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13. ABSTRACT (Maximum 200 words)

Transportation Technology Center, Inc., with Federal Railroad Administration support, conducted a study to review and summarize current practices and issues related to shared operations—particularly freight train operations on curves with cant excess. Shared-track curve design requires a compromise between higher-speed passenger and lower-speed freight operations. Significant superelevation helps passenger trains operate at higher speeds, but it causes deterioration on rail, ties, and surface condition due to freight operations at substantially lower speeds. To develop best practice for such shared operations, future research is recommended in this report.

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1 square yard (sq yd, yd^2)	=	0.8 square meter (m^2)	1 square kilometer (km^2)	=	0.4 square mile (sq mi, mi^2)
1 square mile (sq mi, mi^2)	=	2.6 square kilometers (km^2)	10,000 square meters (m^2)	=	1 hectare (ha) = 2.5 acres
1 acre = 0.4 hectare (he)	=	4,000 square meters (m^2)			
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				=	1.1 short tons
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1 fluid ounce (fl oz)	=	30 milliliters (ml)	1 liter (l)	=	1.06 quarts (qt)
1 cup (c)	=	0.24 liter (l)	1 liter (l)	=	0.26 gallon (gal)
1 pint (pt)	=	0.47 liter (l)			
1 quart (qt)	=	0.96 liter (l)			
1 gallon (gal)	=	3.8 liters (l)			
1 cubic foot (cu ft, ft^3)	=	0.03 cubic meter (m^3)	1 cubic meter (m^3)	=	36 cubic feet (cu ft, ft^3)
1 cubic yard (cu yd, yd^3)	=	0.76 cubic meter (m^3)	1 cubic meter (m^3)	=	1.3 cubic yards (cu yd, yd^3)
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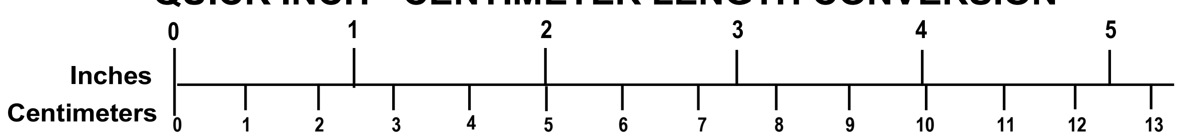

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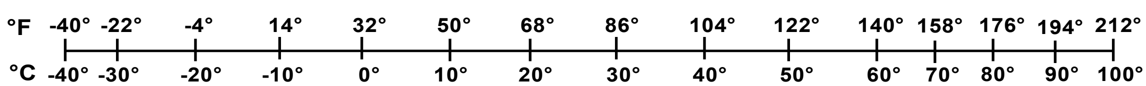

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Executive Summary

Transportation Technology Center, Inc. (TTCI), with Federal Railroad Administration (FRA) support, conducted a study to review and summarize current practices and issues related to cant excess when operating freight trains on shared-track with passenger train operations. TTCI performed the research from March to December 2015 at its Pueblo, Colorado facility. The research team conducted the following work:

- Reviewed and summarized past studies related to cant excess for freight operations.
- Reviewed documents regarding vehicle-track interaction and rolling contact fatigue (RCF) related to curving and superelevation.
- Summarized a survey and discussions with railroads and other stakeholders regarding current planning, design, and maintenance practices, and determined gaps and needs for improvement.
- Presented statistical analysis on curvature and underbalance from 12 corridors with shared operations.

This study discusses that the design of curves on shared track requires a compromise between higher-speed passenger and lower-speed freight operations. Significant superelevation helps passenger trains at higher speeds, but it causes deterioration on rail, ties, and surface conditions due to freight operations at substantially lower speeds. The most common issues related to cant excess identified by the literature review are the following:

- Gauge spreading due to high lateral load on the low rail
- Rail seat deterioration (RSD) due to significant gauge spreading and rail rollover forces for concrete ties
- Deformation and cracking (or RCF) of the low rail due to a shifting of the load to the low rail
- Increased risk of derailment due to tipping is higher, especially if the train comes to a stop on the curve.

The issues brought up from the survey and discussions with railroads confirmed those listed in the literature review. More specifically, surveyed railroads indicated the following common issues for curves with excess cant:

- Excessive flattening or plastic flow on low rail
- Gauge widening
- Rollover of the low rail
- Increased potential of internal rail defects
- Adverse impact on rail, tie, and surface condition due to the elevated vertical loading on the low rail and the increased axle steering forces that result.

To develop a best practice for shared operations in curves, the TTCI research team recommends further research, including modeling and testing for understanding vehicle and track parameters that affect operating safety and track degradation in curves with shared operations.

1. Introduction

The recent increased demand for commuter and long-distance rail passenger service has resulted in relatively lightweight passenger trains frequently sharing existing track designed for heavy freight trains. For example, Amtrak, New Jersey Transit, Utah Transit Authority, Maryland Transit Administration, and the San Diego Trolley—all passenger railroads—share track with freight trains. Passenger trains are comparatively lightweight and travel at higher-speeds than freight trains, sometimes at speeds high enough to be considered high-speed rail (HSR). Whereas freight trains are typically heavier and slower and are often referred to as heavy axle load (HAL) trains. Passenger and freight shared-track operations cause many issues, including complications due to differences in operating speeds in curves.

1.1 Background

Shared-track operations of higher-speed passenger trains and freight trains result in conflicting design and maintenance strategies which require resolution to ensure safe operation while minimizing track and vehicle maintenance costs. The wide range of operating speeds, vehicle suspension characteristics, and service loads require special design and performance strategies.

Superelevation in curves, wheel and rail profiles, and lubrication and friction control require proper design and considerations for shared operations. Shared operations of higher-speed passenger trains and relatively lower-speed freight trains likely require different track curvature and superelevation procedures than those currently in place exclusively for passenger or freight services.

For a steady-state vehicle curving movement, superelevation is simply designed to counteract the effects of centrifugal force (e.g. vehicle overturning, lateral forces on track, etc.). If superelevation is too high or too low (see Figure 1), it shifts more forces onto the low or high rail. However, in terms of dynamic vehicle-track interaction in a curve, optimal superelevation design requires more consideration than just the simple force equilibrium shown in Figure 1. Factors such as those listed in Section 1.3 must be investigated to determine optimal superelevation for shared operations between higher-speed passenger vehicles and lower-speed freight vehicles.

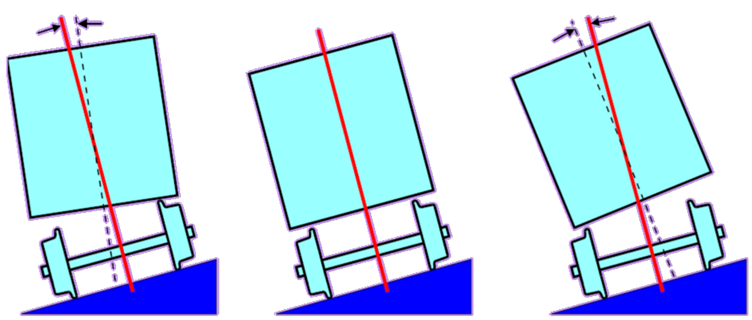

Figure 1. Three types of balance conditions: overbalance or cant deficiency (left), equilibrium or balance (center), and underbalance or cant excess (right)

1.2 Objectives

This study summarizes current practices and issues related to cant excess when operating freight trains in curves at a speed lower than a balance speed, and it included the following tasks:

1. The research team reviewed and summarized past studies related to cant excess for freight operations. The team paid attention to studies completed under FRA and Association of American Railroads (AAR) research. This study also gathered and analyzed information from other countries.
2. The team held discussions with railroads and other stakeholders regarding current planning, design, and maintenance practices, and determined gaps and needs for improvement. Concurrently, they performed a survey on current practices related to shared operations, with focus on cant excess issues for freight operations.
3. The team developed this report to summarize its findings.

TTCI researchers also used the findings of this study to develop recommendations for further research on related topics.

1.3 Overall Approach

Researchers conducted a literature search and review to determine what information was available and how the unique issues of shared operations have been addressed. The review focused on the past studies related to cant excess for freight operations. This study also included gathering and analyzing worldwide practices associated with operations in curves.

Some of the factors related to curving performance include:

<u>Fundamentals of superelevation on curves and special requirements in superelevation:</u>

- Why is optimum superelevation important for shared operations?
- What needs to be considered when operating freight trains at high cant excess?
- How is optimum superelevation determined for shared operations in terms of curving performance and wheel-rail interaction of higher-speed passenger cars and lower-speed freight cars.

<u>Major issues for freight trains operating with high cant excess:</u>

- Safety performance
- Truck lateral stability
- Wheel-rail wear and defect growth
- RCF occurrence
- Track stability, such as rollover and track panel shift

Researchers held discussions with railroads and other stakeholders regarding current planning, design and maintenance practices, and determined gaps and needs for improvement. Concurrently, they performed a survey on current practices related to shared operations, focusing on cant excess issues for freight operations. This survey included getting the following information from railroads that operate trains on shared tracks:

1. Current track curvature and superelevation design, construction, and maintenance practices
2. Speed – curvature profiles under normal operating conditions for both passenger and freight operations
3. Rail vehicle weight distribution (e.g., freight vs. passenger vehicles) for shared tracks
4. Effect of tonnage distributions of freight and passenger trains for shared tracks
5. Associated curving and dynamic performance data of the freight and passenger vehicles for shared tracks
6. Data related to wheel and rail profiles, wear patterns, and RCF occurrences for shared tracks
7. Problems and issues associated with current shared tracks

Items 3 to 6 are not discussed in this report since the survey participants did not provide enough information.

1.4 Scope

This is a white paper study. Much of the information included in this document was taken from previous publications. However, the section related to the current practices and issues in the U.S. is based on the survey and an analysis of track charts provided by the railroads.

1.5 Organization of the Report

Section 2 reviews the principles of cant excess and cant deficiency, including definitions and terms used throughout this report.

Section 3 is a summary of the literature review. Previous studies performed by Transportation Technology Center, Inc. (TTCI) and the University of Illinois at Urbana-Champaign (UIUC) are the primary sources. Researchers also reviewed and summarized worldwide practices associated with the same subjects, including documents regarding vehicle-track interaction and RCF related to curving and superelevation.

Section 4 examines railroad practices in the United States and summarizes survey findings. Current practices and issues related to cant excess are summarized based passenger and freight railroads' survey comments. Statistics on curvatures and underbalance from 12 corridors with shared operations are provided.

Section 5 presents the summary and conclusions of the research performed for the scope of this project.

Section 6 offers recommendations for future research.

2. Definitions

When a track goes through a curve, the outer rail is raised above the inner rail (see Figure 1) so that the centrifugal force from the turn, when combined with the weight of the train, remains normal to the track surface. This difference in height between the inner and outer track is called superelevation, In other countries it is also referred to as cant, and is usually measured by the difference in height between the two rails. However, because the centrifugal force depends on the velocity of the train and the radius of the curve, the superelevation of a curve is balanced at only one speed. When a train goes through a curve too quickly, centrifugal force causes it to lean to the outside of the curve, thus placing more weight on the high (outside) rail. This is called cant deficiency or overbalance. Cant excess, or underbalance, occurs when a train goes through a curve too slowly and places more weight on the low (inside) rail. Both cant excess and deficiency are commonly measured in the amount of inches or millimeters needed to correct the superelevation.

2.1 Balance Speed

At a specific speed, called the balance speed, the compensation due to superelevation balances the acceleration due to curving. Relative to the track plane, the perceived lateral acceleration is then zero. At speeds under the balance speed, the lateral acceleration component is less than the superelevation component . This is called cant excess[1], meaning the track has excessive cant for the present speed. At speeds over the balance speed, the lateral acceleration component is greater than the superelevation term. This is called cant deficiency, meaning the track has insufficient cant for the present speed. With cant deficiency, perceived accelerations are to the outside of the curve; with cant excess, perceived accelerations are to the inside of the curve.

2.2 Cant Excess and Cant Deficiency

Cant deficiency or excess is often expressed as an amount of insufficient or excess superelevation—defined as in inches of cant deficiency. They are expressed sometimes as uncompensated acceleration—in ft/sec^2. As a conversion, 1 inch of cant deficiency corresponds to just over 1/2 ft/sec^2 of uncompensated lateral acceleration.

The forces due to centripetal acceleration through a curve must ultimately be reacted at the wheel-rail interface. Curve lateral acceleration and the compensating effect of track superelevation can be expressed mathematically, as shown in Figure 2 and Figure 3 and Equations 1 and 2.

[1] Track cant is a British synonym for the superelevation of the curve.

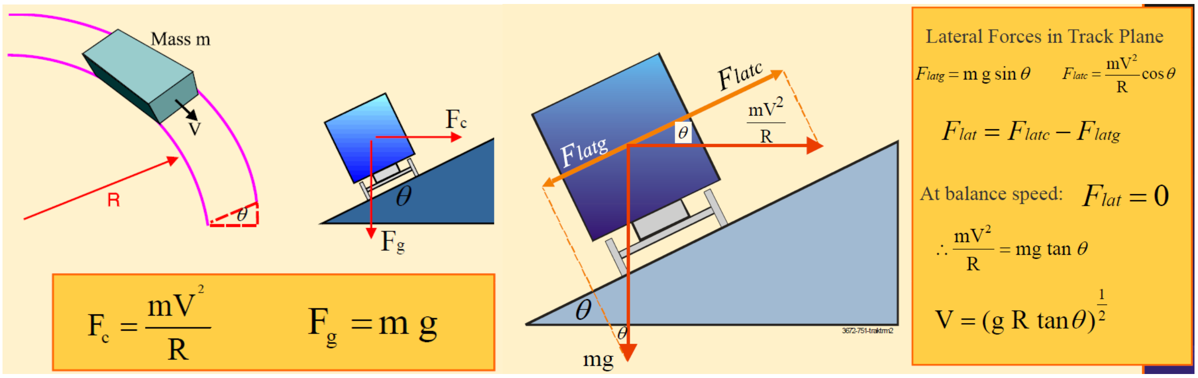

Figure 2. Curving system and force balance

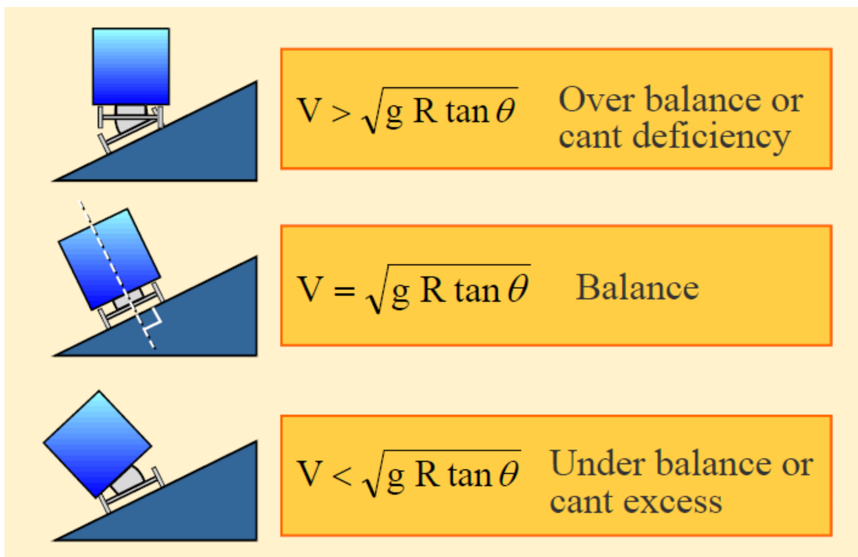

Figure 3. Three types of balance conditions and related velocities

Cant deficiency (overbalance)

$$\frac{V^2}{R} > \frac{g \cdot se}{2E} \qquad \text{(Eq. 1)}$$

Cant excess (underbalance)

$$\frac{V^2}{R} < \frac{g \cdot se}{2E} \qquad \text{(Eq. 2)}$$

*Where: V – balance speed, R – radius of curvature, E – gauge, se – super elevation.

For cant excess, the worst case is a stationary train. The cant excess limit is equivalent to the maximum allowable superelevation. The cant deficiency limit is typically dictated by maximum uncompensated lateral acceleration, rather than derailment safety. Safe operation is possible at much higher cant deficiency levels than trains usually encounter. Tilting trains provide this by operating at cant deficiencies two to four times those of conventional trains.

3. Literature Review

Before World War II, the U.S. railroads had long practiced operating passenger trains and freight trains on the same tracks. Following World War II, passenger service declined significantly. Until early 1970s, very few freight routes were shared with passenger trains. Between the 1980s and the first decade of the 21st century, there has been a slow increase in passenger service returning to freight lines. These were primarily commuter rail services with operational speeds below 90 mph.

More recently, there has been more interest in running higher-speed (above 90 mph) commuter and intercity passenger services on freight routes. These shared-track systems would impose unique challenges for infrastructure design. HSR operations will require more stringent track geometry and maintenance standards, as the effect of typical geometry and track component problems can be amplified at high speeds, causing passenger discomfort and posing a safety concern. For freight traffic, a much more resilient system is needed to mitigate the impacts caused by HALs. For a shared-track system, these challenges must be met simultaneously, because both types of traffic must be supported by the shared-track structure.

Several research projects have already investigated challenges of shared high-speed passenger and freight operation corridors. This section summarizes findings from the literature review.

3.1 Design Overview

3.1.1 Design Provisions in the United States

For passenger traffic, superelevations and authorized speeds can be set so that trains run with as much cant deficiency as is allowed, with considerations given to safety, relevant regulations, and passenger comfort. The U.S. FRA Track Safety Standard 49 CFR 213 regulations limit cant deficiency through a qualification process for operation on particular routes for tilting passenger vehicles, and has a 3.0 inch (76 mm) limit for conventional vehicles. [1] This FRA regulation is based on AAR standards from a single study in the 1950s on a rail line in Connecticut. [2]

Allowed cant deficiency is set below the value that would be allowed by 49 CFR 213 to reduce wheel and rail wear and to reduce the rate of degradation of the geometry of ballasted track. The choice of design cant deficiency will be less constrained by passenger comfort in the case of vehicles that have tilting capability. Contemporary engineering studies would likely use vehicle motion simulations, including cross wind conditions, to determine margins relative to derailment and rollover.

If the superelevation determined for a dedicated passenger route curve using safety regulations is below 6.0 inches (152.4 mm), it may be desirable to increase the superelevation and reduce the cant deficiency. However, if on such a curve some trains regularly travel at lower speeds, then raising the superelevation may be inadvisable for passenger comfort reasons.

On a mixed-traffic route owned by a freight railroad, freight considerations are likely to prevail. On a mixed-traffic route owned by a passenger rail company, a compromise may be needed.

Cant deficiency is generally looked at with respect to ideal track geometry. Geometry of real track is never perfect, so it may be desirable to supplement the static considerations laid out above with simulations of vehicle motion over measured geometries of actual tracks. Simulations also increase understanding of vehicle behavior traversing spirals, turnouts, and other track segments where curvature changes with distance by design. Where simulations or measurements show non-ideal behavior traversing traditional linear spirals, results can be improved by using advanced spirals. Good track geometry including advanced spirals is likely to foster passenger acceptance of higher cant deficiency values.

3.1.2 Design Provisions in Other Countries

France and Germany have maximum superelevation levels equal to the FRA 49 CFR 213 limit of 7.0 inches (178 mm). Japan is marginally higher at 8.0 inches (203 mm). For cant deficiency, all three countries allow higher values of cant deficiency than the 3 inches (76 mm) accepted in the U.S. In U. S., rail cars can go higher than 3 inches of cant deficiency provided they go through qualification. In Germany, where axle loads are typically lower than those in the U.S., tilting trains are allowed to operate with 12.0 inches (305 mm) cant deficiency in some cases. On conventional lines, France and Germany allow operation with up to 6.0 inches (152 mm) cant deficiency. On TGV high-speed lines in France, the limit is 4.0 inches (102 mm), in part because of the very large curve radii on such lines. Thus, there is no requirement to go to higher cant deficiency in the U.S. [3]

Table 1 summarizes acceptable overbalance in other countries. It is worth noting these limits should not be directly related to the limits in the U.S. because train conditions in other countries are often quite different. For example, German freight cars usually weigh 12 to 24 tons in axle load while in the U.S. they generally weigh about 32 to 36 tons in axle load.

Table 1. Acceptable overbalance in other countries

	Maximum superelevation	**Maximum cant deficiency**
France	6.25–7 inches (160–180 mm)	6–4 inches (150–100 mm)
Germany	7 inches (180 mm)	6 inches (150 mm)
Japan	8 inches (200 mm)	unknown

3.2 Issues with Cant Deficiency or Excess

Cant excess can cause many of the same problems as cant deficiency, as well as a few different problems. For example, HAL freight trains often operate with cant excess, so the lower rail is subjected to higher vertical loads in cant excess than the high rail. Also, because the track is already tipping slightly inward, the chance of derailment due to tipping is higher, especially if the train comes to a stop on the curve. Another cant excess issue is commuter discomfort due to lateral accelerations in passenger trains, and in freight trains lateral forces are a concern.

One of the larger concerns for trains operating in cant excess is the development of rolling contact fatigue(RCF) due to the large increase in vertical and lateral loads in the low rail. RCF can lead to shelling, running surface cracks, gauge corner cracks, squats, and ultimately rail failure. When RCF develops, it forms a vicious cycle; the imperfections that it causes increase the load felt during the next cycle, and the imperfections worsen. RCF is best dealt with through preventive design, regular maintenance such as grinding, and making use of the "magic wear rate" (MWR). The MWR is when material is removed from the top of the rail, either through grinding or natural wear, so that all the existing cracks are cleared away without taking off any extra steel.

When a track is being shared between freight and passenger trains, many design choices must be carefully selected, and even existing tracks may need modifications. Most shared track is owned by freight railroads, so passenger trains may need to pay for track modifications or reduce their trains speed when approaching a curve. Either way, trains must pass through a curve within the FRA limits for cant deficiency and freight trains must pass through the curve at a safe level of cant excess. Cant deficiency is generally accepted as being less damaging to the track and wheels than cant excess, and therefore has less restrictive limits. Some dynamicists are even of the opinion that operating at a speed slightly above balance speed is most beneficial to the track and wheels. [4] These dynamicists argue that operating at a cant deficiency of less than 2.0 inches (51 mm) will decrease total trip time, decrease required braking, lower the net gauge widening forces, decrease the overall damage to the rails by up to 50 percent, and decrease the angle-of-attack of the leading wheelset, therefore lowering derailment potential. Other dynamicists disagree, but regardless, it is understood that cant deficiency at high levels will cause problems. These problems include, but are not limited to, increased vertical and lateral load on the high rail, increased RCF on the high rail, increased chance the train will roll to one side (especially with high centers of gravity and/or high winds), increased chance of lateral track buckling (track panel shift) or roll of the high rail (see Section 3.2.2, describing derailment risk), decreased passenger comfort (see Section 3.2.1, describing tilt), and the train being overall more sensitive to rail perturbations (especially HSR).

3.2.1 High-Speed Curving Issues

For passenger trains, the primary high-speed curving issue is lateral acceleration. Rail passengers expect to safely and comfortably stand up and walk around during their journey. Accelerations on the order of 3–4 ft/sec^2 are generally the maximum acceptable for passengers—including the worst-case scenario of standing passengers.

Passenger comfort in curves can be improved by tilting the vehicle body. This reduces the perceived lateral acceleration, thus allowing higher curve speeds. One of the first active tilting trains was the Advanced Passenger Train (APT) in the U.K. Successful designs, coming 10 years later, were the X2000 in Sweden and the Pendolino in Italy. The Pendolino is a clear commercial success, with trains delivered to nearly a dozen countries. Tilt trains of various designs are now used in nearly 20 countries. The Acela and Talgo trainsets are domestic examples of tilt trains.

In Pendolino trains (each car tilts independently) the tilt mechanism is a pair of hydraulic cylinders and inclined links on each truck. These act to rotate the car about a point 60 to 70 inches (1.52 to 1.78 meters) above top of a rail. This corresponds roughly to passenger head or chest level. Experience has shown this roll center maximizes perceived comfort. Tilting trains typically run at maximum uncompensated accelerations of 5–6 ft/sec^2 with 60 to 70 percent compensation. Full compensation leads to greater discomfort. Passengers want some perception of curving, otherwise visual and inner ear signals conflict, leading to motion sickness.

3.2.2 Derailment Risk

The first issue with regard to derailment is wheel climb. The high rail/leading axle lateral to vertical (L/V) ratio tends to decrease with increasing cant deficiency. Lateral loads do not increase substantially, while vertical loads do (load shifts from low rail to high rail). The trailing axle L/V ratio for the high rail increases substantially.

The effect of angle-of-attack should also be considered when analyzing the potential for wheel climb. The Nadal criterion for wheel climb is very conservative at low or negative angles-of-attack. Under these conditions, the critical L/V ratio can be several times greater than the Nadal limit. For most rail vehicles, at high cant deficiency, the leading axle, which is critical in terms of derailment risk, tends to have a low positive angle-of-attack . The trailing axle, which may in fact have a slightly higher L/V ratio, is likely to have a negative angle-of-attack (i.e. be in an over-radial position), and thus reducing the risk of derailment. Although the lateral load can increase substantially, if the wheelset develops a negative angle-of-attack (over-radial position), the L/V required for flange climb to occur will be much higher than conservative safety criteria based on Nadal's limit, so the risk of flange climb derailment is low. Note that the details and magnitude of this curving response and the consequent changes in lateral forces and L/V ratios are also very dependent on the details of the suspension design, degree of curvature, and speed range.

A significant derailment risk at high cant deficiency comes from the fact that the vehicle attempts to push the track out from under itself. As the cant deficiency increases, the lateral forces on the low rail wheel of the trailing axle of a truck also tend to reverse direction and then increase until there is a net lateral force on the trailing axle acting to push the track to the outside. This safety issue is closely related to track buckling (also known as track panel shift). High-speed trains may encounter speed restrictions during extremely hot weather. According to Klauser (2014), "Greater track longitudinal forces due to temperature and greater net axle lateral forces due to cant deficiency increase the risk of track buckling." [3]

The critical value in this track buckling response is the net axle lateral load. In Europe and in the U.S., the limit is usually defined by the Prud'homme formula and FRA Track Safety Standard 49 CFR 213.333. [5, 1] Track lateral strength is defined by a constant term and a term linearly dependent on axle load. Passenger vehicles intended for high cant deficiency usually have comparatively low axle loads, on the order of 15 tons to 20 tons maximum per axle. Note that the details and magnitude of this curving response and the consequent changes in lateral forces and L/V ratios are also very dependent on the details of the suspension design.

Net Axle Lateral L/V Ratio $\leq 0.4 + \frac{5.0}{V_a}$ (Eq. 3)

Where: V_a – static vertical axle load, kip

This same increase in lateral forces on the trailing axle can also increase the risk of rail rollover on the outside rail in curved track, especially in track with weak rail fasteners such as cut spikes. Both the FRA Track Safety Standard 49 CFR 213.333 [1] and the AAR Chapter 11 performance standards for new freight car design [6] define a truck side L/V ratio for evaluating risk of rail rollover:

Truck Side L/V Ratio $\sum L_{side} + \sum V_{side} \leq 0.6$ (Eq. 4)

Where $\sum L_{side}$ and $\sum V_{side}$ are the summed lateral and vertical forces on one side of a truck.

The final safety concern is vehicle overturning. At high cant deficiency, lateral forces may be sufficient to cause unloading of the low rail wheels and possible vehicle overturning. This is particularly an issue for vehicles with high centers of gravity operating in high winds. Speed restrictions may be required for high-speed trains during high wind periods.

A last observation with regard to cant deficiency is that curving resistance often drops with increasing speed. This is true, dependent on curve radius and suspension design, to roughly 3–5 inches (76–127 mm) cant deficiency. The optimum from the view of curve resistance and rail and wheel wear is to generally operate at maximum speed. [3]

Based on research performed at Delft University, to limit or prevent derailment risk the following measures can be implemented: [7]

- "Use of maximum possible curve R, preferable so that no superelevation is necessary."
- "Use of cant in curves so that lateral acceleration is entirely or partly compensated by the gravity component."
- "Speed restriction. This is not an attractive option because of the consequent increase in transit time and the loss in capacity."

3.2.3 HAL Train Issues

Curves on freight lines often have excess superelevation for HAL operation. As a result, HAL trains tend to operate at cant excess, rather than cant deficiency. "Increasing cant deficiency tends to improve curving behavior and reduce RCF damage. Conversely, traveling slower in curves can increase damaging forces and increase the risk of flange-climbing derailment of the leading wheels." [8] A reduction in superelevation would move freight trains to operating at balance speed or slightly above balance speed (slight cant deficiency). This change would be accompanied by small but nonetheless realizable benefits. [9, 10, 11] One is a reduction in low rail plastic deformation. There is also potential for a reduction in total wheel and rail wear.

Finally, there is a reduction in gauge-widening force. Operating at cant deficiency reduces the low rail lateral load more than it increases the high rail lateral load. Thus, the net gauge-spreading load will be reduced. Since low rail rollover is generally of greater concern than high rail rollover, reducing the lateral load on the low rail is a further benefit.

However, if superelevation is increased to accommodate higher-speed passenger trains, HAL trains would then operate with more cant excess. Operating at cant excess shifts the load to the low rail. Since hollow-worn wheels generate large contact stresses on the rail field side, crushing, plastic flow, and surface defects are likely more severe with cant excess. Previous research [9, 10, 11, 12, 13, 14, 15, 16] has shown that other issues for HAL trains at cant excess include:

- Increased chance for high rail flange climb due to decreased vertical load on outside rail
- Increased gauge-widening forces and rail rollover due to increased vertical load on low rail

A significant portion of the lateral force that acts to push the wheelset into flange contact with the high rail in curves is generated by the low rail wheel. This lateral force increases with increasing vertical load on the low rail wheel. The corresponding drop in vertical force on the high rail wheel tends to increase the high rail L/V ratio, increasing the risk of flange climb derailment.

This increased lateral force on the low rail wheel is reacted by the rail in the outward, gauge-widening direction. The increased vertical load from HAL trains also tends to flatten the low rail, which can contribute to the wheel contacting the rail on the field side. This contact condition, in combination with the increased low rail lateral forces, leads to increased risk for rail rollover.

3.3 Previous Studies

3.3.1 University of Illinois at Urbana-Champaign

The FRA report by UIUC discusses various technical challenges related to shared HSR passenger and freight rail corridors, describes an effort to prioritize the challenges, and presents an in-depth literature review on the high-priority challenges to identify existing research and future research needs. [17]

When both freight and passenger trains use the same track, the track may have to be designed for the highest load combination possible. Increasing the superelevation and reducing cant deficiency in the design for a diverging track of a turnout can allow for higher-speed train operations.

<u>Curve Superelevation</u>

Curve superelevation is typically set for the predominant traffic speed on a rail line. On freight lines, curves are typically elevated for the balancing speed or slight unbalance for a freight train. Conventional passenger trains may operate at a higher unbalance than freight traffic, but especially on lines with many curved track sections this may lead to numerous speed restrictions that would reduce the average speed of a passenger train. With HAL freight operations, changing curve elevation to accommodate passenger trains could potentially impact rail life and increase risk of low rail rollover on curves.

Rail Wear and Defect Rate

A railway line can accommodate higher-speed traffic for the same degree of curve by increasing superelevation on curves. Freight traffic traveling at speeds below the balancing speed of the curve will impart higher loads and stresses on low rails in curves. Increased rail stress can lead to the increased rate of rail defect formation. Rail corrugation and other short wave irregularities can increase dynamic loads on the track structure. In particular, weld geometry can have an impact on higher-speed dynamic loads. At higher-speeds, these types of defects may have a detrimental effect on passenger ride quality. The impact of weld geometry could be investigated as it relates to ride quality and dynamic track loads. [18]

Tilting Equipment

On rail lines where curves restrict the speed of train operation, tilting equipment may be used to increase speeds without increasing curve elevation. Active or passive tilting equipment may be used to operate passenger trains at higher, unbalanced elevations through curves. Despite enhanced passenger comfort, utilizing tilting equipment does not mitigate the increased rail stresses by operating at a higher unbalance speed through curves. Overall increases in passenger train speeds may increase stresses on the high rails of curves. Different levels of curve unbalance could be investigated in terms of vehicle dynamics in addition to relation to rail wear.

Special Trackwork

Introducing higher-speed passenger service in North American creates unique challenges in railway infrastructure, requiring a higher standard for track quality on existing track typically carrying HALs. In order to meet the track design conditions required for the growth of HSR, turnout designs must be reanalyzed. Many countries elsewhere in the world, especially in Europe and Asia, could provide valuable insight on HSR track design. [19, 20, 21] However, there is still much to be learned from operating on shared track, as the combination of North American freight axle loads and more robust passenger car designs than those generally seen globally on existing HSR lines contributes to this challenge. [22]

3.3.2 TTCI

TTCI produced a document for FRA that outlined a series of recommended tests related to shared-track in the United States. [18] The document used previous studies by the UIUC, TTCI, and other past reviews and tests to identify the most important areas. Many of these tests incorporated superelevation, cant deficiency, or cant excess in some way, and those are the tests that this summary focuses on.

The document recommended that any test track needs to be chosen carefully to incorporate all of the possible issues that shared-track operations encounter (including varying levels of superelevation). Three possible test track locations are on routes that plan to incorporate both HSR and HAL trains in the future are:

- Chicago, IL – St Louis, MO (Union Pacific, Amtrak, Illinois Department of Transportation)

- Charlotte, NC – Greensboro/Raleigh, NC (Norfolk Southern , Amtrak, State of North Carolina)
- Seattle, WA – Portland, OR (BNSF and Amtrak, State of Washington)

This study described the vehicle model recommended for computerized simulations of shared-track issues. HSR and HAL vehicles were proposed for study in detail to duplicate their physical properties. In order to confirm the accuracy of the model, instrumented wheelsets (IWS) and wayside detectors; i.e., wheel impact load detectors (WILD), truck (curving) performance detectors (TPD), and truck hunting detectors (THD), were recommended for use on all revenue service tracks that were studied.

The study suggested a study of the best practices relating to superelevation on shared-track. A literature review was proposed to focus on the following issues for HSR and HAL train types:

- Existing track curvature and superelevation guidelines
- Speed-curvature profiles under normal operating conditions for both passenger and freight trains
- Rail vehicle loading (e.g., freight vs. passenger loads, magnitude of freight loads, etc.)
- Effect of tonnage distributions of freight and passenger trains
- Associated curving and dynamic performance of the freight and passenger vehicles
- Wheel and rail profiles, wear patterns, and RCF occurrences
- Problems in the existing shared tracks

These issues would then be analyzed through computer modeling, and at least two representative shared-rail systems (with suitable curves) would be selected for testing. These systems would be monitored using IWS and strain-gauged rails for three years, with rail profiles being taken every 6 months. Rail profile measurements would include wear rates and changes in superelevation due to loading over time.

The following tests were proposed that directly or indirectly relate to issues with superelevation on curves:

- RCF – RCF is known to be more severe on certain curved sections of track due to the higher net vertical force. [23] One intent of this study is to identify how operating on a curve in cant excess or cant deficiency affects these results. This would be tested through computer modeling and then compared to IWS tests in the field.
- RSD – Cant deficiency and especially cant excess cause gauge spreading and rail rollover forces. These forces are known to contribute to RSD, and therefore are of great interest. Monitoring newly converted shared-railway track would help to determine the likelihood of RSD developing more frequently in these sections.
- HSR turnouts – The effect of canted plates and/or ties on HSR turnouts (among other things) would be investigated to see how they compare to turnouts without canted plates. It is hoped that canted turnouts can reduce delays due to HSR needing to slow on approaches and also improve passenger ride quality. Computer models and field tests would be performed.

- Ride quality and track geometry – Trains can be much more sensitive to track irregularities when traveling around a curve, especially when operating at cant deficiency/excess. Both computerized modeling and multiple-year field tests would be completed to investigate the effect of several types of irregularities on curves.
- Slab track – Slab track is initially more expensive to build, but often has much lower maintenance costs over its lifetime. Tests at TTCI have shown that dynamic vertical and lateral loads can be dramatically decreased from rails to the slabs in curves (Table 2). [24] Change in track geometry was also decreased from that of ballasted track over the same amount of time.

Table 2. Rail vs. slab accelerations in slab track [24]

Location of Acceleration	Range of Accelerations (g's)
Rail	10 – 25
Slab	0.4 – 2

- Low–speed derailment – HSR trains are designed and tested for high speeds, and may more easily derail when forced to slow well below operating speed due to shared-track conditions (e.g., turnouts, switches, crossings, etc.). Cant excess in curves is thought to be of particular concern. "For example, in the past 20 years several new design passenger vehicles have experienced flange climb derailment over short wavelength cross-level perturbations in sharp curves that were within FRA standards for the particular track class. [18] Computer models and on-track tests are suggested to further investigate this issue.

Overall, this report details several proposed tests as part of a continuation of this study. Many, but not all, of the tests are related in some way to superelevation, cant excess, or cant deficiency.

3.4 Worldwide Practices Associated with Curving and Superelevation

In 2001, Martin Lindahl, of the Department of Vehicle Engineering at the Royal Institute of Technology (KTH) in Stockholm, Sweden, completed a literature survey and dynamic vehicle response model to investigate worldwide practices and issues associated with superelevation. [25] The analysis focused on, among other things, the practices and concerns associated with superelevation, cant deficiency or excess, and curve radii on track that may be shared between HSR and HAL. Lindahl's study concluded that acceptable superelevation is between 5.9–7.9 inches (150–200 mm), acceptable cant deficiency is as high as 8.9–9.8 inches (225–250 mm) for HSR with tilt technology, suitable bogie (truck) technology, and high quality rail, and tolerable cant excess is 4.3–5.1 inches (110–130 mm).

The following subsections summarize the standards of several countries and a few organizations, including those of Sweden, Germany, France, Japan, the Technical Specification for Interoperability (TSI), and the Committee for European Standardization (CEN). Some countries defined limits that others did not define.

3.4.1 Sweden [26]

Trains in Sweden are categorized into three groups:

Category A – freight trains or trains with older equipment

Category B – newer trains and/or improved HSR trains

Category S – Category B type trains equipped with tilt technology

- The legal limits for cant deficiency are 3.9 inches (100 mm) for Category A, 5.9 inches (150 mm) for Category B, and 9.6 inches (245 mm) for Category S (Table 3).
- The legal limit for lateral jerk in transition curves (change in cant deficiency) is 1.8 in/s (46 mm/s) for Category A, 2.2 in/s (55 mm/s) for Category B, and 3.1 in/s (79 mm/s) for Category S (Table 3).
- Cant Excess is defined by Banverket (Swedish Rail Administration) to be limited at 3.9 inches (100 mm) for curves of radius over 3,280 feet (1,000 meters) and 2.8 inches (70 mm) for curves of radius under 3,280 feet (1,000 meters) (Table 4).

Table 3. Permissible cant deficiency and the corresponding acceleration

Train Category	Permissible cant deficiency	Lateral acceleration a_y
A	3.9 inches (100 mm)	1.4 ft/s^2 (20.65 m/s^2)
B	5.9 inches (150 mm)	3.2 ft/s^2 (0.98 m/s^2)
S	9.6 inches (245 mm)	8.4 ft/s^2 (1.60 m/s^2)

Table 4. Maximum rate of cant and rate of cant deficiency

Train Category	Maximum Rate of Superelevation(Cant)	Maximum Rate of Cant Deficiency
A	1.8 in/s (46 mm/s)	1.8 in/s (46 mm/s)
B	2.2 in/s (55 mm/s)	2.2 in/s (55 mm/s)
S	2.8 in/s (70 mm/s)	3.1 in/s (79 mm/s)

3.4.2 Germany [27]

- German limits are split into a recommended limit value, an absolute limiting value (without special permission), and a limiting value with special permission from the government.

- Superelevation (Cant) is recommended to be limited at 3.9 inches (100 mm), absolutely limited at 6.3–6.7 inches (160–170 mm) depending on train/track type, and limited with permission at 6.3–7.1 inches (160–180 mm). See Table 5 for more details.
- Cant deficiency is recommended to stay under 2.8 inches (70 mm), limited at 5.1 inches (130 mm), and limited with permission at 5.9 inches (150 mm). See Table 6 for more details.

Table 5. German design values of superelevation(cant)

Without Permission	**Superelevation(Cant) (inches and mm)**
Recommended	3.9 inches (100 mm)
Limit	6.3–6.7 inches (160–170 mm)
With Permission	-
Permission	6.3–7.1 inches (160–180 mm)
Exception	> 7.1 inches (> 180 mm)

Table 6. German design values of cant deficiency

Without Permission	**Cant Deficiency (inches and mm)**
Recommended	2.8 inches (70 mm)
Limit	5.1 inches (130 mm)
With Permission	-
Permission	5.9 inches (150 mm)

3.4.3 France

- Superelevation(Cant) should not exceed 6.3–7.1 inches (160–180 mm), depending on train/track type.
- Cant deficiency is limited at 5.9–6.3 inches (150–160 mm), depending on train/track type.
- Cant excess is limited to 2.8–3.9 inches (70–100 mm) or 4.1–5.3 inches (105–135 mm) for non-freight trains.

3.4.4 Japan

- Few Japanese standards were found in English; however, the top companies in Japan limit superelevation(cant) to 7.1–7.9 inches (180–200 mm), depending on company policy.

3.4.5 TSI [28] and CEN [29]

- Superelevation(Cant) limits are set at 7.1–7.5 inches (180–190 mm) or 7.9 inches (200 mm) for HSR only.
- Cant deficiency for HSR is limited to 3.9 inches (100 mm) and 3.1 inches (80 mm) for speeds over 186 mph (300 km/hr). For HSR with difficult topography at 5.1–7.1 inches (130–180 mm), permission is needed. And freight trains are recommended to stay under 3.1–3.9 inches (80–100 mm), but limited at 5.1 inches (130 mm) (Table 7).
- CEN recommends cant excess to stay below 4.3 inches (110 mm) and absolutely limited to 5.1 inch (130 mm).
- Change in superelevation(cant) per time is limited to 2–2.5 in/s (50–60 mm/s) (Table 8).
- Change in cant deficiency per time is limited to 2.0–3.5 in/s (50–90 mm/s) (Table 8).

Table 7. TSI limiting values of cant deficiency

Speed Range	Limiting Cant Deficiency Value (inches & mm)
Normal Conditions (HSR)	-
< 99 mph (< 160 km/h)	6.3 inches (160 mm)
99–124 mph (160–200 km/h)	5.9 inches (150 mm)
124–143 mph (200–230 km/h)	5.5 inches (140 mm)
143–155 mph (230–250 km/h)	5.1 inches (130 mm)
Difficult Topographical Constraints (HSR)	-
< 99 mph (< 160 km/h)	6.3–7.1 inches (160–180 mm)
99–124 mph (160–200 km/h)	5.9–6.5 inches (150–165 mm)
124–143 mph (200–230 km/h)	5.1–5.9 inches (130–150 mm)
143–155 mph (230–250 km/h)	3.9–5.1 inches (100–130 mm)
Freight Train (HAL)	-
Recommended	3.9 inches (80–100 mm)
Limit	5.1 inches (130 mm)

Table 8. CEN limiting values of rate of superelevation (cant) and rate of cant deficiency

	Recommended Limit (mm/s)	Maximum Limit (mm/s)
Rate of Superelevation(Cant)	2 in/s (50 mm/s)	2.5 in/s (60 mm/s)

	Recommended Limit (mm/s)	Maximum Limit (mm/s)
Rate of Cant Deficiency	2 in/s (50 mm/s)	3.0–3.5 in/s (75–90 mm/s)

3.4.6 Others

Other major European and Asian companies analyzed had similar limits, holding superelevation(cant) to 2.6–7.9 inches (65–200 mm), cant deficiency to 2.4–3.9 inches (60–100 mm), and cant excess to 2.0–4.3 inches (50–110 mm) (all depending on the company).

3.5 Modeling and Analysis of Vehicle-Track Interaction

Lindahl [25] reviewed two studies regarding transition curves (or spirals), which concluded that S-shaped curves have very little advantage over linearly changing curves, [30] and that longer transition curves are needed for trains using tilt technology to maintain passenger comfort, due to additional roll accelerations [31].

The second half of the paper described the development and results of a computerized model made using GENSYS to analyze track-vehicle interaction. The modeled vehicles ranged in mass from 89.5 kips to 98.3 kips (40,600 kg to 44,600 kg), and were designed to represent a typical car. Nine tracks were modeled with various levels and types of irregularities, ranked according to the Banverket Q scale (lower Q score means more irregularities). Several tests were performed (all simulating HSR) and the results were as follows:

- Operating at a high level of cant deficiency can have negative effects on hunting stability. When hunting was simulated without cant deficiency, the lateral acceleration peaked at about 3.9 feet/s^2 (1.2 m/s^2) before finding equilibrium at 0 feet/s^2 after approximately 492 feet (150 m). When simulated operation at a cant deficiency of 9.80 inches (250 mm), equilibrium lateral acceleration was just below 6.6 feet/s^2 (2 m/s^2) and the peak lateral acceleration was 13.1 feet/s^2 (4 m/s^2) (all measured above first bogie).
- Along a curve with a superelevation (cant) varying between 6.3–7.9 inches (160–200 mm), with track irregularities Q = 99, all levels of superelevation (cant) reached the limiting lateral acceleration (approximately 10 kips (44 kN)) operating at approximately 11 inches (275 mm) of cant deficiency. This showed that superelevation (cant) in this range has little effect on limiting value of cant deficiency.
- Along a curve with a superelevation (cant) of 7.1 inches (180 mm), the track with the most irregularities (Q = 65) had a cant deficiency limit of 5.5 inches (140 mm), and the track with the fewest irregularities (Q = 107) was limited at approximately 12 inches (300 mm) cant deficiency. A track with no irregularities remained well below the lateral acceleration limit over 12 inches (300 mm) of cant deficiency. Track condition was seen to have a large impact on acceptable levels of cant deficiency.
- With a track of Q value 80, a cant deficiency of 7.3 inches (185 mm) led to acceptable lateral accelerations. A cant deficiency of 11 inches (275 mm) showed that in order to be deemed acceptable, the track would need to have 25 percent fewer severe irregularities. A

cant deficiency of 14 inches (350 mm) would require a track with 50 percent fewer severe irregularities.

- Cant deficiency was limited by the lateral wind speed (blowing toward the outside of the curve), as the two combined can lead to train roll. With a cant deficiency of 5.9 inches (150 mm), a lateral wind velocity of 60 mph (27 m/s) could potentially cause rollover. With a cant deficiency of 11 inches (275 mm), wind velocity was limited to 52 mph (23.4 m/s). Cars with low heights, tilting technology, and/or aerodynamic frames were less prone to lateral winds.

Superelevation (Cant) Issues with Freight Trains

HAL freight trains on curves usually have an issue with cant excess. European freight trains are often lighter than American HAL trains. (Germany is limited to 22.5 tons, and the U.S. commonly allows 33 tons or more in axle load.) The damage to the lower rail due to increased forces has been largely exaggerated at 22.5 tons and 4.3–5.1 inches (110-130 mm) of cant excess. [25] The damage increase was minor for curves above 2.2 degrees (2,625 foot radius, or 800 m) and above 0.9 degrees (6,562 foot radius, or 2,000 m) the increase was negligible, at the weight and cant excess levels stated above. [32, 26]

On the basis of the practices for several countries revolving around cant, cant excess, and cant deficiency, Lindahl developed a model to demonstrate some issues associated with cant and curves. His model showed that cant deficiency could be acceptable as high as 9.8 inches (250 mm) with top of the line tilting and bogie technology as well as very well maintained track. He also demonstrated the relationship between acceptable cant deficiency and both track quality and wind speed. Lindahl's research showed that legal levels for superelevation (cant) and cant excess are acceptable, especially for large radii curves. [25] However, his findings are for European freight trains.

3.6 RCF

Network Rail, in conjunction with the Rail Safety and Standards Board (RSSB), retained TTCI (U.K.) Ltd. to further understanding the effects of primary yaw stiffness on vehicle performance and the formation of RCF. [4] Their study covered many aspects of vehicle and track parameters. Among others, they studied cant deficiency, and their modelling results quantified the long-held opinion of dynamicists that by increasing cant deficiency within established limits, RCF damage is reduced. The detailed findings of their study included:

- Regardless of the value of the primary yaw stiffness, the largest amount of damage occurred for 2 inches (50 mm) cant excess and 0 mm of cant deficiency. This was contrary to the popular belief that operating at balance or just below balance speed is the best practice.
- Results suggested that overall RCF damage can be reduced by 50 percent if high cant deficiencies could be allowed and maintained.
- The benefits of increasing cant deficiency are more pronounced for vehicles with higher primary yaw stiffness values. For moderate curvatures, lighter weight vehicles with medium-to-soft suspensions operating at high cant deficiencies were likely to significantly reduce RCF damage.

- The study demonstrated that the general effects of track roughness were diminished as cant deficiency was increased, particularly for bogies with high primary yaw stiffness.
- The maximum cant deficiency studied was 5.9 inches (150 mm). The limited number of modelling cases performed indicated that on the basis of the ratio of lateral-wheel-rail-force-to-vertical-wheel-rail-force, known as the Y/Q (L/V) ratio value, cant deficiency can be increased safely.

In addition, the results showed the dramatic effect increasing cant deficiency had on reducing track damage due to track roughness, particularly for stiff bogies. For the 64 MN m/radian case on a 6,562 foot (2,000 m) radius curve, the damage factor was reduced from 10 at 0 mm cant deficiency to approximately 4 at 5.9 inches (150 mm) cant deficiency. This indicated that for the roughest track, the time to initiation of RCF could potentially be more than doubled by increasing and maintaining cant deficiency from 0 to 5.9 inches (0 to150 mm).

However, Network Rail field engineers reported cases where a reduction in track superelevation (cant) had reduced RCF, including the observation that tilting trains operating at enhanced permissible speeds on the West Coast Main Line had not increased RCF.

Moreover, this study was performed only for passenger vehicles, and overall RCF damage will be dependent on vehicle- and route-specific cases. By dissecting each route into histograms of curvatures, track superelevation (cants) , and operating speeds, the best balance of primary yaw stiffness, cant deficiency, and operating speed can be identified that will minimize the RCF potential for each route. Since heavier high stiffness vehicles are highly prone to cause RCF and since other damage modes to track are associated with vehicle weight, it was recommended to reassess the current trend toward heavier rolling stock.

3.7 The Effect of Track Superelevation (Cant) on Vehicle Curving

TTCI was tasked by AAR to investigate and report on the effect of superelevation on the vehicle-track interaction of freight cars, particularly under HAL conditions. [9, 10, 11] The study contained three main topics:

- Theoretical studies of vertical and lateral loads on single cars under different cant conditions
- Tests on single cars in curves at TTC near Pueblo, Colorado
- In-service tests at an instrumented crib in a 4.5-degree curve on a 1.22 percent grade

The study concluded that optimum vehicle-track interaction conditions were achieved when vehicles negotiated curves at balance speed. However, this ideal condition may often not be realized in revenue service, because train speeds vary and drawbar forces in long, heavy trains create lateral forces on the railcars that compromise steering.

Curve negotiation with superelevation (cant) imbalance result in transfers of vertical load between high and low rails and in increased lateral loads on both rails. The most desired condition for vertical loads is to maintain superelevation for the speed of prevailing tonnage. However, it is difficult to maintain track superelevation when prevailing heavy traffic and tonnage operates at speeds predominantly over or under the balance speed, as this can lead to differential settlement between high and low rail.

Curving with excess cant generally increases high rail L/V ratios, because vertical load is transferred from the high to the low rail; this reduces the high rail load for substantially the same high rail lateral load.

The study by TTCI confirmed that balance conditions for the prevailing tonnage was the optimum condition. It strongly suggested that, if anything, curves should be negotiated with cant deficiency because:

- Lead axle low rail vertical and lateral forces are lower, reducing RCF.
- Lead axle high rail L/V ratios are lower because of increased vertical loads (and, incidentally, lower lateral loads and angles of attack not shown explicitly in TTCI's report).
- Heavy trains curving with excess cant generally impose high vertical and lateral loads on the track, and this condition should be avoided when possible.

For a given curvature, superelevation is proportional to the square of the speed. Figure 4 shows this relationship for a 4.5-degree curve. The balance speed for a 4.5-degree curve, superelevated to 3.5 inches, is 33.3 mph. The balance superelevation for 40 mph in a 4.5-degree curve is 5 inches.

In addition, a 3-inch range of cant imbalance provides (Figure 4) a 31 mph speed range from zero mph and a 13 mph speed range from 30 mph. Consequently, it becomes more difficult to optimize cant conditions for higher track speeds (this also applies for sharper curvatures).

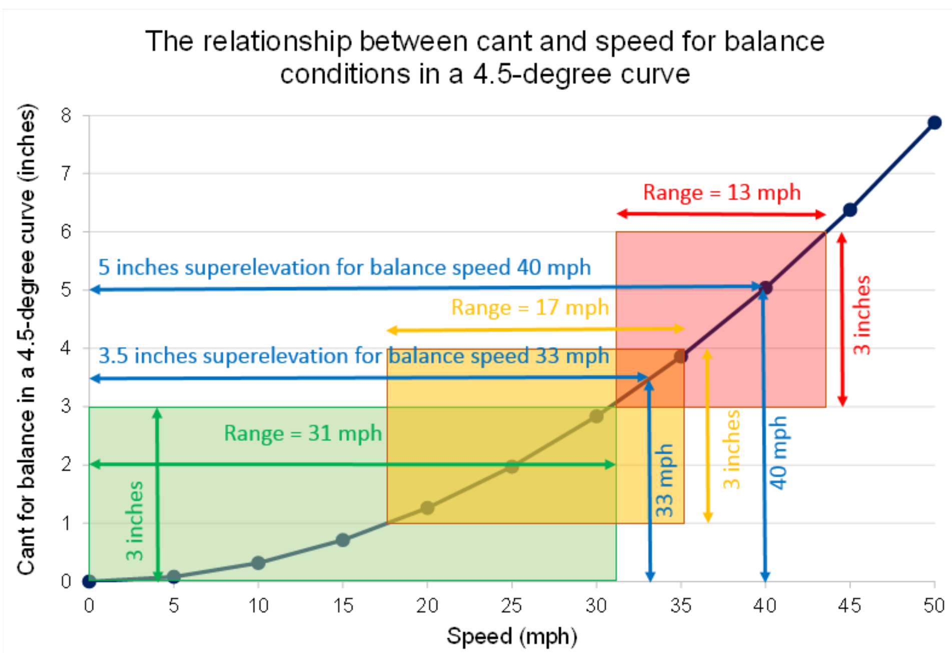

Figure 4. Relationship between cant and speed for balance conditions in a 4.5-degree curve (green, orange, and red box show the allowable speed range for elevation of 0, 1, and 3 inches cant deficiency) [10]

Theoretical studies suggested that balance conditions were optimal, but that, if imbalance does occur, cant deficiency is preferable to that of excess cant. Revenue service tests in a 4.5-degree curve showed the following:

- Significant (~10 percent) gain/loss in nominal wheel load when curving at 3 inches under balance. This condition can be improved by reducing the superelevation in the curve from 3.5 inches to 1 inch.
- A nominal wheel load gain/loss of 1.6 percent due to in-train forces was measured. This became significant (1.6 percent x 4 = 6.4 percent) for trains with head-end power versus 3.2 percent for trains with the equivalent distributed power.
- Lead axle low rail lateral forces:
    - Measured in the middle of the train (zero coupler force) were of the order of those measured on 3-piece trucks at TTC in similar curves under a prevailing friction of approximately 0.45.
    - Did not change measurably (approximately 1 percent) through the length of the train. Nevertheless, many of the forces measured suggested limiting friction. If so, any attempts to reduce these forces could prove valuable.

4. North America Railroad Practices Review

This section provides a summary of railroad practices in the U.S. gathered by reviewing railroads' standards and the survey. Sections 4.2 to 4.9 are the citations from the standards of passenger and freight railroads. Direct quotations from particular standards and survey responses are identified by quotation marks.

Current practices and issues related to the cant excess are summarized from comments provided by participating passenger and freight railroads. The statistics about curvatures and underbalance are presented from 12 corridors with shared operations.

4.1 FRA Standards

All reviewed railroads standards follow the FRA 49 CFR 213 Track Safety Standard criteria for curves, elevation, and speed limitations [1] as follows:

§213.57 (a) The maximum elevation of the outside rail of a curve may not be more than 8 inches on track Classes 1 and 2, and 7 inches on track Classes 3 through 5. The outside rail of a curve may not be lower than the inside rail by design, except when engineered to address specific track or operating conditions; the limits in §213.63 apply in all cases. (Paragraph §213.63 provides allowable limits for maintenance of the track surface and cross level.)

§213.57 (b) The maximum allowable posted timetable operating speed for each curve is determined by the following formula:

$$V_{\max} = \sqrt{\frac{E_a + E_u}{0.0007D}} \qquad \text{(Eq. 3)}$$

V_{max} = Maximum allowable operating speed, (MPH)

E_a = Actual superelevation of the outside rail (inches)[1]

E_u = Underbalance (inches)

D = Degree of curvature (degrees)[2]

[1] Actual superelevation for each 155-foot track segment in the body of the curve is determined by averaging the elevation for 10 points through the segment at 15.5-foot spacing. If the curve length is less than 155 feet, average the points through the full length of the body of the curve.

[2] Degree of curvature is determined by averaging the degree of curvature over the same track segment as the elevation.

All other rules listed under FRA §213.57 are also cited in the railroad standards.

4.2 Passenger Railroad A

Passenger Railroad A, Limits and FRA's Specifications for Track Safety, provided that the maximum superelevation on the outside rail of a curve may not be more than 8 inches on Track Classes 1 and 2 and may not be more than 7 inches on Track Classes 3–5. Except as provided in

FRA §213.63, the outside rail of a curve may not be lower than the inside rail (§213.57). According to Passenger Railroad A:

"The Deputy Chief Engineer-Track shall establish the amount of superelevation, underbalance and speed to be placed and maintained on each curve. Maximum maintenance superelevation shall not exceed 6 inches."

"The Deputy Chief Engineer-Track shall establish the amount of superelevation, underbalance and speed to be placed and maintained on each curve. Design superelevation shall not exceed 6 inches."

"Underbalance (cant deficiency) is the amount of superelevation less than equilibrium superelevation for any given combination of speed and curvature. The maximum allowable operating speed in curves is to be calculated using an underbalance of 3 inches unless otherwise directed by the Deputy Chief Engineer–Track." Note: this definition for underbalance is the opposite from standard practice as defined in Section 2 above. The confusion with this definition may be related to the fact that it refers to track instead of to the speed of operation. In the FRA Track Safety Standard definition provided in Section 2, underbalance and overbalance refer to the speed of operation relative to the amount of superelevation present in the track.

Passenger Railroad A provides tables with up to 9 inches underbalance. However, the following rules should apply when the underbalance is higher than 3 inches:

- "The Deputy Chief Engineer–Track or Assistant Chief Engineer–Track shall maintain a list of curves and the designated 'underbalance' to be used. To operate at speeds which use 'underbalance' greater than 3 inches, the equipment must be qualified and approved by the Federal Railroad Administration."

"Overbalance is the amount that superelevation exceeds equilibrium superelevation, and is produced by the operation of a train around a curve at less than equilibrium speed, or stopping on the curve." No limits of overbalance (i.e., cant excess) are provided in the Passenger Railroad A specifications. As noted above for underbalance, this definition of overbalance is the opposite from standard practice as defined in Section 2 above.

<u>Passenger Railroad A Engineering – Track Design Specification</u>

"Superelevation on the outside rail of a curve shall not exceed 5½ inches. Alignments that include curves greater than 3 degrees or that have superelevation greater than 4 inches should be avoided wherever freight trains are operated. Superelevation in these areas should be limited by increasing the underbalance where possible."

"All curves should have at least ½ inch of superelevation with the following exceptions:

a. Curves that are no sharper than 0°-15' may have a minimum of ¼ inch superelevation if the resulting underbalance is not less than 0;
b. Curves that have less than ¼ inch of balanced elevation (Ee) should have no superelevation thereby making the outside rail the line rail;
c. Curves that connect the diverging sides of turnouts with tracks that are parallel to the normal side of the turnout may have no superelevation.

Superelevation runoff must be at a constant rate and should be completely bounded by the limits of the spiral. All exceptions must be approved by the Deputy Chief Engineer Track."

Similar to specifications of most railroads, spirals should have constant (linear) change in superelevation and curvature. Superelevation change in spirals is limited to ¼ to ½ inch, depending on track class.

Cant deficiency is permitted up to a maximum value of 1.5–7 inches, depending on the type of train (Table 9). Cant deficiency is further limited to 5 inches on open deck curves and bridges. Curves cannot use maximum superelevation and maximum cant deficiency at the same time; the sum must be 1 inch under the sum of the maximums.

Table 9. Maximum underbalance[2] (cant deficiency) and speed for various trains

Class of Train	Equipment	Maximum Underbalance (inches)	Maximum Speed (mph)
A	With tilt on curves up to 0º-16’	7	135 or 150*
A	With tilt curves greater than 0º-16’	7	130
B	With tilt on curves up to 0º-16’	5	135 or 150*
B	With tilt curves greater than 0º-16’	5	130
C	Other passenger cars	4	110
D	Mail and express	3	90
E	Freight	1.5	50

* Depends on location

4.3 Passenger Railroad B

Passenger Railroad B does not provide a separate limit on superelevation; however, they do give limits for the variation of superelevation from the balance level. These limits are ¾ inch to 2 inches in the maintenance standards and 1 inch to 3 inches in the safety section, both depending on track class.

4.4 Passenger Railroad C

“The maximum superelevation on the outside rail of a curve may not be more than 8 inches on Track Classes 1 and 2 and may not be more than 7 inches on Track Classes 3–5.”

“The maximum maintenance superelevation shall not exceed 5 inches unless authorized by the Assistant Vice President – Maintenance of Way. Where authorized, elevation shall not exceed 6 inches.”

“Design superelevation shall not be less than ½ inch or more than 5 inches unless approved by the Assistant Vice President - Maintenance of Way.”

Superelevation is allowed to deviate from the balance level by 1 to 3 inches for inspection, ¾ to 2 inches for maintenance (½ to 1½ inch for special track work), and ⅛ to ¾ inch for construction

[2] See comments in this section regarding Passenger Railroad A’s definition of underbalance compared to the standard definition in Section 2.

(⅛ to ½ inch for special track work). Several limits are given in these categories for change in superelevation per 31 feet and 62 feet. Similar limits are given for Class 1 and Class 2 miter rails. In addition, superelevation should not be above 1 inch on tangent track.

4.5 Passenger Railroad D

Passenger Railroad D limits the superelevation to 7 inches on track Classes 3–5 and 8 inches on Classes 1–2. The outside rail of a curve may not be lower than the inside rail by design, except when engineered to address specific track or operation conditions.

Also, 3 inches underbalance shall be used unless otherwise authorized by the Chief Engineer–Track.

Superelevation is allowed to deviate by 1 to 3 inches (values are slightly less for maintenance limits). Superelevation cannot change more than 1½ to 3 inches in 62 feet of track, depending on track type.

4.6 Freight Railroad E

"Superelevations may not be less than 3/4 inch or greater than 5 inches in any curve. The Chief Engineer must approve all changes to designated superelevations. Chief Engineers may approve a greater superelevation for passenger train operations than is necessary for freight train operations to accommodate local operating needs."

At Freight Railroad E, shared-track superelevation should be designed for the freight train speed, and a maximum allowable speed for 3 inches underbalance (4 inches with special permission) should be assigned for passenger train use.

Maximum superelevation is 5 inches, with a minimum of ¾ inch. Superelevation deviations are allowed to be between 1⅛ to 2½ inches, but overall maximum cant deficiency is 3 inches. The maximum superelevation on a grade crossing is 1 inch. The superelevation also cannot change more than 1⅛ to 2⅞ inches per 62 feet depending on track type. The company also notes that it follows FRA standards.

4.7 Freight Railroad F

The maximum superelevation is 5 inches (6 inches with special permission). The superelevation is further limited for HAL traffic and other limiting factors. The maximum cant deficiency is 4 inches, and the superelevation can vary from 1 inch to 3 inches, depending on track type. A ½-inch variation from the balance superelevation due to specific conditions is allowed with approval.

The maximum allowable superelevation on any curve is 5 inches. There are several situations where lesser limits apply:

"The Chief Engineer – Maintenance of Way must approve the use of more than:

- 4 ½ inches superelevation on curves greater than 3° – 00' when required to maintain maximum authorized speed.
- 4 inches superelevation on non-signaled branch lines having a maximum authorized speed of 30 miles per hour or less.

- 4 inches superelevation on grades where freight trains regularly operate below 25 mph."

4.8 Freight Railroad G

The maximum superelevation shall not exceed 4 inches for freight trains unless approved by AVP-Maintenance. The maximum superelevation shall not exceed 5 inches for passenger trains.

On curves where passenger and freight trains both operate, the higher superelevation is to be used.

4.9 Freight Railroad H

"The maximum cross level on the outside rail of a curve may not be more than 7 inches on any track. Curves exceeding 6 inches cross level must be monitored and have a remedial action plan to bring it back to 6 inches or less cross level. The outside rail of a curve may not be lower than the inside rail, except as described in Track Surface section."

"A track owner or a railway company may request approval to operate specified railway equipment at a level of cant deficiency greater than 3 inches."

"The Local Engineering Manager is responsible for determining the proper elevation for each curve on his territory and curve elevations may only be changed on his authority."

"Curve elevations are not permitted to be set to more than 5 inches unless specially authorized by the Director Track Standards."

"The proper curve elevation for a particular curve is based on the degree of the curve and the maximum authorized speed of the fastest train on that curve."

"Preferred curve elevation when designing curve for freight speeds is calculated with 1 inch underbalanced. Maximum curve elevation is calculated with balance speed and minimum elevation is with 2 inches underbalanced."

"Maximum permissible speeds for passenger trains can be calculated with 3 inches underbalance; however, this should not be used for design of curve unless authorized by the Director Track Standard."

4.10 Freight Railroad L

The design maintenance standard for freight trains by Freight Railroad L is elevations for 2-inch unbalanced[3] operation (rounded to the nearest ⅛ inch). For passenger trains the standard is elevations for 3-inch unbalanced operation (rounded to the nearest ⅛ inch).

These standards are also be used to determine FRA exception limits for freight train unbalanced elevation. The elevations for 4-inch unbalance (rounded to the nearest ⅛ inch) to determine FRA exception limits for passenger train unbalanced elevation are provided for informational purposes.

The requirements to determine the proper elevation to install in a circular (full body) curve are:

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[3] The exact wording of the Railroad L response implies that, in this context, the word "unbalance" refers to operation at overbalance (cant deficiency) conditions, as defined in Section 2 of this report.

“1. Use the 3-inch unbalanced table for passenger trains and the 2-inch unbalanced table for freight trains.

2. On curves where both passenger and freight trains operate, compare the 2-inch and 3-inch unbalanced tables; use larger elevation of the two.”

4.11 Analysis of Curvature and Superelevation

From the requests of the survey sent to railroads, TTCI received six responses. The survey questionnaire is presented in the Appendix. Along with responses to the questions, several track charts were received.

Twelve shared passenger and freight corridors were reviewed to find more information about current practices. Most of corridors had curvatures up to 6 degrees, and one corridor had a few very sharp curves in the range of 16 to 35 degrees. Figure 5 presents an exceedance plot and Figure 6 presents distributions of curvature on specific lines.

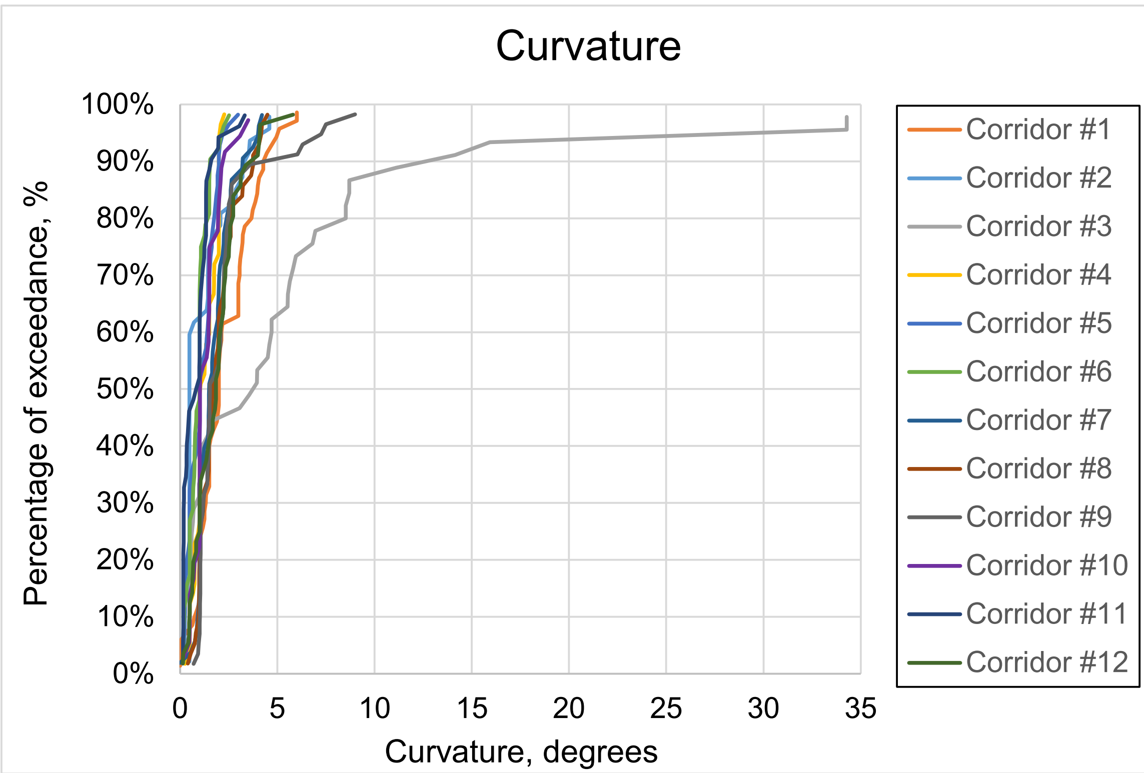
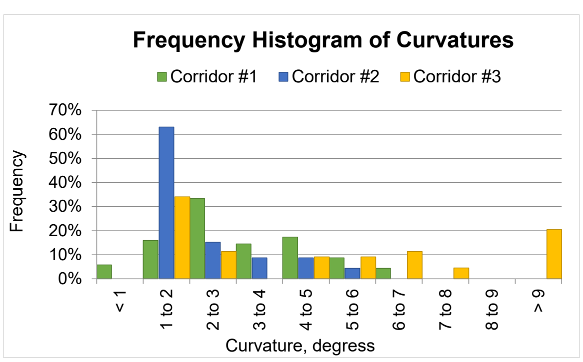
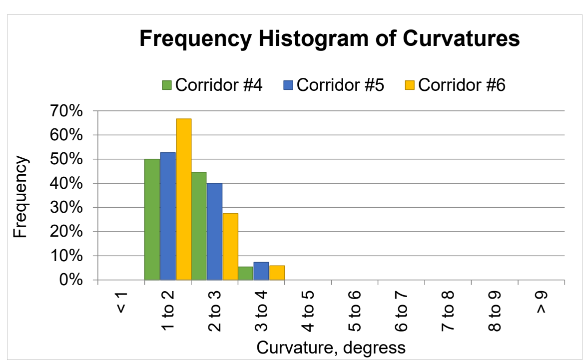


Figure 5. Percentage of curvature degrees on shared corridors





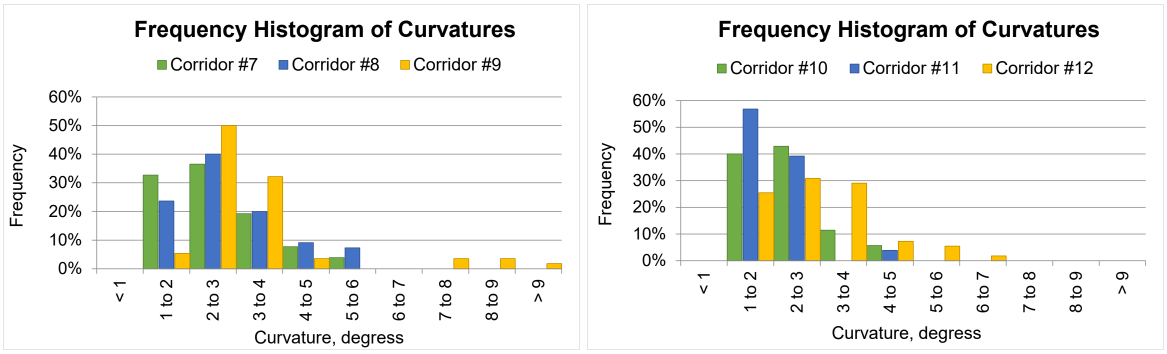


Figure 6. Distributions of curvature degrees on shared corridors

Corridor 1 has curvatures up to 6 degrees and superelevation from 0 to 4.5 inches. The passenger trains travel with speeds from 30 to 79 mph, while freight trains operate at speeds from 25 to 60 mph. Distribution of underbalance for both trains is presented in Figure 7. The maximum cant excess is 1.1 inches for freight operation, and maximum cant deficiency is 3.5 inches for passenger trains.

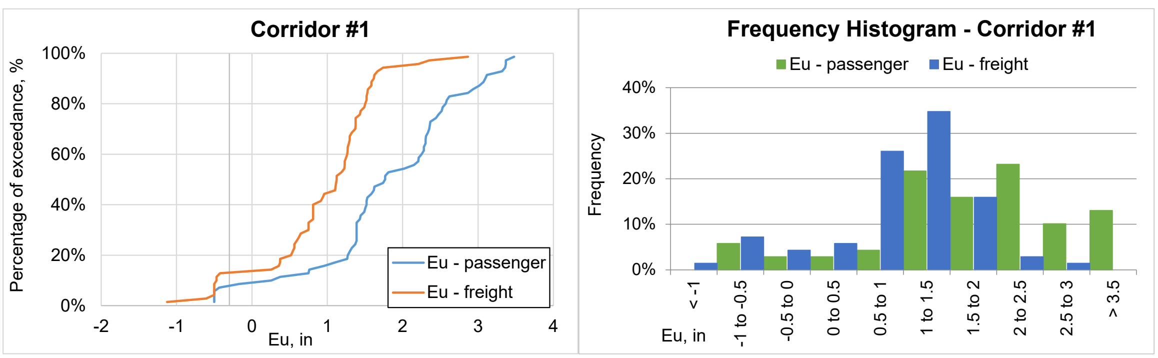


Figure 7. Percentage of underbalance on corridor 1

Corridor 2 has curvatures up to 4.6 degrees and superelevation from 0 to 3.5 inches. The passenger trains travel with speeds from 25 to 55 mph, while freight trains operate at speeds from 25 to 35 mph. The distribution of underbalance (cant excess) for both freight and passenger trains is presented in Figure 8. The maximum cant excess is 0.4 inch for freight trains and maximum cant deficiency is 2.9 inches for passenger trains.

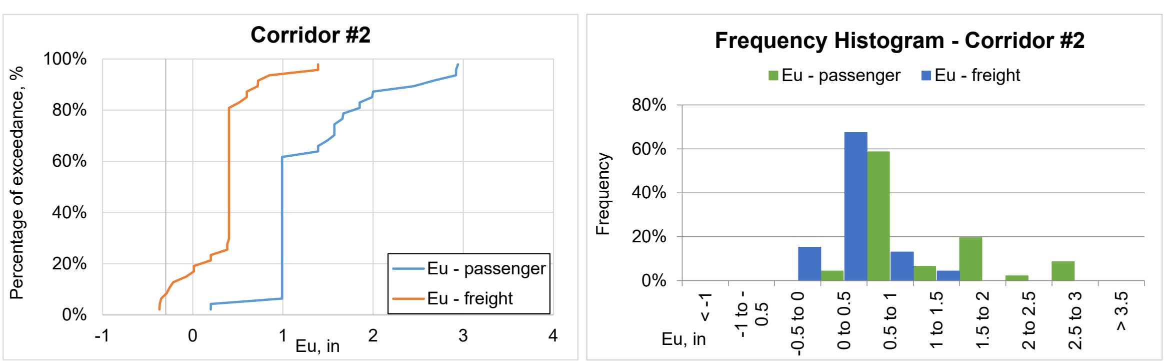


Figure 8. Percentage of underbalance on corridor 2

Corridor 3 has curvatures up to 34 degrees and superelevation from 0 to 4 inches. The passenger trains travel with speeds from 10 to 65 mph, while freight trains operate at speeds from 10 to 25 mph. The distribution of underbalance for both types of trains is presented in Figure 9. The maximum cant excess is 2.3 inches for freight trains and maximum cant deficiency is 3.0 inches for passenger trains.

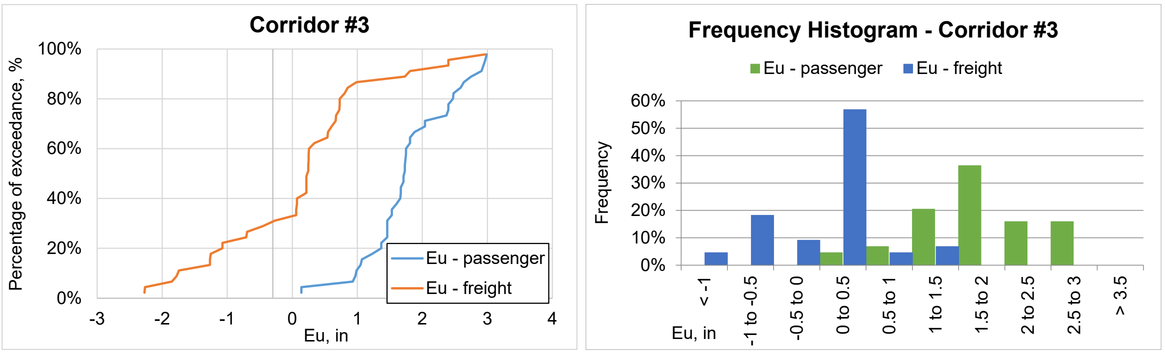


Figure 9. Percentage of underbalance on corridor 3

Corridor 4 has curvatures up to 2.3 degrees and superelevation from 0.5 to 3.5 inches. The passenger trains travel with speeds from 30 to 79 mph, while freight trains operate at speeds from 30 to 60 mph. The distribution of underbalance for both types of trains is presented in Figure 10. The maximum cant excess is 1.9 inches for freight trains and maximum cant deficiency is 3.0 inches for passenger trains.

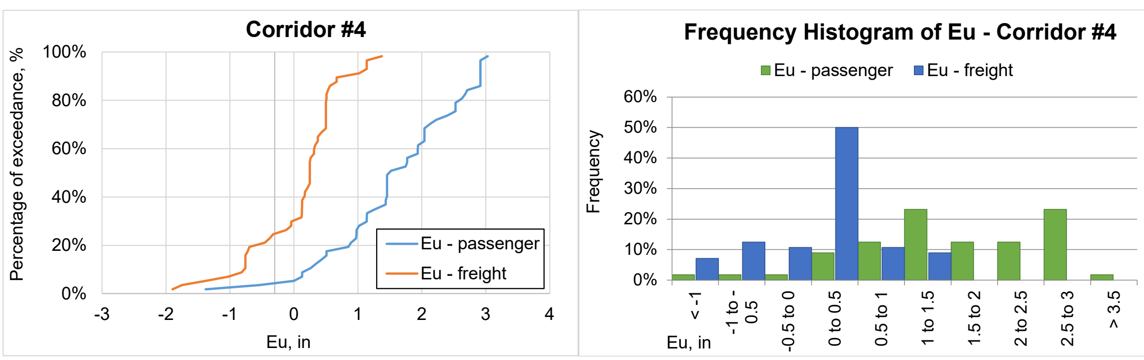


Figure 10. Percentage of underbalance on corridor 4

Corridor 5 has curvatures up to 3.0 degrees and superelevation from 0.25 to 4.5 inches. The passenger trains travel with speeds from 30 to 70 mph, while freight trains operate at speeds from 25 to 70 mph. The distribution of underbalance for both types of trains is presented in Figure 11. The maximum cant excess is 2.0 inches and maximum cant deficiency is 5.9 inches for both for freight and passenger trains.

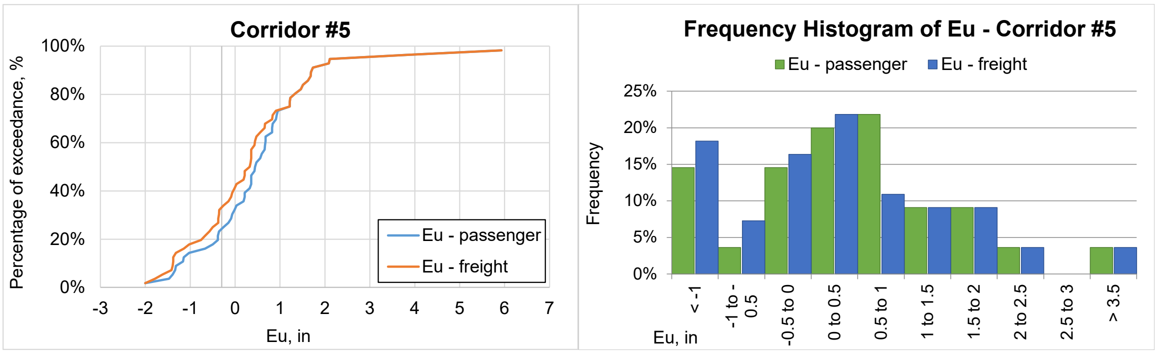


Figure 11. Percentage of underbalance on corridor 5

Corridor 6 has curvatures up to 2.5 degrees and superelevation from 0.5 to 4.5 inches. The passenger and freight trains travel with speeds from 50 to 70 mph. The distribution of underbalance for both types of trains is presented in Figure 12. The maximum cant excess is 0.7 inch for freight trains and maximum cant deficiency is 6.9 inches for passenger trains.

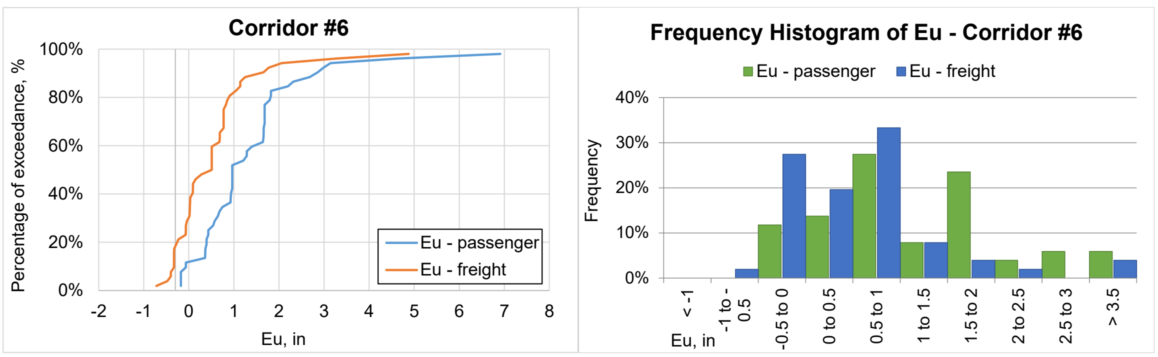


Figure 12. Percentage of underbalance on corridor 6

Corridor 7 has curvatures up to 4.2 degrees and superelevation from 0.75 to 4.5 inches. The passenger trains travel with speeds from 40 to 70 mph, while freight trains operate at speeds from 35 to 55 mph. The distribution of underbalance for both types of trains is presented in Figure 13. The maximum cant excess is 1.5 inches for freight trains and maximum cant deficiency is 4.1 inches for passenger trains.

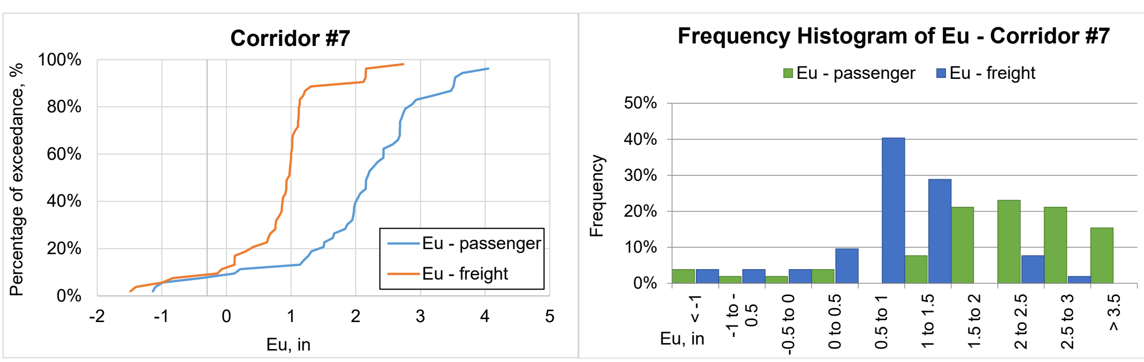


Figure 13. Percentage of underbalance on corridor 7

Corridor 8 has curvatures up to 4.5 degrees and superelevation from 0.5 to 4.25 inches. The passenger and freight trains travel with speeds from 20 to 70 mph. The distribution of underbalance for both types of trains is presented in Figure 14. The maximum cant excess is 1.5 inches for freight trains and maximum cant deficiency is 4.1 inches for passenger trains.

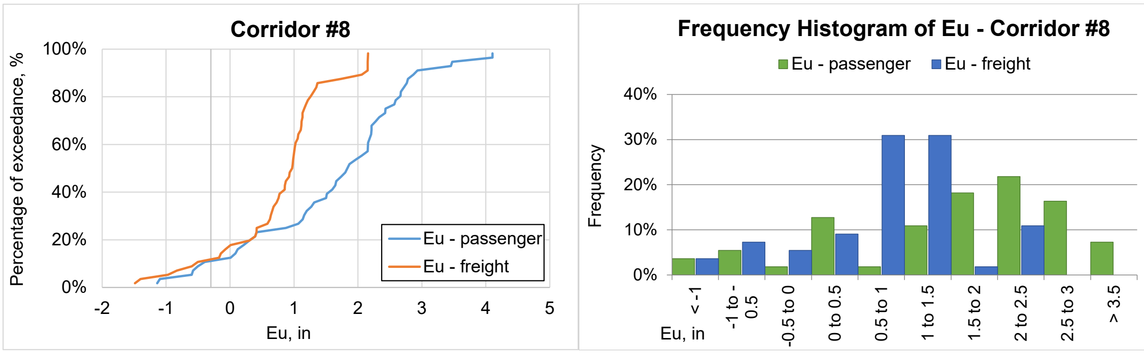


Figure 14. Percentage of underbalance on corridor 8

Corridor 9 has curvatures up to 9.0 degrees and superelevation from 1.0 to 5.5 inches. The passenger trains travel with speeds from 25 to 75 mph, while freight trains operate at speeds from 25 to 70 mph. The distribution of underbalance for both types of trains is presented in Figure 15. The maximum cant excess is 0.7 inch for freight trains and maximum cant deficiency is 3.9 inches for passenger trains.

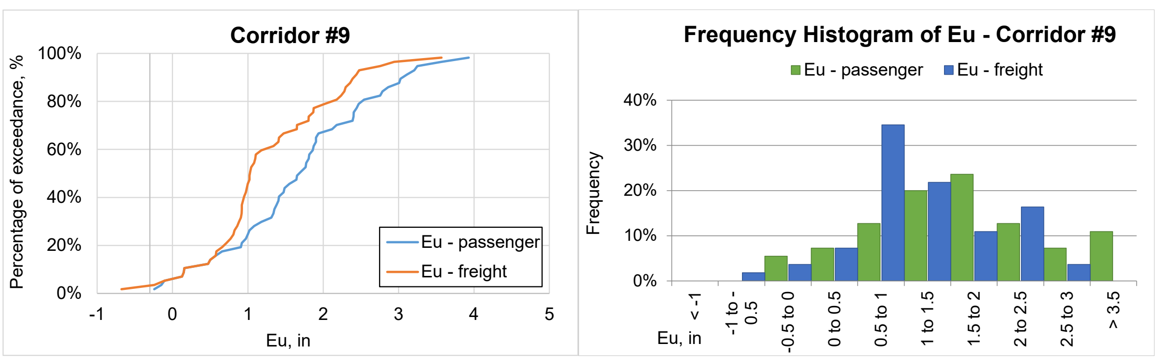


Figure 15. Percentage of underbalance on corridor 9

Corridor 10 has curvatures up to 3.5 degrees and superelevation from 0 to 5.0 inches. The passenger and freight trains travel with speeds from 30 to 70 mph. The distribution of underbalance for both types of trains is presented in Figure 16. The maximum cant excess is 1.3 inches for freight trains and maximum cant deficiency is 4.4 inches for passenger trains.

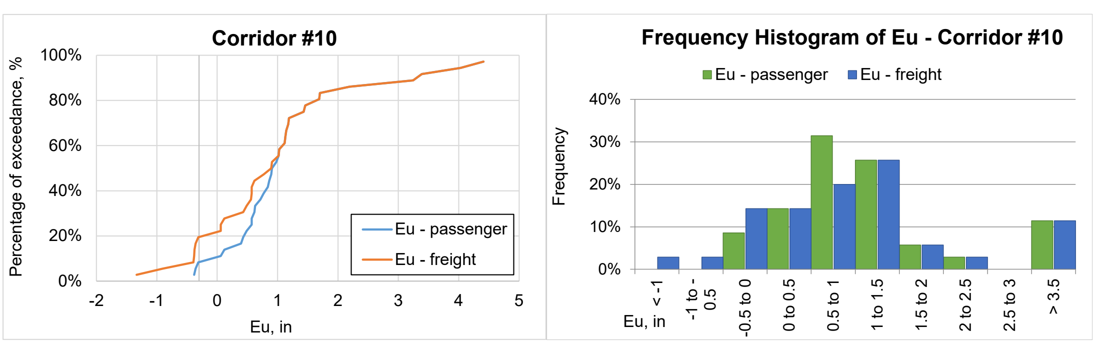


Figure 16. Percentage of underbalance on corridor 10

Corridor 11 has curvatures up to 3.3 degrees and superelevation from 0.15 to 3.3 inches. The passenger and freight trains travel with speeds from 50 to 70 mph. The distribution of underbalance for both types of trains is presented in Figure 17. The maximum cant excess is 1.6 inches and maximum cant deficiency is 4.4 inches for both freight and passenger trains.

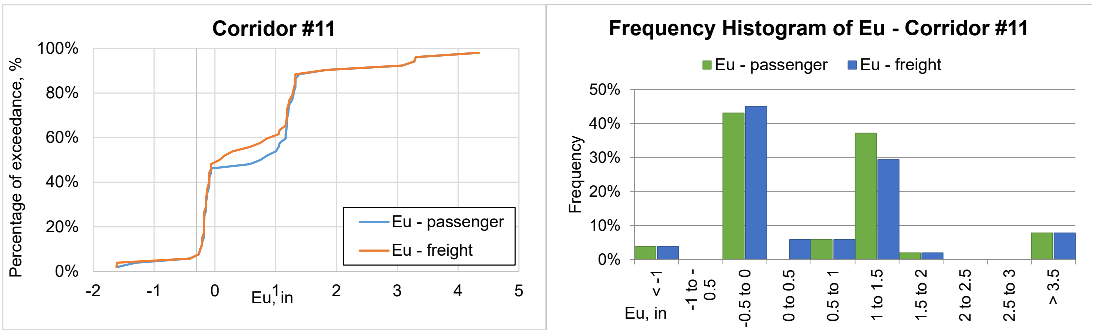


Figure 17. Percentage of underbalance on corridor 11

Corridor 12 has curvatures up to 5.8 degrees and superelevation from 0.5 to 5.25 inches. The passenger trains travel with speeds from 20 to 79 mph, while freight trains operate at speeds from 20 to 70 mph. The distribution of underbalance for both types of trains is presented in Figure 18. The maximum cant excess is 1.9 inches and maximum cant deficiency is 6.0 inches for passenger trains.

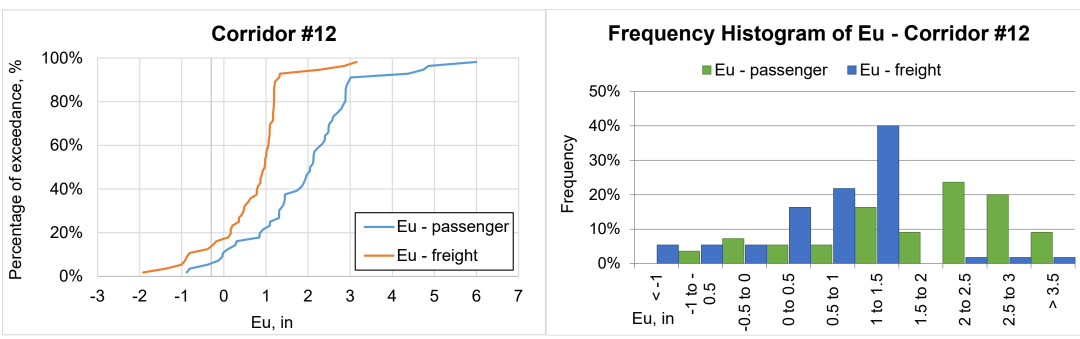


Figure 18. Percentage of underbalance on corridor 12

As a summary of Figures 7–18, all 12 corridors have a practice of allowing more trains operating with cant deficiencies than cant excess, even for freight trains operating on these corridors.

4.12 Current Issues Related to Curvature and Superelevation

All responses to the survey questionnaire were considered, but only responses to the last question, "current issues related to curvature and superelevation," are cited:

- Passenger Railroad C: "Excessive overbalance may produce accelerated flattening of the low rail, gauge widening, rollover of the low rail and the potential for the generation of internal rail defects." (Again, a note about the previous discussions regarding definitions of overbalance versus underbalance, depending whether a train or a track is used as the reference).

- Freight Railroad F reported that excessive flattening or flow on the low rail indicated cant excess and that abrasion on the high rail indicated cant deficiency.
- Freight Railroad G: "The biggest issue is excess elevation for freight operations. On some curves, freight trains operate at substantially under Time Table speed, due to grade, tonnage, or nearby permanent speed restrictions, or for reasons related to traffic or switching. Freight trains that operate at underbalance speed on curves that have significant superelevation – say 2 to 5 inches, can have an adverse impact on rail, tie, and surface condition, due to the elevated vertical loading on the low rail and the increased axle steering forces that result."

  "To elevate a curve with the goal of achieving balance speed for freight trains can have an adverse impact on passenger train operations: Removing, say, 2 to 3 inches of superelevation from a curve could reduce passenger train speed significantly."
- Passenger Railroad I: "Maintaining operating speed for curves that are designed too close to the design speed for both operations. Surfacing and lining curves shortly after geometry car runs."

4.13 Summary

This section provides summary of railroad practices in the United States related to: safety and inspection, maintenance and construction, design, maximum cant deficiency, and variation in superelevation.

4.13.1 Safety and Inspection

Passenger railroads usually allow 8 inches maximum superelevation on track Classes 1–2 and 7 inches maximum superelevation on track Classes 3–5 for safety and inspection. Freight railroads permit 5 inches maximum superelevation. Maximum superelevations allowed for safety and inspection are listed in Table 10. None of the standards and survey responses received provided information on maximum superelevation for track Class 6 and above.

Table 10. Maximum superelevation – safety and inspection

Railroad	Maximum Superelevation	
	Track Classes 1–2	Track Classes 3–5
Passenger Railroad A	8 inches (Classes 1–2)	7 inches (Classes 3–5)
Passenger Railroad B	N/A	
Passenger Railroad C	8 inches (Classes 1–2, safety)	7 inches (Classes 3–5, safety)
Passenger Railroad D	8 inches (Classes 1–2)	7 inches (Classes 3–5)
Freight Railroad E	5 inches	
Freight Railroad F	5 inches	

4.13.2 Maintenance and Construction

Some passenger railroads allow 6 inches maximum superelevation limit for maintenance and construction. Others will allow 6 inches if it is authorized, otherwise 5 inches of maximum superelevation is the limit. Freight railroads permit 5 inches maximum superelevation for maintenance and construction. Maximum superelevations allowed for maintenance and construction are listed in Table 11. None of the standards and survey responses received provided information on maximum superelevation for track Class 6 and above.

Table 11. Maximum superelevation – maintenance and construction

Railroad	Maximum Superelevation	
	Track Classes 1–2	**Track Classes 3–5**
Passenger Railroad A	6 inches	6 inches
Passenger Railroad B	N/A	
Passenger Railroad C	5 inches (maintenance, where authorized, elevation shall not exceed 6 inches) 5 inches (construction)	5 inches (maintenance, where authorized, elevation shall not exceed 6 inches) 5 inches (construction)
Freight Railroad E	5 inches	
Freight Railroad F	5 inches	

4.13.3 Design

The most common limit for design is 5 inches of maximum superelevation. Some railroads will allow 5½ inches of maximum superelevation. Maximum superelevations allowed for design are listed in Table 12. None of the standards and survey responses received provided information on maximum superelevation for track Class 6 and above.

Table 12. Maximum superelevation – design

Railroad	Maximum Superelevation	
	Track Classes 1–2	Track Classes 3–5
Passenger Railroad A	5½ inches	5½ inches
Passenger Railroad B	N/A	
Passenger Railroad C	5 inches	5 inches
Freight Railroad E	5 inches	
Freight Railroad F	5 inches	

4.13.4 Maximum Cant Deficiency

Maximum cant deficiency allowed for passenger operation is 7 inches. On shared operation it varies from 1 to 3 inches. Passenger Railroad A allows only 1½ inches of maximum cant deficiency for freight operation. Freight railroads allow usually 3 inches of cant deficiency, and with permission 4 inches is acceptable. Maximum cant deficiency used by various railroads are listed in Table 13.

Table 13. Maximum cant deficiency by railroads provisions

Railroad	Maximum Cant Deficiency
Passenger Railroad A	1½ inches (freight) and 7 inches (passenger)
Passenger Railroad B	1 inch to 3 inches
Passenger Railroad C	N/A
Freight Railroad E	3 inches (4 inches with permission)
Freight Railroad F	4 inch

4.13.5 Variation in Superelevation

Railroads allow superelevation to deviate from the balance level by up to 3 inches per 62-foot chord. Maximum allowed variation by various railroads are listed in Table 14.

Table 14. Variation in superelevation by railroads provisions

Railroad	Superelevation Deviation (per 62 feet)	Superelevation Difference (per 62 feet)
Passenger Railroad A	½ inch to 3 inches	1½ inches to 3 inches
Passenger Railroad B	1 inch to 3 inches (safety) ¾ inch to 2 inches (maintenance)	N/A
Passenger Railroad C	1 inch to 3 inches (inspection) ¾ inch to 2 inches (maintenance) ⅛ inch to ¾ inch (construction)	1⅛ inches to 2¼ inches (inspection)
Passenger Railroad D	1 inch to 3 inches	1½ inches to 3 inches
Freight Railroad E	1⅛ inches to 1½ inches	1⅛ inches to 2⅞ inches
Freight Railroad F	1 inch to 3 inches	N/A

Note: Some values are further limited for special track work.

5. Conclusion

TTCI completed a literature review and a survey concerning general practices and issues related to cant excess or deficiency on shared operations. The most common issues reported in the literature related to cant excess were:

- Gauge spreading due to high lateral load on the low rail.
- RSD for concrete ties due to large gauge spreading and rail rollover forces.
- Plastic deformation and cracking (or RCF) on the low rail due to a shift of the load to the low rail. Increased risk of derailment due to tipping was higher, especially if the train came to a stop on a curve.

The survey and discussions with railroads confirmed items listed above from the literature review. More specifically, railroads that participated in thus survey indicated the following issues for curves with a cant excess:

- Excessive flattening or flow on low rail
- Gauge widening
- Rollover of the low rail
- Increased potential of internal rail defects
- Adverse impact on rail, tie, and surface condition due to the elevated vertical loading on the low rail and the increased axle steering forces that resulted.

European countries have set a limit for cant excess that varies from 2.8 to 5.3 inches (70–135 mm), depending on conditions specific to each country. However, current U.S. practices (neither the government nor private railroads) do not specify an allowable maximum cant excess. The maximum superelevation allowed is the maximum cant excess when a train stops in a curve.

It is important that the compromise between higher-speed passenger and lower-speed freight operations be addressed when designing and maintaining curves on shared tracks. Significant superelevation helps to achieve passenger trains' higher speeds, but it causes deterioration on rail, ties, and surface condition due to cant excess for freight operation at substantially lower speeds.

6. Recommendations for Future Research

The findings of this report indicated that shared passenger and freight operations may result in increased freight operations at large cant excess with significant potential of detrimental effects. Findings from the literature review also tended to indicate a preference in allowing more cant deficiency for higher-speed passenger trains than cant excess for freight trains when a curve is under shared operations. To develop a best practice for designing superelevation in curve with shared operations, further research is recommended in order to quantify these detrimental effects with large cant excess and to identify the trade-offs between freight train and passenger train operations.

Based on the industry survey results, two or three existing shared corridors can be selected for onsite observations and measurements. In conjunction with or even prior to field research, however, further studies are recommended to perform vehicle-track interaction simulations using validated vehicle models. These simulations will include passenger and freight cars through varied curvatures with different superelevations running in a given speed range. The proposed vehicle models to be used in the simulations will include:

- Typical high-speed passenger coaches operating on shared-track
- Two types of typical freight cars operating on shared-track, including a representative HAL car and a representative intermodal car
- A representative six-axle freight locomotive operating on shared track
- A representative four-axle passenger locomotive

Several combinations of new and worn wheels and rails, selected from the common shapes of wheel and rail profiles in North American passenger and freight services, will be used in the simulations. The results will be analyzed for safety performance, passenger ride quality, and forces into the vehicle and track systems. Force data will also be used to predict wheel and rail wear and RCF growth over time for various curvature and superelevation combinations. Simulation results in safety performance, ride quality, track degradation, wheel and rail wear, and RCF growth will then be used to establish the basis for developing a best practice in designing and maintaining proper superelevation in curves with shared operations.

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Appendix A.
Survey Questionnaire

Existing shared-track route of higher-speed passenger and freight trains

TTCI is working on the FRA project to develop a white paper that will summarize issues and current practices related to cant excess when operating freight trains in curves with cant excess. Therefore, we would like to ask you to provide answers to the following questionnaire.

1. Affiliation

Please provide your name, affiliation, and years of experience with shared operation.

2. Shared-track route location

Please provide specific location of the track route where the higher-speed passenger and freight trains operate concurrently. If available please send the track charts to anna_rakoczy@aar.com

3. MGT of passenger traffic

Please provide approximate annual MGT of passenger traffic.

4. MGT of freight traffic

Please provide approximate annual MGT of freight traffic.

5. Curvatures of the route

Please provide the following information about curvatures of particular route: Length of shared route; Percent of shared route (by miles) of curves that are between 0.5 and 4 degree; Percent of shared route (by miles) that are sharper than 4 degree.

6. Current operating speed/cant excess for freight trains

Please provide the allowed speed of freight trains on the particular route. If known please provide cant excess.

7. Current operating speed/cant deficiency for passenger train

Please provide the allowed speed of passenger trains on the particular route. If known please provide cant deficiency.

8. Current polices and guideline for design practice

Please provide current practice for design and maintenance of shared corridors.

9. Current issues related to curvature and superelevation

Please describe current issues related to curvature and superelevation when the freight and passenger trains are operating together on the same route.

Abbreviations and Acronyms

Abbreviation or Acronym	Name
APT	Advanced Passenger Train
AAR	Association of American Railroads
CFR	Code of Federal Regulations
CEN	European Committee for Standardization
FRA	Federal Railroad Administration
HAL	Heavy Axle Load
HSR	High-Speed Rail
IWS	Instrumented Wheelsets
L/V	Lateral-to-Vertical Ratio
MWR	Magic Wear Rate
RSSB	Rail Safety Standards Board
RSD	Rail Seat Deterioration
RCF	Rolling Contact Fatigue
TTC	Transportation Technology Center (FRA-owned facility)
TTCI	Transportation Technology Center, Inc. (wholly owned subsidiary of the Association of American Railroads)
TSI	Technical Specification for Interoperability
THC	Truck Hunting Detectors
TPD	Truck Performance Detectors
UIUC	University of Illinois at Urbana-Champaign
WILD	Wheel Impact Load Detectors