condition 3](image)

The wheel/rail contact conditions recorded in the video are shown in a drawing in Figure 19. The
restored high rail, with strong restraint due to the elastic fasteners, produced severe two-point contact,
with tread contact toward to the field side, while the low rail experienced a large rotation that resulted
in wheel contact toward the gage corner. Under this contact condition, the rolling radius of the high-
side wheel may be smaller than that of the low-side wheel. This poor wheel/rail contact condition was
likely one of the major contributors to the high lateral forces that were measured.
Figure 19. A drawing of the wheel/rail contact condition showing the high rail restored to normal cant and firmly secured with elastic fasteners, and the low rail poorly secured with cut spikes

4. When the elastic fasteners were installed on the low rail, the gage opened to 56-3/4”, and TOR units turned on, leading wheel lateral forces dropped dramatically, to half the levels recorded during maintenance condition 3. Trailing wheel forces dropped even more, to less than half their previous levels. The relative contribution of each of the track maintenance changes was not determined, however.

5. Grinding cycle 2 resulted in a slight decrease in lateral forces, with the change more apparent on the trailing wheels. Like cycle 1, cycle 2 restored a desirable center-rail contact pattern on the low rail. On the high rail, cycle 2 emphasized field-side relief, which shifted wheel contact back toward the center of the rail, reducing (but not eliminating) the two-point contact. This change likely improved axle steering, thereby reducing lateral forces slightly.

6. Turning the TOR units off appears to have caused a slight increase in lateral forces.

7. Grinding cycle 3 emphasized additional field-side relief on the high rail; the low rail was not ground. This work resulted in a further decrease in lateral forces.
8. Turning the TOR units back on appears to have eliminated the increase caused by turning them off, in condition 6. At this point, forces have been reduced to their lowest levels of the test: leading wheels between 5 and 10 kips, and low wheels between 3 and 5 kips.

9. Reducing elevation from 4” to 2-1/2” resulted in a further reduction in lateral forces. At 4” of elevation, all trains operated significantly under balance speed of 27 mph. (According to the test data, 80% of loaded coal trains operated over the test site between 20 to 25 mph; the other 20% operated at less than 20 mph.) At 2-1/2” of elevation, balance speed is 21.5 mph, near the middle of the operating range. Figure 18 shows the lateral force readings of train nos. 1200 through 1295. The trains to the left of the blue line operated under track condition 8, and continued to show the same lateral forces as did trains at the end of the graph in Figure 17. After the change in elevation, lateral forces reached their lowest levels of the test: leading wheels under 9 kips, and trailing wheels at 3 kips.

![Figure 20: Average lateral force measurements for train nos. 1200 – 1295, operating on curve with 4” of elevation (left of the blue line) and with 2-1/2” (right of the blue line)](image-url)
L/V (lateral-over-vertical) force ratios follow the same trends as lateral forces, due to the similarity of weights of the loaded coal cars.

Figure 21 shows a different presentation of force data. Lateral force measurements for the individual leading wheels from two entire trains are displayed. The blue plot reflects train no. 178, which operated during condition 3, when elastic fasteners were on the high rail only, gage was 56-3/8”, and lateral forces were at their maximum. The top graph shows the leading wheels on the high rail, and the bottom graph shows leading wheels on the low rail. Most high-rail wheels generated forces around 15 kips, though some wheels were significantly lower. Low-rail wheels generated considerably higher forces – between 20 and 25 kips, with some wheels significantly lower. The red plot reflects train no. 481, which operated after grinding cycle 3, when lateral forces were near their minimum.

Common to each of these data points is wheel vertical load – all of the coal cars are rated at 286,000 lbs. and their actual weight is close to that value. Also in common to each high-side and low-side wheel is the rail profile. Thus, the variation in lateral forces among wheels within each train can be attributed primarily to axle steering performance, which is influenced by wheel profiles and truck condition. (The impact of longitudinal train forces on lateral forces is minor, due to the use of air brakes over the test site; trains are not likely to have high buff or draft forces).
Figure 21: Lateral forces of individual lead wheels from two trains. Train no. 178 (blue) operated during condition 3 (elastic fasteners on high rail and tight gage). Train no. 481 (red) operated after grind cycle 3.

CONCLUSIONS

Results obtained from the Wills test site support these conclusions:

- Changing the wheel/rail contact conditions can change lateral forces.
• Tight gage and field-side wheel/rail contact can generate very high lateral forces and significant rail cant (approaching rail roll-over).

• Track maintenance tasks that restore a rail to its normal, upright position can have the unintended consequence of causing field-side wheel/rail contact, resulting in higher lateral forces.

• Managing the wheel/rail interface by modifying track gage, rail profiles, elevation, fastening systems and TOR friction control can lower lateral forces.

• Cut spikes do not provide sufficient vertical rail restraint when subjected to high lateral forces (spikes are not designed to provide strong vertical restraint).

• Elastic fasteners appear capable of handling high lateral forces.

• Reducing lateral forces reduces the rate of rolling contact fatigue growth. Figure 22 shows the low rail nine months after grinding cycle 2; while not free of RCF, the rail is in much better condition than it was only two months after grinding cycle 1.

![Image of low rail](image)

**Figure 22: Condition of low rail in June, 2012, nine months after grinding cycle 2**

• The progression of cant to rail roll-over depends on the strength of the track structure and the changes made to the wheel/rail interface. But even with the most adverse wheel/rail contact demonstrated in this test, a vigilant track inspector still has the opportunity to detect a dangerous trend during a normal inspection schedule.
WAY FORWARD

While the work at the Wills test site provided much valuable information, it also raised three important questions.

1. What were the relative contributions of the wider gage, elastic fasteners, change in rail profile and TOR to the dramatic reduction in lateral forces observed when the low rail was restored?

2. Is it possible to reduce lateral forces to an acceptable level by managing gage, rail profiles, and friction control such that (the more expensive) elastic fasteners don’t have to be used? Defining “acceptable” is part of this question.

3. So far, TOR does not appear to have been a significant factor in the test results. What is the impact of an optimally-installed TOR system, and can that impact be measured in terms of lateral force?

To answer these questions, and to further understand the causes of reverse rail cant, NS and TTCI have established a second test site, at Hardy, VA, on a line that carries the same traffic as Wills. The Hardy site is on a 5.7° curve with a slightly higher speed – 35 mph, wood ties, 8” x 18” tie plates, cut spikes and a developing cant condition - 2° on both high and low rails. To isolate the impact of elastic fasteners, the existing plates and spikes will remain in track at Hardy for the duration of the test.

Testing at both Wills and Hardy is scheduled to be completed by early 2013.
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BIOGRAPHICAL SKETCH OF PRESENTER

Brad Kerchof is Director Research and Tests for Norfolk Southern in Roanoke, VA. NS’s R&T Department is responsible for track geometry car operations, track quality analysis, derailment investigation, and train operations research. Before joining NS’s R&T Dept, Brad spent 31 years in maintenance-of-way, working as Director of Engineering in Atlanta and Division Engineer in Birmingham, Pittsburgh and Indianapolis. Brad began as an engineering management trainee with Conrail, and one of his early career assignments was with TTC in Pueblo, CO. Brad has a BSCE from the University of Virginia and is a registered Professional Engineer in Pennsylvania.
Causes of Rail Cant and Controlling Cant through Wheel/Rail Interface Management

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Outline

• Description of Rail Cant
• Rail cant test
• Test Variables - Track Maintenance Conditions
• Test Results
• Conclusions & Next Steps
Description of Rail Cant

Cant is the amount of rail rotation referenced from standard tie plate position (typically 1:40 inward)

Two types of rail cant:
1. Static
2. Dynamic
Video 1: Almost no cant
Description of Rail Cant

Static Cant

• Tie plate cutting
Description of Rail Cant

Static Cant

- Tie plate cutting
- Uneven adzing

Photograph shows 1.5° of outward cant – the adzer took too big a bite out of the field side!
Description of Rail Cant

Static Cant
- Tie plate cutting
- Uneven adzing
- Worn tie plates

10/64” wear
Video 2: Cant due to worn tie plates
Description of Rail Cant

Static Cant

- Tie plate cutting
- Uneven adzing
- Worn tie plates
- Hot weather - impacts high rail
Description of Rail Cant

Static Cant

- Tie plate cutting
- Uneven adzing
- Worn tie plates
- Hot weather – impacts high rail
- Cold weather – impacts low rail
Description of Rail Cant

Dynamic Cant

- The amount of rail rotation caused by wheel loading
- Can vary from truck to truck
- Included in geometry car gage & cant measurements
Rail Cant Test

- Confirm geometry car results
- First measurement tool: fish gage
Rail Cant Test

- Wills, WV, Roanoke - Bluefield Line
- 7.8° curve
- TT Speed 25 mph
- Superelevation 4"
- 8" x 18" tie plates, cut spikes
- Gage 57-3/8"
- Rail cant 3° both high and low rails
Rail Cant Test

- Strain gages measure vertical and lateral forces
- String pots measure displacement
Track Maintenance Conditions

1. April 19, 2011: both rails with 3° cant, gage 57-3/8”
2. April 26: grinding cycle #1
5. June 21: TOR friction modifier turned on
6. August 23: grinding cycle #2
7. Sept 1: TOR turned off
8. October 1: grinding cycle #3
9. October 12: TOR turned on
Test Results - Lateral Forces

Loaded 286k Coal Trains, Lateral Forces, Lead Wheels

Loaded 286k Coal Trains, Lateral Forces, Trail Wheels
Track Maintenance

1) starting condition

- Tie plates 8” x 18” with spikes
- Gage under load 57-3/8”
- Cant 3° both high and low rails
Track Maintenance

1) starting condition

- Abundant gage-face lubrication
- No top-of-rail friction modifier (units were turned off)
Track Maintenance

2) grinding cycle 1

- Cycle 1 – 5 passes each on both high & low rails

- Grinding template was applied to a canted high rail, result was gage-side relief
Track Maintenance
3) Elastic fasteners (Pandrols) on high rail

- Pandrols installed on high rail
- Gage 56-3/8 (tight)
- 8 x 18” plates on low rail
- Wheel contact moved to field side
Video 3: Low rail, after elastic fasteners were installed on high rail
Scuff marks from wheel/rail friction saturation
3) Elastic fasteners on high rail

- 40 feet from first video
- Spikes were already raised 7/8”; we drove two of them down in advance of a train
Video 4: Low rail, after two spikes were driven down
Track Maintenance

4) Elastic fasteners on low rail

- Pandrols installed on low rail
- Gage widened to 56-3/4”
- Wheel contact on low rail now on field side
Track Maintenance
5) TOR units turned on

- Two nearby TOR units turned on
Video 5: Low rail, elastic fasteners now on both rails
Track Maintenance
6 & 8) Grinding Cycles 2 & 3

- Grinding cycle 2 - two passes high rail, five passes low rail

- Grinding cycle 3 - two passes high rail only
Track Maintenance
7 & 9) TOR turned off, then on

- TOR turned off
- TOR turned on
Test Results - Lateral Forces

Loaded 286k Coal Trains, Lateral Forces, Lead Wheels

- Start test 04/19/2011
- Grinding 1 04/26/2011
- High rail Pandrols 06/06/2011
- Low rail Pandrols 06/21/2011
- TOR on
- Gridding 2 08/23/2011
- TOR off
- Gridding 3 10/01/2011
- TOR on
- 10/30/2011

Low Rail
High Rail

Loaded 286k Coal Trains, Lateral Forces, Trail Wheels

- Low Rail
- High Rail
Each data point represents the average truck-side L/V for an entire loaded coal train

- blue = low rail
- pink = high rail
Test Results – Lateral Forces

- Each data point is a lead wheel from one of two trains loaded coal trains.
- Blue train shows worst condition – when Pandrols were on high rail.
- Red train shows optimum condition - post-grind cycle 3.
Conclusions

1. Tight gage and field-side wheel/rail contact can generate very high lateral forces

2. Track maintenance tasks that restore a rail to its normal, upright position can have the unintended consequence of causing field-side wheel/rail contact

3. Managing the wheel/rail interface (gage, rail profiles, fasteners, TOR) can lower lateral forces
Conclusions

4. Cut spikes do not provide sufficient vertical restraint under adverse wheel/rail contact

5. Elastic fasteners appear able to out-muscle high lateral forces caused by poor wheel/rail contact

6. The progression of cant to rail roll-over can be caught by a vigilant track inspector
2012 Research Objectives

1. What caused the dramatic force reduction at Wills?
   - Gage?
   - Elastic fasteners?
   - Rail profiles?
   - TOR?
2. Can wheel/rail contact be managed, and lateral forces kept low enough, such that elastic fasteners are not needed?

A second test site was established this year to answer these questions.
Thank you!