ABSTRACT

In order to validate the theory that trains curving with excessive elevation impose higher vertical loads on the low rail and result in higher steering tractions on lead axles, a revenue service test was undertaken by Transportation Technology Center, Inc. (TTCI) and Norfolk Southern Railway (NS) to compare speed and lateral and vertical forces on a curve with two different elevations. The measurement site was in a 4.5-degree curve with superelevation, initially, of 3.5 inches. Loaded unit coal trains operated on an ascending 1.22 percent grade under constant throttle (notch 8) at 11 to 14 mph, well under balance speed of 33 mph. In Phase 2, elevation on the test curve was reduced to 1 inch and similar data was collected under similar trains, which were now operating much closer to the new balance speed of 17 mph. Data analysis explored vertical force distribution between high and low rails, L/V ratios, and gage-spreading forces.

When operating closer to balance speed:

- Vertical wheel loads were approximately equal on high and low rails.
- Low rail vertical loads and lead axle L/V ratios were reduced, which should lead to a reduction in rail wear.
- High rail L/V ratios were also reduced, reducing the propensity for wheel climb derailments under adverse car, track, and operating conditions.
- Gage spread forces were reduced.
- It was inferred from the results that the rolling resistance in the curves was likely reduced, leading to a potential benefit in fuel consumption.

In order to minimize both the stress and track maintenance on a curve, when determining elevation consider the full spectrum of train speeds, identify the dominate tonnage trains, and try to balance the speed and elevation for those trains.
INTRODUCTION

When confronted with the challenges of rail wear, gage widening, and tie deterioration on curves, maintenance-of-way personnel have been known to look at the highway vehicle dynamics model for a solution. In this model, adding elevation to over-balance centrifugal force results in the vehicle moving toward the low side, noticeably reducing the outward lateral force felt by the vehicle’s tires. Applying this concept to a rail vehicle would mean by adding elevation and expecting that lateral forces applied to the high rail would decrease, thereby reducing rail wear and gage widening. In theory and in practice, however, the reverse is true. Elevation above what is needed to achieve balance speed actually increases lateral forces, rail wear and gage widening.

Railway vehicle curving theory suggests that:

1. Trains curving with excess elevation generally impose greater vertical loads on the low rail and greater steering tractions on the lead axle, resulting in low rail rolling contact fatigue (RCF) and high gage spread forces.

2. Trains curving at overbalance speed impose greater vertical loads on the high rail; however, trucks curve with a reduced angle of attack (AOA) and generate lower lead axle steering tractions with resulting lower lateral over vertical (L/V) ratios.

3. Optimum vehicle/track interaction conditions are achieved when vehicles negotiate curves at balance speed.

Balance speed may not be realized in revenue service because authorized speeds for passenger, intermodal, mixed freight, and unit trains may all be different. Further, a train’s speed may be dependent on its locomotive power and trailing tonnage. The reasons for choosing an elevation for a specific curve are complex, depending primarily on operational considerations. However, this research suggests that wheel/rail forces can be minimized if curves are elevated for the speed of the prevailing maximum tonnage.

THEORY

Curves are elevated to balance the centrifugal force (as determined by curvature and speed) with gravitational forces related to the track’s elevation.

![Figure 1. Forces at balance speed in elevated curve.](image)
The ideal or balance speed is given by:

\[ V^2 = \left( \frac{gs}{2l} \right) R_c \]  

(1)

where: \( g = 32 \text{ ft/sec}^2 \); \( R_c = \text{curve radius (feet)} \); \( 2l = 59.5 \text{ inches (track gage + railhead width)} \); \( s = \text{elevation (inches)} \) and \( V = \text{speed (ft/sec)} \).

This equation is closely related to the \( V_{\text{max}} \) equation provided by the Federal Railroad Administration (FRA): (2)

\[ V_{\text{max}} = \sqrt{\frac{E_a + 3}{0.0007 + D}} \]  

(2)

where: \( D = \text{curvature (degrees)} \); \( V = \text{speed (mph)} \); \( E_a = \text{actual elevation (inches, “s” in Figure 1)} \) and the additional factor of 3 inches is the amount of underbalance (cant deficiency) generally allowed by FRA.

### Influence of Elevation Deficiency or Excess on Vertical Loads

Curving with elevation imbalance transfers vertical load between the high and low rails. Figure 2 shows 2W (equal to the weight on one truck), acting at a distance, \( d \), from the centerline of the track toward the low rail due to excess cant \( s_u \).

![Figure 2. Vertical reaction forces under imbalance conditions.](image)

For a center-of-gravity (CG) height, \( h \); axle load, \( W \); and zero lateral or roll deflection of the carbody on the truck:

\[ d = \frac{s_u h}{2l} \]  

(3)

Consequently, reactions \( R_L \) and \( R_R \) are:

\[ R = \frac{W}{2} \left( 1 \pm \frac{d}{l} \right) \]  

(4)
As an example, for \( h = 96 \text{ inches} \) (a relatively high center of gravity), 5.4 percent of nominal wheel load is gained/lost on each wheel per inch of elevation imbalance. This is a minimum value, as suspension deflection causes lateral deflection of the carbody due to carbody roll that will further increase the load transfer across low and high rails.

Coupler forces also influence the distribution of vertical wheel loads. Longitudinal train forces act at coupler height and can develop a moment with respect to the wheel/rail interface. When a railcar is located on a curve, its couplers are not co-linear with the car’s center sill; thus, the coupler force can be resolved into longitudinal and lateral components. If couplers are in draft (locomotives pulling), they will exert a lateral force toward the inside of the curve, resulting in vertical wheel load transfer from high rail to low. If couplers are in buff (locomotives pushing), the reverse is true: they will exert a lateral force toward the outside of the curve, resulting in vertical wheel load transfer from low rail to high.

**Influence of Elevation Deficiency or Excess on Lateral Loads**

Curve negotiation with elevation imbalance will also result in increased lateral loads on both rails. Figure 3 shows that lateral load, \( L \), must be generated at the wheel/rail interface to counter the gravitational component of the vertical load. If \( 2W \) equals the weight of half a car, the lateral wheel/rail contact forces required to be reacted by one truck are:

\[
L = 2W \frac{s_u}{2l}
\]

Considering a car weight of 286,000 pounds, \( L = 2,403 \) pounds per inch of elevation imbalance \((s_u = 1)\). This implies that if the lateral force was to be “shared” equally between the 4 wheels of the truck, each wheel would experience a lateral load of \( 2,403/4 = 601 \) pounds per inch of elevation imbalance.

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**Figure 3. Overall lateral forces on a truck/car**
Wheel-rail forces in curves are generated from a combination of track elevation, centrifugal force and the angle of attack that axles take relative to the rail. Generally, because of curve and truck geometry, the AOA of the lead wheelset is greater than that of the trail wheelset with the angle of the trail wheelset being approximately zero on shallow curves. When running significantly under balance speed, trucks align with increased AOA on the lead axle as illustrated in Figure 4(a). When running over balance speed, the trucks align with lower angle of AOA the lead axle, due to shift of the trail axle toward the high rail, as shown in Figure 4(b).

Figures 4(a) and (b): When operating at underbalance speed, the truck aligns with an increased AOA (left); when operating at overbalance speed, the truck aligns with a decreased AOA (right).

REVENUE SERVICE TEST

A revenue service test was proposed by TTCI and NS in which the effect of elevation theory could be validated. A test site was sought having the following characteristics:

- Relatively tight curvature to maximize the lateral component of coupler force and its influence on wheel/rail forces
- Appreciable grade where all locomotives in the train are operating consistently at maximum power and tractive effort, and, consequently, constant grade-balanced speed.
- Consistent train configurations with predominantly similar cars so that results from the instrumented cribs could be analyzed statistically.

Such a test site was found at Maybeury, West Virginia, on NS’s Bluefield-Portsmouth Line. Attributes included a 4.5-degree curve with 3.5 inches elevation on a 1.22 percent ascending grade in the eastward (loaded train) direction. Timetable speed was 40 mph. The combination of curvature and elevation produced a balance speed of 33 mph. Unit coal train makeup was very consistent — typically 100 to 110 loaded cars with two 6-axle locomotives pulling and another two 6-axle locomotives pushing. The consistent train makeup removed train length and weight as variables. Trains were generally all gondolas or all hoppers (both with a weight of 286,000 pounds). Because of the grade, all locomotives operated through the test site in notch 8. Track 1 was chosen for instrumentation because it carried the vast majority of unit coal train traffic.

Superelevation was determined by NS’s curve speed and elevation table which, for a curve of 4.5 degrees and speed of 40 mph, calls for 3.5 inches. The table uses a 2-inch elevation underbalance (deficiency) for freight trains (the FRA allows up to 3 inches of underbalance). This standard gives no latitude to adjust the elevation to prevailing train speeds and tonnages. Elevation is set based on Timetable speed, which is typically determined by the maximum speed that the horizontal geometry (curvature) will allow, even if only a small percentage of trains can achieve that speed.
There are two 4.5-degree curves immediately adjacent to the test curve (one east and one west), also elevated at 3.5 inches. Though not recognized as important at the start of the test, these curves were subsequently identified as contributing to the resistance experienced by trains as they traveled across the measurement site, and they would play a role in the later Phase II testing.

DATA COLLECTION & ANALYSIS – PHASE 1

For each axle of the targeted trains — those with 100-110 loaded coal cars and locomotives distributed 2 + 2, speed and vertical and lateral forces were measured using strain gauges installed in two cribs. The spacing between the cribs provided speed data. The targeted trains were generally either all gondolas or all hoppers. Data for 89 trains was collected between June 13 and July 1, 2013.

Figure 5 shows the axle speed distribution of all eastbound trains. Balance speed of 33.3 miles per hour is only met by 3 percent of the axles. Due to the grade, all locomotives operated through the test site in notch 8. Traffic across the site was predominantly eastbound (ascending grade), and included intermodal, mixed freight, and loaded coal trains.

Recalling Equation 1, balance elevation is proportional to the square of the speed. This relationship for a 4.5-degree curve is shown with the curved black line in Figure 6. A pair of blue lines indicates that for 3.5
inches of elevation, balance speed is 33 mph. Another pair of blue lines indicates that for 5 inches, balance speed is 40 mph (Timetable speed).

The green, orange, and red boxes each represent a speed range that is possible for elevations of 0, 1, and 3 inches (represented by the bottom limit of each box) using 3 inches elevation deficiency (the top limit of each box). Looking at the green box, a 3-inch range of elevation provides a 31-mph speed range, from 0 to 31 mph. Considering the red box, the same 3-inch range of elevation provides only a 13-mph speed range, from 31 mph to 44 mph. Defining optimal elevation conditions as trains operating with the speed range defined by a 3-inch elevation band, it should be apparent that it becomes more difficult to optimize elevation conditions for higher track speeds (this also applies for sharper curvatures).

Figure 6. Relationship between elevation and speed for balance conditions in a 4.5-degree curve. The green, orange, and red boxes show the allowable speed ranges for elevations of 0, 1, and 3 inches using 3 inches elevation deficiency.

Vertical Forces

Each targeted train was analyzed separately, with analysis of vertical force data of one train presented in Figure 7. The difference in vertical wheel load between high and low rails for all lead axles is shown with blue lines (individual car values and a regression line for the train), and is plotted against position in train. These lines reflect the load transfer across axles as a result of:

- The effect of excess elevation (approximately 5,700 pounds at the middle car in the consist).
- The effect of the lateral component of the coupler force (the difference between the blue lines and the 5,700 pounds at the middle car).

The wheel load differential is greatest at the head end (7 kips) where draft coupler force, with its lateral component directed toward the low rail, adds to the weight transfer (from high to low rail) caused by elevation. The differential is least at the rear of the train (4 kips) where buff coupler force, with its lateral component directed toward the high rail, mitigates the weight transfer caused by elevation.

Interestingly, the speed of the train (measured at the instrumented cribs and shown by the red line) slowed from approximately 11.8 mph for the lead car to 11.4 mph for the 40th car. Speed then increased
to approximately 12 mph as the last car passed the crib. It is presumed that the reduction in speed is due to the increased rolling resistance as the train spanned the three 4.5-degree curves (this occurred when the 40th car passed the instrumented crib; see inserted track diagram in Figure 7). Resistance decreased as the train exited the trailing 4.5-degree curve and entered the next (2-degree) curve. This observation may be useful in future tests where the elevation might be reduced, as it may provide insight into train resistance and possible energy savings to be obtained through a more optimal elevation design.

![Figure 7](image)

Figure 7. Vertical wheel load differential across each lead axle versus position in train (blue lines); also car speed by the measurement site (red line).

The vertical load transfer data from each train was then superimposed (Figure 8). Each line represents one train. The top bundle represents the hopper trains and bottom bundle the gondola trains. Differentials are larger for hopper cars because their center of gravity is higher.

The midpoint of each train (identified by red circles) is the point of zero coupler force — it is assumed that the lead locomotives are pulling the first half of the train, and that the trail locomotives are pushing the rear half. The vertical wheel load differential at mid-train is due entirely to elevation. The hopper trains show a difference of roughly 7 kips and gondola trains about 5 kips. Differentials above and below these values are due to coupler draft (head half) and buff (rear half) force.
Figure 8. Superposition of regression lines of wheel load differentials across lead axles versus position in train. Each line represents a train.

A net linear regression line was formed for each group of trains with equations:

\[ y = -0.0465x + 7.6607 \quad \text{(gondolas)} \] ……….…….. (6)
\[ y = -0.046x + 9.7286 \quad \text{(hoppers)} \] …...…………. (7)

Table 1 shows these equations solved for \( x = 1 \) (lead car), \( x = 50 \) (mid train car/s) and \( x = 100 \) (trail car). The mid-train values approximate the load transfer due to 3.1 inches of excess cant (from 3.5 – 0.4, where 0.4 inch is balance elevation at 11.5 mph).

Table 1: Load transfer across lead wheelsets - Phase I

<table>
<thead>
<tr>
<th></th>
<th>Lead Car</th>
<th>Mid Train Car</th>
<th>Trail Car</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gondolas</td>
<td>7.61</td>
<td>5.33</td>
<td>3.01</td>
</tr>
<tr>
<td>Hoppers</td>
<td>9.68</td>
<td>7.43</td>
<td>5.13</td>
</tr>
</tbody>
</table>

The gain/loss of nominal wheel load (35,750 lbs.) is:

- Gondolas: \((5,330/2)/35,750 = 7.5\) percent
- Hoppers: \((7,430/2)/35,750 = 10.4\) percent

These values are compared with a theoretical gain/loss of nominal wheel load of 5.4 percent for a car with maximum (96 inch) center of gravity height (3).

The difference between the mid-train wheel load differential values and those for the lead/trail cars is the load transfer due to buff or draft coupler forces. This difference is approximately 2,300 pounds for both car types, and it is equivalent to a gain/loss of nominal wheel load of \((2,300/2)/35,750 = 3.2\) percent for two locomotives \((3.2\) percent/2 = 1.6 percent for one locomotive) in a 4.5-degree curve.
To summarize, curving with ~3 inches excess cant in a 4.5-degree curve can produce a gain/loss in nominal wheel load of up to 10 percent, with a further gain/loss of approximately 3 percent due to locomotive-induced coupler forces.

Lateral Forces

Figure 9 shows the results of a similar analysis of the lead axle lateral forces. Variation in lateral wheel loads between trains is greater than variation within a train; this is assumed to be due to frictional variations (limiting friction of 0.45, considering both lateral and longitudinal tractions on the low rail; it possibly occurs under lateral loads of 14,000 pounds). The general slope of the curves (0.0081) suggests a maximum 1 percent difference within a unit train. The coupler force effect on lateral wheel/rail forces was not the same as what was observed on vertical wheel/rail forces — lateral forces appear to be independent of position in train.

![Figure 9. Lead axle lateral wheel load versus car position in train. Each line represents a train.](image)

Results - Phase I

Analysis of the data collected in the 4.5-degree curve with 3.5 inches of elevation show the following (3):

- There is significant (~10 percent) gain/loss in nominal wheel load when curving at 3 inches under balance.
- A nominal wheel load gain/loss of 1.6 percent per locomotive due to coupler forces was measured (1.6 percent x 2 = 3.2 percent for two locomotives).

DATA COLLECTION AND ANALYSIS – PHASE II

The research in Phase I led to a recommendation that a Phase II test be conducted with the curve at a reduced elevation. Data collection would be repeated for a similar number of unit coal trains. The test team recognized the importance of the two adjacent 4.5-degree curves on train resistance and asked Norfolk Southern’s Transportation department to agree to a Timetable speed reduction from 40 mph to 30 mph over a 1.1-mile long stretch of track that included all three curves. The team also asked the NS Engineering department to reduce the elevation on those curves from 3-1/2 inches to 1 inch (the minimum curve elevation on NS). In support of this request, the team produced a speed distribution graph
(Figure 10) indicating that 83 percent of tonnage travels at speeds between 5 and 20 mph while only 8 percent travels above 30 mph (and would be adversely affected by a speed reduction). Both departments agreed to support Phase II, and changes to both maximum authorized speed and elevation were implemented.

![Figure 10. Train speed distribution, both directions (percent of total train passes).](image)

Figure 11 shows the axle speeds for all eastbound trains measured during Phase II. The new balance speed of 17.8 mph is much closer to the prevailing train speeds. Phase II measurements were taken in late summer to early fall of 2015, roughly the same season as Phase I.

![Figure 11. Axle (train) speed for all eastbound traffic – Phase II.](image)
Vertical Forces

Figure 12 shows the difference between vertical wheel loads (low rail vertical minus high rail vertical) for Phase I and II tests. Table 2 summarizes these results. The difference between high and low rail wheel loads at the mid-train location have been reduced almost to zero by reducing the elevation by 2.5 inches. (Coupler forces at mid-train are also zero.)

Table 2. Load transfer across lead wheelsets – Phase I & II

<table>
<thead>
<tr>
<th>Load Transfer Across Lead Wheelset (x1000 pounds)</th>
<th>Lead Car</th>
<th>Mid Train Car</th>
<th>Trail Car</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gondolas Phase I</td>
<td>7.61</td>
<td>5.33</td>
<td>3.01</td>
</tr>
<tr>
<td>Phase II</td>
<td>3.07</td>
<td>0.08</td>
<td>-1.51</td>
</tr>
<tr>
<td>Hoppers Phase I</td>
<td>9.68</td>
<td>7.43</td>
<td>5.13</td>
</tr>
<tr>
<td>Phase II</td>
<td>3.27</td>
<td>1.29</td>
<td>-0.73</td>
</tr>
</tbody>
</table>

In Phase II, the vertical wheel load differentials for hopper cars approaches that of gondola cars (both differentials approach zero as balance speed is reached). A reduction in wheel load differential implies a reduction in low rail wheel load. This has the potential to reduce low rail wear and RCF; especially if associated with a reduction in low rail L/V. (This will be quantified in future research using TTCI’s Rolling Contact Fatigue Simulator, or RCFS.)

The slope of the graphs in Figure 12 is approximately equal for both Phase I and II tests. The slope is a function of coupler force, which is a function of tractive effort. Because locomotives operated in notch 8 in both tests, tractive effort is approximately equal for each phase.

Given the same locomotive consists and throttle position (notch 8), the trains traveled at a slightly higher speed during Phase II (14.7 mph versus 14.0 mph), which suggests a lower curving resistance (associated with lower flange and low rail creep forces). This reduction may be as high as 5,000 pounds x 4 locomotives = 20,000 pounds and reflects potential fuel savings as trains negotiate sharp curves at balance speed.

Figure 12. Superposition of regression lines of wheel load differentials (low rail vertical minus high rail vertical) across lead axles versus the position in train.

Lateral Forces (L/V Ratios and Gage-spread Forces)
Lateral wheel loads are expressed in terms of high and low rail L/V ratios and gage spread force. Figure 13 compares Phase I and II high rail L/V ratios for lead axles, lead trucks. L/V ratios are noticeably less in Phase II, a reduction that is attributable to increased vertical loads on the high rail (the V in L/V). With the 2.5-inch reduction in elevation, vertical load transfer from high rail to low rail was reduced.

![High Rail L/V Ratio of Lead Axle/Truck](image)

Figure 13. Phase I and Phase II high rail L/V ratios for lead axles.

Figure 14 compares Phase I and II low rail L/V ratios for lead axles, lead trucks. Low rail L/V ratios are also less in Phase II, which might be unexpected given the reduction in vertical wheel load experienced by the low rail (due to the reduced load transfer between rails). One would expect that a reduced V in L/V would cause the ratio to increase. However, L/V decreased, due to an even more significant drop in L (lateral forces).

Lateral force on the low rail is generated by friction between wheel tread and rail. Maximum lateral force occurs when the friction is saturated (when $F = N \times \mu$). By reducing the wheel load, N (due to reduced load transfer), maximum friction force is also reduced due to reduced load transfer. In fact, there are 11 percent fewer wheel loads with low rail L/V ratios greater than 0.3 — a ratio that is closer to limiting friction and associated with low rail wear and RCF damage. This will be quantified in future RCFS research.

But this calculation simply holds L/V constant. There is an additional reduction in lateral force, one that serves to reduce L/V and that can be attributed to improved truck steering.
Figure 14. Phase I and Phase II low rail L/V ratios for lead axles.

Figure 15 compares gage spread forces for lead axles, lead trucks. Gage spread forces decreased from Phase I to Phase II — a change that could be anticipated based on reduced low rail lateral loads. Note the reduction in the 4-12 kip bins and the 15-point increase in the 0-2 kip bin. Reduced gage spread forces indicate the potential to reduce rail, tie, and fastener wear; to reduce gage-widening; and to reduce the likelihood of rail rollover.

Figure 15. Phase I and Phase II gage spread forces for lead axles.
CONCLUSIONS

When operating closer to balance speed, lead axles demonstrated:
- Smaller vertical wheel load differentials between high and low rails.
- Reduced high rail L/V ratios.
- Slightly reduced low rail L/V ratios.
- Reduced gage-spreading forces.
- A very slight increase in speed.

Lower L/V ratios for lead axles should lead to a reduction in low rail RCF. Lowered high rail L/V ratios should reduce the propensity for flange climb derailments under adverse car, track, and operating conditions. An inferred reduction in rolling resistance in the curve could lead to benefits in fuel consumption.

In order to achieve the lowest stress and the least maintenance for the rail, when deciding the elevation, consider the full spectrum of train speeds, identify the dominate tonnage trains, and try to balance the speed or elevation for those heavy trains.

FUTURE WORK

TTCI will utilize the recently constructed RCFS to quantify the benefits to rail wear and RCF provided by operating closer to balance speed versus operating at under balance speed.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the following individuals for their contributions to this research.
- Strain gauge and data collection equipment – Instrumentation Services and Kevin Conn (NS).
- Project originator and data analysis – Harry Tournay (TTCI).
- Additional data analysis and graphs – Chris Pinney, Russ Walker, Ryan Alishio, Sabri Cakdi, and Kenny Morrison (TTCI)
- Changes to train speed and track elevation – Norfolk Southern’s Pocahontas Division

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Table 2. Load transfer across lead wheelsets - Phase I & II
Effects of Superelevation and Speed on Vehicle Curving in Heavy Axle Load Service

Brad Kerchof  
Director Research & Tests  
Norfolk Southern Railway

Harry Tournay  
AVP, Mechanical Projects  
TTCI

Chris Pinney  
Senior Economist II  
TTCI
"Hey boss, I think I found a solution to my rail wear and gage-widening problem!"

- "I added 2 inches of elevation to all of my curves!"
- The supervisor is thinking of the highway vehicle dynamics model, where over-balancing centrifugal force causes a vehicle to move toward the low side.
- He believes that as he adds elevation, high rail lateral forces will decrease.

What is the 2nd myth of track maintenance?

- "More elevation is better. I can fix my rail wear and gage-widening problems by adding more elevation!"
- In theory and in practice, the reverse is true. Elevation above what is needed to achieve balance speed actually increases rail wear and gage-widening!

In theory...

1. Trains curving with excess elevation generally impose greater vertical loads on the low rail and greater steering tractions on the lead axle, resulting in low rail RCF and high gage-spread forces.
2. Trains curving at overbalance speed impose greater vertical loads on the high rail, however trucks curve with a reduced angle of attack and generate lower lead axle steering tractions with resulting lower L/V ratios.

Can we validate these theories with a field test?

TTCI and NS proposed a revenue service test where these theories could be validated. We looked for a site with these characteristics:

- A high-degree curve to maximize the lateral component of coupler force.
- Repeatable, heavy axle load train consists (similar car types, car weight and train length), such as loaded unit coal and grain trains.
- An ascending grade that causes trains to operate at maximum power and constant speed.

Test site established at Maybeury, WV

- NS’s Bluefield - Portsmouth Line
- 4.5’ curve
- 3.5 inches elevation
- 1.22% ascending grade
- Timetable speed 40 mph
- Balance speed 33 mph
- Consistent unit train make-up

Which trains did we evaluate?

To remove car weight, train length & train tonnage as variables, we looked at trains with:

- 100 – 110 loaded cars (unit trains)
- 4 locomotives – 2 pulling & 2 pushing

Trains were generally all gondolas or all hoppers.

Because of the grade, all locomotives operated through the test site in notch 8.
What data did we collect?

- For each axle: speed and vertical & lateral forces
- Date range June 13 – July 1, 2013
- 89 trains

Train speed distribution (Phase 1)

Axle speed distribution of all eastbound trains
Axle speed distribution of target trains (eastbound, 100-110 cars, 2 + 2 locomotives)

What does a 100-car train, 2 + 2, at 12 mph look like? (video 1)

What does a 100-car train, 2 + 2, at 12 mph look like? (video 1)

What forces act on a car? How are these forces transmitted to the wheel/rail interface?

1. Gravity - the weight of the car
2. Centrifugal force - created by the combination of curvature and speed
   - the load differential between high & low rails is determined by centrifugal force and elevation
3. Coupler force; the lateral component of draft (tension) acts toward the low side; the lateral component of buff (compression) acts toward the high side
4. Axle steering forces

What forces act on a car? How are these forces transmitted to the wheel/rail interface?

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   - the load differential between high & low rails is determined by centrifugal force and elevation
3. Coupler force; the lateral component of draft (tension) acts toward the low side; the lateral component of buff (compression) acts toward the high side
4. Axle steering forces
Impact of coupler forces on vertical wheel load distribution between low and high rails (video 2)

- First video segment: Coupler buff force rotates car body, and pushes truck, toward high rail.
- Second video segment: Coupler draft force rotates car body, and pulls truck, toward low rail.

How much of this model reflects full-scale conditions?

- Car body rotation and vertical load transfer - yes (though exaggerated)
- Truck translation - No! Steering forces dominate, keeping the lead axe flanging on the high rail.

Vertical wheel load differentials vs. position in train (Phase 1)

For one train, vertical wheel load differentials and speed vs. position in train (Phase 1)

- Graph shows wheel load differentials (low rail minus high rail) of multiple trains: top bundle includes hopper trains (higher CG); bottom bundle includes gondola trains.
- Wheel load differential at mid-train (red circles), the point of zero coupler force, is due entirely to elevation: hoppers 7 kips, gons 5 kips).
- Differentials above and below these values are due to coupler draft (head half) and buff (rear half) force.

For one train, vertical wheel load differential and speed vs. position in train (Phase 1)

- Blue lines represent vertical wheel load differentials; the differential is greatest at the head end
- Vertical differential varied from roughly 7 kips (more weight on low rail) to 4 kips.
- Red line represents train speed
- Train speed varied between 12.0 and 11.4 mph; minimum speed was recorded when the train occupied the three 4.5 curves simultaneously.

Conclusions (Phase 1)

- Balance elevation for trains operating on a 4.5 curve at 11.5 mph is 0.4 inch. The majority of tonnage trains operate at 3.1 inches excess (overbalance) elevation.
- Significant wheel load transfer when curving at 3 inches underbalance. Load transfer was 10% (3.7 kips) for higher-CG hopper cars.
- Additional wheel load transfer of up to 3.2% (2.3 kips) was measured due to coupler forces applied by 2 locomotives.
- Coupler buff & draft forces have a significant impact on vertical wheel load transfer, but a minimal impact on lateral forces as measured at the wheel/rail interface.

Recommendation

Add a phase 2 to the test:
- Reduce the elevation of the test curve and the two adjacent curves to 1 inch (the minimum curve elevation on NS).
- Repeat the data collection to measure changes in speed and lateral & vertical forces.
Following Phase 1, we asked, can we reduce elevation to see how vehicle dynamics change?

Objective: Convince Pocahontas Division Transportation to reduce speed on 1.1-miles of track from 40 mph to 30 mph, and ask Engineering to reduce elevation from 3-1/2 inches to 1 inch.

How did we justify our request?

1. Advancement of our knowledge of train dynamics - research!
2. Only a small number of trains would be adversely affected by a 10 mph speed reduction

Speed and track changes for Phase 2

- Transportation agreed to reduce speed from 40 mph to 30 mph through the three 4.5° curves.
- Engineering was able to reduce elevation with a minimum of trackwork – elevation could be reduced on an inside track without concern for clearance because of wide track centers.

In Phase 2, what trains and data did we evaluate?

The same type trains:
- 100 – 110 loaded cars (unit trains)
- 4 locomotives – 2 pulling & 2 pushing
- Operation - still in notch 8

The same data:
- For each axle: speed and vertical & lateral forces
- Date range Aug 27 – Oct 10, 2015
- 85 trains

Data analysis:
- Train speed
- Vertical wheel load differential
- L/V ratios, high and low rails
- Gage-spread force

Train speed distribution, Phases 1 & 2

Graph: Average Wheel Load Differentials Across Lead Axles vs. Position in Train for Multiple Gondola and Hopper Trains.

Vertical wheel load differentials vs. position in train, Phases 1 & 2

Table: Load transfer (in kips) across lead axles for gondolas and hoppers at three locations in train. The difference between gondola and hopper values is due to height of CG.
High rail L/V ratio, Phases 1 & 2

- High rail L/V ratios decreased from Phase 1 to Phase 2.
- Primary reason: In Phase 2, the vertical wheel load "V" in L/V increased, due to less wheel load transfer from the high rail.

Low rail L/V ratio, Phases 1 & 2

- From previous slide: High rail vertical wheel load "V" increased from Phase 1 to 2, thereby reducing L/V. This slide: Low rail vertical wheel load decreased; wouldn’t that be expected to increase in L/V?
- In fact, low rail L/V ratios actually decreased from Phase 1 to Phase 2!

Why did low rail L/V ratios decrease?

- Lateral force on the low rail is generated by friction between wheel tread and rail. Maximum lateral force occurs when the friction is saturated - when $F = N \times \mu$. By reducing $N$ (due to reduced load transfer), maximum friction force is also reduced.
- But this simply holds L/V constant. The additional reduction in lateral force (and thus the reduced L/V) shown in the previous slide can be explained by improved truck steering.

Gage-spread force, Phases 1 & 2

- Gage-spread forces were reduced from Phase 1 to 2 (note reduction in the 4 – 12 kip bins and a 15-point increase in the 0 – 2 kip bin.

Conclusions

When operating closer to balance speed, lead axles demonstrated:
- Smaller vertical wheel load differentials between high and low rails
- Reduced high rail L/V ratios
- Slightly reduced low rail L/V ratios
- Reduced gage-spread forces
- No measurable change in speed

For the lowest stress and the least maintenance,
- Consider the full spectrum of train speeds
- Identify the dominate tonnage trains
- Try to balance the speed or elevation for those heavy trains

Acknowledgements – who gets the credit for this project?

- Strain gauge & data collection equipment – Instrumentation Services & Kevin Conn (NS)
- Project originator and data analysis – Harry Tournay (TTCI)
- Additional data analysis & graphs – Chris Pinney, Russ Walker, Ryan Alishio, Sahri Cakdi & Kenny Morrison (TTCI)
- Changes to train speed and track elevation – NS’s Pocahontas Division
Questions & Discussion