APTA STANDARDS DEVELOPMENT PROGRAM
STANDARD
American Public Transportation Association
1300 I Street, NW, Suite 1200 East, Washington, DC 20005

APTA PR-M-S-031-22
First Published: September 22, 2022

PRESS Mechanical Working Group

Low-Speed Curving Performance of Railroad Passenger Equipment

Abstract: This standard contains requirements for evaluating low-speed vehicle curving performance of railroad passenger equipment.

Keywords: derailments, low-speed curving performance, multi-body simulations, rail vehicle dynamics, suspension, track twist, warp, wheel climb, wheel load equalization, wheel unloading

Summary: This standard defines vehicle and track conditions to evaluate the ability of passenger equipment to resist wheel climb derailments when operating at low speeds over track curves with high-degree of curvature. The methodology in this standard shall be used for simulations conducted using industry-accepted rail vehicle dynamics software.

Scope and purpose: This standard defines an evaluation methodology to minimize the risk of low-speed derailments for passenger equipment. It shall apply to railroad passenger equipment as defined in 49 CFR 238.5, originally contracted on or after one year from the date of publication, or sooner as specified by the railroad as defined by 49 CFR 270.5.

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Introduction

This introduction is not part of APTA PR-M-S-xxx-19, "Low-Speed Curving Performance of Railroad Passenger Equipment."

This document is part of a series of APTA standards designed to mitigate railroad passenger equipment derailment concerns. Specifically, it is designed to address potential risks from derailment under conditions of slow operating speeds in tight-radius curved track with large rail-to-rail cross level (track warp) variations. In response to occurrences of rail vehicle derailments in the field under such track geometry conditions which were within limits of the Federal Railroad Administration (FRA) Track Safety Standards, the FRA in 2013 issued Safety Advisory 2013-02 to alert railroads and other industry members of the potential for low-speed, wheel-climb derailments of certain passenger equipment designs. Findings from derailment investigations conducted by the FRA and railroads have highlighted the need to ensure that passenger equipment suspension systems are suitable for demanding track conditions found in low-speed operating environments. The industry recognized that this is a potential concern for all equipment designs, and this standard is a result of these findings.

A subset of this Safety Advisory recommends that the industry evaluate the trackworthiness performance of passenger equipment on track with high degree of curvature and limiting values of track warp. This standard is the third in a series of complementary APTA standards for passenger equipment operating on passenger rail lines or freight rail lines specifically designed to work together to provide greater confidence in the safe operation of trains under these conditions. The other two related standards set minimum wheel flange angle (APTA PR-M-S-015, latest revision) and establish wheel load equalization performance criteria (APTA PR-M-S-014, latest revision).

This standard applies to all:

1. Railroads that operate intercity or commuter passenger train service on the general railroad system of transportation; and
2. Railroads that provide commuter or other short-haul rail passenger train service in a metropolitan or suburban area, including public authorities operating passenger train service.

This standard does not apply to:

1. Rapid transit operations in an urban area that are not connected to the general railroad system of transportation;
2. Tourist, scenic, historic, or excursion operations, whether on or off the general railroad system of transportation;
3. Operation of private cars, including business/office cars and circus trains; or
4. Railroads that operate only on track inside an installation that is not part of the general railroad system of transportation.

Low-Speed Curving Performance of Railroad Passenger Equipment

1. Overview

Safe performance of railroad passenger equipment is the result of several design and maintenance factors. These generally fall into the four categories listed below: track conditions, vehicle conditions, wheel/rail interface and individual railroad operating practices:

- Track conditions:
    - entry and exit spirals
    - degree (radius) of curvature
    - track geometry as per 49 CFR 213(alignment/profile/cross-level)
    - track superelevation
    - track gage
    - friction modifiers
    - rail profile (new/worn)
    - cant deficiency/cant excess
- Vehicle conditions:
    - loading condition
    - suspension characteristics (new/degraded)
    - wheel profile (new/worn)
    - truck frame torsional stiffness
    - rail vehicle height and center of gravity
    - wheel load equalization
    - truck rotational resistance
    - carbody stiffness
- Wheel/rail interface:
    - tread conicity
    - wheel/rail contact angle
    - tread friction coefficient
    - flange friction coefficient
- Operation:
    - vehicle speed
    - in-train forces (buff/draft)

While this document does not address all the above factors, it focuses on track warp in high-degree curves, as these aspects are known to have contributed to many derailments. As such, representative track scenarios involving limiting warp conditions are to be analyzed using computer simulations and model validations as described within this document.

2. Low-speed curving performance requirements

Optimal design characteristics for high-speed operations may not result in satisfactory performance at low speeds (e.g., on Class 1 tracks), especially in curves. Balancing high-speed and low-speed performance requirements is a challenging design optimization problem. This standard provides a method to evaluate low-speed curving performance during the equipment design and qualification process. Simulation requirements, including modeling and model validation, are described herein to provide a proven and consistent method to evaluate low-speed curving performance.

2.1 Modeling software requirements

Vehicle low-speed curving response through a track twist input is to be predicted using railway industry-standard multi-body simulation software as approved by the railroad. At minimum, the software must represent the vehicle as a system of masses and suspension elements and include a wheel-rail interaction model. The wheel-rail model must consider contact geometry variations arising from the transition between tread contact to flange contact, the possibility of multiple contact points at a flanging wheel, and the effect of friction saturation at any contact point. The multi-body simulation models built with such software shall represent the vehicle design adequately. As an example, when modeling a primary suspension with a swing arm (or radius arm), the model should accurately account for the coupling between axle box vertical and longitudinal motion that results in a change in overall vertical suspension stiffness.

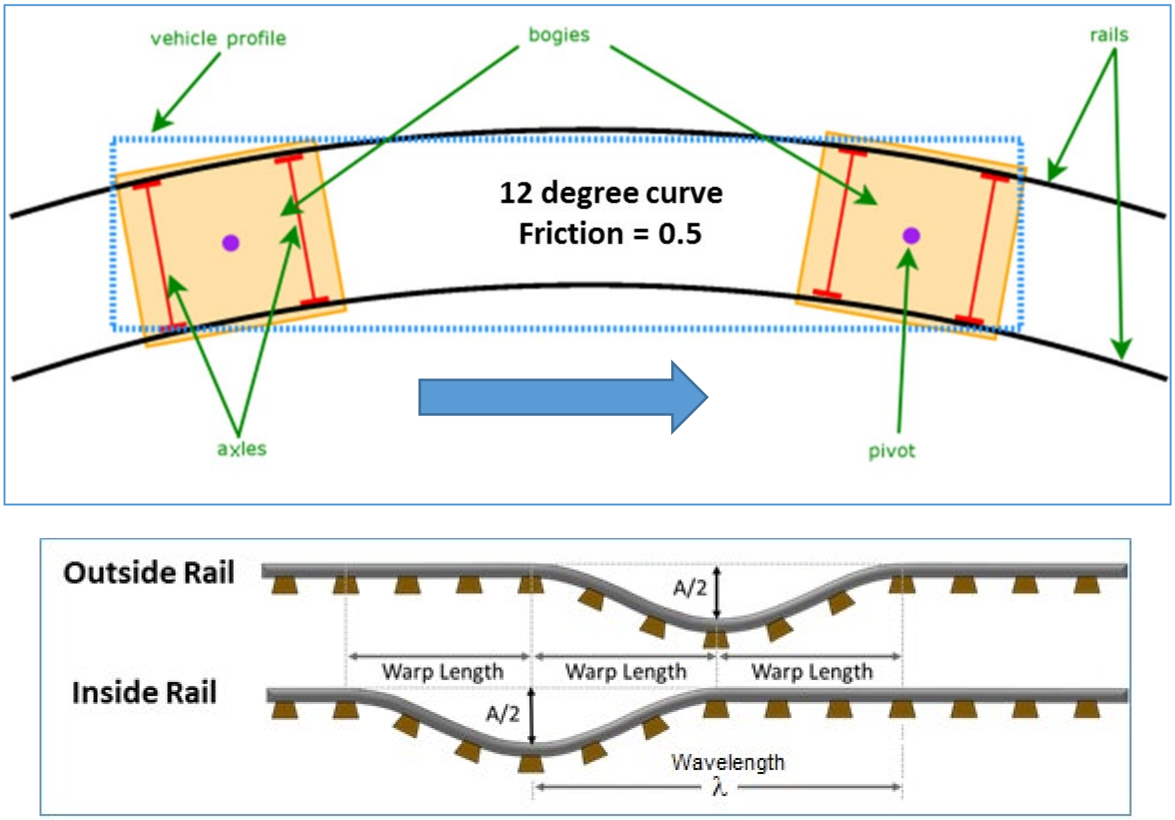
2.2 Track parameters

For each simulation involving assessment of curving performance in this standard, the degree of curvature shall be 12 deg. and the superelevation equal to zero. The basic layout of the curved track section is shown in **Figure 1**. The body of the curve shall contain a pair of versine profile (track surface) deviations to produce the amplitude associated with a maximum permissible warp threshold for Class 1 track derived from the 3 inches[1] mentioned in 49 CFR 213.63(a). The special layout of these perturbations begins on the inside rail, followed by perturbation on the outside rail separated by a distance referred to as the warp length. Each deviation has a wavelength, λ, defined as twice the warp length. Separate simulations shall be used to study warp lengths of 10, 20, 40 and 62 ft. All simulations shall be performed using a new American Railway Engineering and Maintenance-of-Way Association (AREMA) 136 RE (8" head radius) rail profile with a 1:40 rail cant and a nominal track gage of 57.0 in.

> **NOTE:** Additional simulations may be considered if the actual new rail profile and/or nominal cant used on a particular railroad differs from the AREMA 136 RE (8" head radius) and 1:40 rail cant specified above. In addition, it is important to note that worn rail profiles (particularly heavily curved worn rails) can result in a maximum contact angle between wheel and rail that is lower than the maximum wheel flange angle and therefore increase the risk of low-speed wheel climb derailments. These additional rail profile considerations should be included based on an agreement between the railroad and carbuilder.

[1] Perturbation thresholds and wavelengths were utilized from the FRA Safety Advisory 2013-02

FIGURE 1
Track Parameters



2.3 Vehicle parameters

Simulations using the vehicle model shall consider variations of vehicle parameters (e.g., mass, center of gravity, and moments of inertia) to accurately represent the conditions defined in **Table 1**.

TABLE 1
Vehicle Parameters

Parameter	Condition
Vehicle load	AW0 (empty ready to run[1]) AW3 (fully loaded[1]) Additional worst-case condition between AW0 and AW3, if applicable (e.g., nonlinear vertical suspension), as determined by the carbuilder[2]
Suspension system	Nominal condition Deflated air spring condition, if applicable[3] Evaluation of critical suspension components with tolerances greater than 15 percent[2]

1. As per definition of the railroad.
2. These evaluations shall be conducted using additional simulations to be defined by an agreement between the carbuilder and railroad.
3. The only failure to be considered is with all air springs deflated.

The vehicle model shall be correlated with test results as per the model validation process defined in Section 2.7.

NOTE: If the carbuilder uses the structural flexibility of the carbody, truck frame or any other body to achieve the performance requirements in this standard, a detailed description and justification based on testing under section 2.7.2 (c) (truck twist and vehicle twist) shall be provided in the report as required in Section 2.8.

2.4 Wheel/rail interface parameters

In addition to the track parameters defined under Section 2.2 and vehicle parameters defined under Section 2.3, the following wheel/rail condition shall be used for conducting simulations as required by this standard:

- Constant coefficient of friction equal to 0.5 between the wheel and rail.

2.5 Operational parameters

All simulation scenarios shall be conducted at constant speeds as identified in **Table 2**. Tractive and/or braking forces, and/or in-train forces (buff/draft), may be included based on an agreement between the railroad and the carbuilder.

2.6 Simulation requirements

Simulations shall be performed based on the simulation matrix defined in **Table 2** and as defined in sections 2.2 (track), 2.3 (vehicle), 2.4 (wheel/rail interface) and 2.5 (operational parameters). Because these simulations consider a track perturbation in a curve, the simulations should be of sufficient length such that the track perturbation is encountered only after the model has settled to steady-state curving equilibrium.

TABLE 2
Simulation Requirements

Suspension Condition	Load Condition	Speed	Warp Lengths (λ/2), with Initial Warp Amplitude (A) of 3 in. (twice the value of A/2 as shown in Figure 1)			
Nominal	AW0	5 mph	10 ft	20 ft	40 ft	62 ft
		10 mph	10 ft	20 ft	40 ft	62 ft
		15 mph	10 ft	20 ft	40 ft	62 ft
		20 mph	10 ft	20 ft	40 ft	62 ft
	AW3 (fully loaded)	5 mph	10 ft	20 ft	40 ft	62 ft
		10 mph	10 ft	20 ft	40 ft	62 ft
		15 mph	10 ft	20 ft	40 ft	62 ft
		20 mph	10 ft	20 ft	40 ft	62 ft
	Worst case if applicable	Carbuilder to determine if there is a worst-case loading condition between AW0 and AW3 (fully loaded)				
		Matrix of worst-case simulations should be done to satisfaction of railroad and carbuilder				
Deflated air springs, if applicable	AW0	5 mph	10 ft	20 ft	40 ft	62 ft
		10 mph	10 ft	20 ft	40 ft	62 ft
		15 mph	10 ft	20 ft	40 ft	62 ft

Vehicle response is to be evaluated based on the predicted worst-case single wheel L/V ratio. Worst-case response typically occurs at the leading axle outside-rail wheel, but the simulations should not make this assumption. Analysis of the predicted results is to be per the derailment wheel/rail force safety criteria defined in 49 CFR 213.333. Reporting of the safe perturbation amplitude should be based on the single-wheel L/V ratio, as well as any values that are exceeded for the other criteria.

Should the worst-case single wheel L/V ratio for any one simulation case exceed the limit value, and the option of modifying the suspension design is not available, that simulation case shall be repeated with the track twist amplitude reduced by ⅛ in. This process of incrementally reducing the track twist amplitude shall be repeated until a predicted worst-case single-wheel L/V ratio within the limit value is obtained. For each simulation case, the final result shall clearly identify the track twist amplitude, worst-case single wheel L/V ratio, and any other derailment safety indicators exceeding their respective limit values.

2.6.1 Criteria

Performance shall be evaluated using the following criteria from 49 CFR 213.333:

- single wheel L/V
- truck side L/V
- single wheel vertical load ratio (V_{min})
- net axle lateral (NAL) L/V

2.7 Validations

To demonstrate validity of the simulation model used for these analyses, comparison with results of physical tests must be made to demonstrate the correctness of the model formulation, vehicle input data, and the simulation calculations. At a minimum, the following comparisons for model validation are required:

1. Provide test data of the individual suspension components to justify the characteristics used in the model:
    a. Stiffnesses and damping (vertical, lateral, longitudinal, yaw, etc.) as appropriate for the suspension design.
    b. Non-linearities (such as increasing stiffness of a rubber bushing the more it is compressed, stops, etc.) should be included as appropriate.

2. Provide test data for mass and center of gravity height of major assemblies (carbody, truck frame and components, wheelsets, etc.).

3. Provide a comparison between test data and simulations of the following quasi-static tests:
    a. APTA PR-M-S-014-06, latest revision, “Wheel Load Equalization.”
    b. Static Lean tests performed to meet the requirements of APTA PR-M-RP-009-98, latest revision. Please note as the safety advisory (FRA 2013-02) recommends a determination that the suspension systems control static wheel-load distribution when the equipment is stationary on perfectly level track such that the lightest wheel load deviates by no more than 5 percent from the nominal wheel load.
    c. If utilizing structural flexibility of the carbody to meet the requirements of the standard, as described in Section 2.3, a full car end-to-end twist/load equalization test is required. This can be accomplished by raising both wheels on one side of a truck at diagonally opposite corners (i.e., four wheels) of the car by 1.5 in. or by raising both wheels on one side of one truck by at least 3 in., while all other wheels on the same truck and all wheels of the second truck remain level. In either method, wheels shall be raised in increments of 0.5 in. to reach the maximum raise. An alternative test method may be proposed for non-conventional designs, for example articulated trainsets.

   d. Comparisons to include tables of results for the loads on all wheels measured as described in a. through c. above, and any additional measurements as agreed to between the railroad and carbuilder such as primary and secondary suspension deflections.

4. Provide a comparison between test data and simulations to validate the lateral and yaw characteristics as agreed to between the railroad and the carbuilder. Acceptable methods include:
   a. Quasi-static truck rotation tests performed for an entire vehicle:
      - For trucks with side bearings and/or center plates, the comparison needs to demonstrate that yaw resistance output from the friction model is a reasonable match to the test data for the full range of truck rotation.
      - For trucks with shearing springs/airbags, the comparison needs to demonstrate that the effective yaw stiffness due to shearing is a reasonable match to the test data for the full range of truck rotation.
      - If the model predicts variability in rotation resistance to rate of rotation (yaw), the test shall be designed to assess such sensitivity.
   b. On-track testing
      - Tests conducted on a representative curve (including entry and exit spirals) with a radius of curvature of at least 6 deg., or the maximum radius of curvature on the operating railroad if less than 6 deg.
      - Measurements may be done using instrumented wheelsets on one truck or by instrumenting the test curve to measure vertical and lateral forces.
      - The test shall be designed to assess any sensitivity of rotation (yaw) resistance to speed.
      - Comparisons should be conducted between the model predictions using measured track geometry and the measurements from the test site.

2.8 Analysis and reporting

The carbuilder shall perform analyses that assess the vehicle performance according to the simulation requirements identified in Section 2.6. To reduce the risk of wheel climb derailment, vehicles should be designed to meet vehicle track interaction (VTI) performance criteria identified in Section 2.6.1 for the maximum allowable warp amplitude of 3 in. for each wavelength.

A report shall provide the following:

- Detailed description of track, vehicle and truck suspension, reflecting elements mentioned in sections 2.1 through 2.5. Identify wheel profile including flange angle, rail profile and limiting performance criteria required by Section 2.6.1.
- Compliance matrix detailing and confirming simulation track/vehicle parameters, and scenarios that have been analyzed.
- Single-wheel L/V results for all flanging wheels, expressed as L/V or percent of limit (not pass/fail), shall be provided for the maximum amplitude of 3 in. for each wavelength and speed condition analyzed. Should any predicted wheel L/V value exceed the VTI safety criteria for the maximum allowable warp amplitude of 3 in., the report shall provide tables and/or trend plots that clearly indicate the VTI safety limit and the results of additional analysis conducted to determine the track warp amplitude for each wavelength that the vehicle can safely negotiate.
- The worst-case values of all the other Section 2.6.1 performance criteria shall be reported in a table along with the simulation condition(s) and location of wheel/axle on the vehicle for which they occurred. If any value exceeds the limiting value for that performance measure, then the results for that particular criterion shall be provided in tables and/or trend plots that clearly indicate the VTI

safety limit and identify the change in that performance measure as a function of speed and track warp (amplitude and wavelength) conditions.

2.9 Application recommendations

Results from all simulations should be reported to the railroad, clearly defining any limiting track geometry or speed restrictions required to safely operate the equipment in low-speed curving scenarios, with inflated or deflated air springs (for vehicles fitted with air springs).

Based on review of the results with the carbuilder, including potential suspension changes, the railroad at its discretion shall define any limiting conditions for track geometry and maintenance standards, and/or operating instructions to ensure safe operation of the equipment under evaluation. The railroad shall maintain this report as long as the vehicles are owned and it shall be provided to any other railroad or agency for shipping, lease or resale purposes.

Related APTA standards

APTA PR-M-S-015-06, Latest revision, "Wheel Flange Angle for Passenger Railroad Rolling Stock"
APTA PR-M-S-014-06, Latest revision, "Wheel Load Equalization for Passenger Railroad Rolling Stock"
APTA PR-M-RP-009-98, Latest revision, "Truck Design"

References

Where applicable, this standard shall be used in conjunction with the following publications:

49 CFR 213 Code of Federal Regulations, Track Safety Standards

49 CFR 238 Code of Federal Regulations, Passenger Equipment Safety Standards

FRA Safety Advisory 2013-02, Low-Speed, Wheel-Climb Derailments of Passenger Equipment with "Stiff" Suspension Systems, Federal Register Vol. 78, No. 50, March 14, 2013

Definitions

AW0 load: Ready-to-run car weight without any passenger loading as per definition of the railroad.

AW3 load: Car weight with maximum number of passengers both seated and standing as per definition of the railroad.

body of a curve: The portion of a curve that has a constant curvature.

cant: Angle relative to the horizontal plane. For individual rails it refers to the base of the rail. For track it refers to the track superelevation as measured across the top of the two rails.

cant deficiency: The amount by which superelevation must be increased to produce equilibrium. Cant deficiency occurs when a train travels around a curve at a speed higher than the equilibrium speed.

cant excess: The amount by which superelevation must be decreased to produce equilibrium. Cant excess occurs when a train travels around a curve at a speed lower than the equilibrium speed.

coefficient of friction: The ratio of the magnitude of the maximum tangential force acting on a surface due to friction to the magnitude of the normal force on that surface.

cross-level: The vertical distance between the left and right rail.

degree of curvature: The central angle of an arc subtended by a 100-ft chord.

equilibrium speed: The operational speed in a superelevated curve in which the centrifugal forces acting on a vehicle are perfectly opposed by the component of the gravitational force in the lateral direction (parallel to the plane of the running rails).

net axle lateral force L/V ratio: The net axle lateral force, exerted by an axle on the track, divided by the static nominal vertical load exerted by that axle on the track. dynamic static

single-wheel L/V ratio: The ratio of the lateral force that any wheel exerts on an individual rail to the vertical force exerted by the same wheel on the rail.

single-wheel vertical load ratio: The ratio of the vertical wheel load to the static load that the wheel would carry when stationary on level track.

spiral: A length of track of varying curvature (or radius) transitioning between tangent (straight) track and circular curved track. The spiral may also include a corresponding transition in superelevation.

superelevation: The design vertical distance that the outer rail is above the inner rail in a curve.

track twist: The difference in cross-level of any two points at a specific chord length along a segment of track.

track warp: The difference in cross-level of any two points within a specific chord length along a segment of track.

truck-side L/V ratio: The ratio of the lateral forces that the wheels on one side of any truck exert on an individual rail to the vertical forces exerted by the same wheels on that rail.

Abbreviations and acronyms

FRA Federal Railroad Administration
L/V lateral to vertical ratio
NAL net axle lateral
VTI vehicle track interaction

Document history

Document Version	Working Group Vote	Public Comment/ Technical Oversight	Rail CEO Approval	Policy & Planning Approval	Publish Date
First published	Jan. 15, 2022	Mar. 31, 2022	Apr. 4, 2022	June 10, 2022	Sept. 22, 2022
First revision	—	—	—	—	—
Second revision	—	—	—	—	—