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Side Structure Integrity Research for Passenger Rail Equipment

DOT/FRA/ORD-22/42

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14. ABSTRACT

FRA sponsored research to evaluate the side impact strength of Tier I passenger rail equipment designs built to the current rollover and side structure regulations. This report presents results from the first stage of this research program, including: (1) the makeup of the U.S. passenger car fleet; (2) the accident history involving side structures in the U.S.; (3) a review of passenger rail-side structure design and performance criteria in current standards and regulations; (4) an evaluation of proof loads for similar vehicle structures used in other modes of transportation; and (5) a discussion of the technical challenges in proposing side impact criteria.

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METRIC/ENGLISH CONVERSION FACTORS

ENGLISH TO METRIC

LENGTH (APPROXIMATE)

1 inch (in)	=	2.5 centimeters (cm)
1 foot (ft)	=	30 centimeters (cm)
1 yard (yd)	=	0.9 meter (m)
1 mile (mi)	=	1.6 kilometers (km)

AREA (APPROXIMATE)

1 square inch (sq in, in^2)	=	6.5 square centimeters (cm^2)
1 square foot (sq ft, ft^2)	=	0.09 square meter (m^2)
1 square yard (sq yd, yd^2)	=	0.8 square meter (m^2)
1 square mile (sq mi, mi^2)	=	2.6 square kilometers (km^2)
1 acre = 0.4 hectare (he)	=	4,000 square meters (m^2)

MASS - WEIGHT (APPROXIMATE)

1 ounce (oz)	=	28 grams (gm)
1 pound (lb)	=	0.45 kilogram (kg)
1 short ton = 2,000 pounds (lb)	=	0.9 tonne (t)

VOLUME (APPROXIMATE)

1 teaspoon (tsp)	=	5 milliliters (ml)
1 tablespoon (tbsp)	=	15 milliliters (ml)
1 fluid ounce (fl oz)	=	30 milliliters (ml)
1 cup (c)	=	0.24 liter (l)
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 yard (cu yd, yd^3)	=	0.76 cubic meter (m^3)

TEMPERATURE (EXACT)

[(x-32)(5/9)] °F = y °C

METRIC TO ENGLISH

LENGTH (APPROXIMATE)

1 millimeter (mm)	=	0.04 inch (in)
1 centimeter (cm)	=	0.4 inch (in)
1 meter (m)	=	3.3 feet (ft)
1 meter (m)	=	1.1 yards (yd)
1 kilometer (km)	=	0.6 mile (mi)

AREA (APPROXIMATE)

1 square centimeter (cm^2)	=	0.16 square inch (sq in, in^2)
1 square meter (m^2)	=	1.2 square yards (sq yd, yd^2)
1 square kilometer (km^2)	=	0.4 square mile (sq mi, mi^2)
10,000 square meters (m^2)	=	1 hectare (ha) = 2.5 acres

MASS - WEIGHT (APPROXIMATE)

1 gram (gm)	=	0.036 ounce (oz)
1 kilogram (kg)	=	2.2 pounds (lb)
1 tonne (t)	=	1,000 kilograms (kg)
	=	1.1 short tons

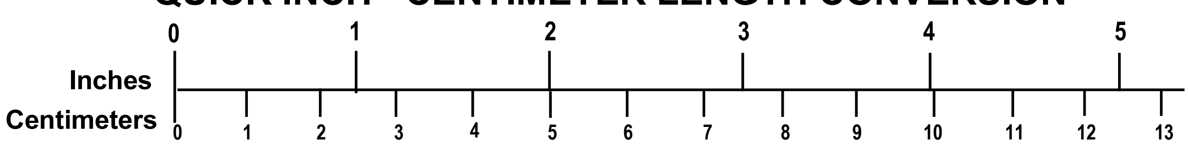
VOLUME (APPROXIMATE)

1 milliliter (ml)	=	0.03 fluid ounce (fl oz)
1 liter (l)	=	2.1 pints (pt)
1 liter (l)	=	1.06 quarts (qt)
1 liter (l)	=	0.26 gallon (gal)
1 cubic meter (m^3)	=	36 cubic feet (cu ft, ft^3)
1 cubic meter (m^3)	=	1.3 cubic yards (cu yd, yd^3)

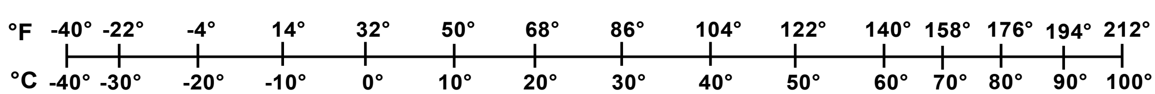
TEMPERATURE (EXACT)

[(9/5) y + 32] °C = x °F

QUICK INCH - CENTIMETER LENGTH CONVERSION



QUICK FAHRENHEIT - CELSIUS TEMPERATURE CONVERSIO



For more exact and or other conversion factors, see NIST Miscellaneous Publication 286, Units of Weights and Measures. Price $2.50 SD Catalog No. C13 10286

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The publicly available tractor-trailer model discussed in this report was developed by a team from Battelle Memorial Institute, Oak Ridge National Laboratory, and the University of Tennessee at Knoxville under the direction of the National Transportation Research Center Inc. for the Federal Highway Administration.

Contents

Illustrations

Tables

Executive Summary

The U.S. Department of Transportation (DOT), Federal Railroad Administration (FRA) began promulgating regulations for the structural crashworthiness of passenger rail equipment in the Code of Federal Regulations (CFR) at Title 49, Part 238 on May 12, 1999. These Passenger Equipment Safety Standards (PESS) [1] include requirements affecting the designs of sidewall structures on Tier I passenger rail equipment. The FRA Office of Research, Development, and Technology and the DOT Volpe National Transportation Systems Center (Volpe) are conducting research to evaluate the side impact strength of Tier I passenger rail equipment designs built to the current rollover and side structure regulations.

In the section analysis of the PESS rulemaking, FRA stated the objective of a side impact strength requirement should be to ensure the passenger car is pushed sideways rather than having the side structure collapse and expose the occupant survival space to hazards. It is not clear whether current longstanding design practices are sufficient to meet this goal, particularly for passenger cars that have low floors.

Following a fatal 2011 accident in which a highway semi-trailer truck impacted the side of a passenger train that was transiting a grade crossing in Miriam, Nevada, the National Transportation Safety Board (NTSB) recommended that FRA "develop side impact crashworthiness standards (including performance validation) for passenger cars that provide a measurable improvement compared to the current regulation for minimizing encroachment to and loss of car occupant survival space." [2]

This report, prepared by Volpe and sponsored by FRA, presents results from the first stage in the side structure integrity research program including: (1) the makeup of the U.S. passenger car fleet; (2) the accident history involving side structures in the U.S and Canada; (3) a review of passenger rail side structure design and performance criteria in current standards and regulations; (4) an evaluation of proof loads for similar vehicle structures used in other modes of transportation; and (5) a discussion of the technical challenges in proposing side impact criteria. Volpe researchers examined how passenger cars designed to meet the current performance and design criteria have performed in accidents, and how the composition of the U.S. passenger car fleet has changed over approximately 20 years since the criteria were promulgated. Next, they reviewed the performance criteria from other modes of transportation was conducted to determine what lessons could be learned and possibly applied to Tier I passenger rail equipment. Finally, Volpe considered the technical challenges with proposing static or dynamic side load criteria.

1. Introduction

1.1 Background

Passenger Equipment Safety Standards (PESS) [1] in the U.S. Code of Federal Regulations (CFR) include requirements affecting the designs of sidewall structures on passenger rail equipment. The Federal Railroad Administration (FRA) and the Volpe National Transportation Systems Center (Volpe) are conducting research to evaluate the side impact strength of Tier I[1] passenger rail equipment designs that have been constructed according to the current rollover and side structure regulations.

In the section analysis section of the PESS rulemaking, FRA stated the following regarding side impact strength:

> *As a general principle in specifying a side impact strength requirement for a passenger car, the objective is to ensure that the side of the passenger car is strong enough so that the car derails and is pushed sideways—rather than collapses—when struck in the side by another rail vehicle or a highway vehicle. FRA believes that current practice may not be adequate to meet this goal, and that cars with low floors are particularly vulnerable to penetration when struck in the side. A more meaningful side structure requirement than contained in this section is necessary to address this concern. Such a requirement will include specifying minimum shear values at the car's floor as well as at some point above the floor to protect the car's occupants. This will be a priority in the second phase of the rulemaking. The requirement in this final rule is, therefore, an interim measure. As FRA believes that this section does not address in particular the vulnerability of low-floor passenger cars to a side impact by a heavy highway vehicle, FRA has, in effect, deferred consideration of a requirement to do so.*

In 2011 in Miriam, Nevada, an accident occurred involving a highway semi-trailer truck and Amtrak multi-level passenger cars which resulted in a significant loss of occupant survival space to both the lower and upper floors. The National Transportation Safety Board (NTSB) recommended (R-12-039) that FRA "develop side impact crashworthiness standards (including performance validation) for passenger cars that provide a measurable improvement compared to the current regulation for minimizing encroachment to and loss of car occupant survival space." [2]

To follow up with issues raised during the PESS rulemaking and respond to NTSB's recommendation, FRA has sponsored Volpe research to examine side structure integrity.

1.2 Objectives

As a first stage in the research program, the current state of side structure integrity was examined, including: (1) the makeup of the U.S. passenger car fleet; (2) the accident history involving side structures in the U.S. and Canada; and (3) a review of side structure design and performance criteria in current passenger rail equipment standards and regulations. The authors also performed an evaluation of side impact loads used in other modes of transportation. This

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[1] *Tier I* refers to passenger railroad equipment on the general railroad system operating at speeds not exceeding 125 mph (49 CFR 238.5).

approach examined how the side structure requirements have influenced the design of passenger rail vehicles, how vehicles designed to those criteria have performed in incidents, how the current fleet compares to what existed when the current standards and regulations were issued in 1999, and what approaches have been used in addressing other side impact loads encountered in the U.S. transportation system.

1.3 Overall Approach

This report documents the first stage of the FRA's side structure integrity research program. It presents a survey of the current makeup of the U.S. passenger car fleet, the accident history involving side structures within the U.S. and Canada, and the design and performance criteria for passenger vehicle side structures in standards and regulations.

1.4 Scope

As used in this report, the term "conventional" refers to passenger cars designed and constructed according to longstanding design practice for service on the U.S. general railroad system. These design practices pre-date FRA's 1999 PESS rulemaking, meaning cars built before 1999 might comply with the current requirements without having formally demonstrated such compliance to FRA.

The phrase "alternatively designed" is used in this report to describe passenger rail vehicles that were not originally designed specifically to meet the U.S. design criteria, but are operated on the U.S. general railroad system. For example, an alternatively designed passenger car may have been originally designed to operate on the European rail network, but has been granted a waiver by FRA to operate in the U.S. under specific conditions. Alternatively designed vehicles are not designed to have the same structures as cars of conventional U.S. design. For instance, alternatively designed vehicles may feature aluminum extrusions in place of discrete structural members. Alternatively designed vehicles may be operating under an FRA waiver or they may have demonstrated alternative compliance with regulations.

1.5 Organization of the Report

Section 2 describes existing regulations and standards containing performance and design criteria for side structure integrity.

Section 3 describes the accident history in the U.S. and Canada involving the side structure of passenger rail cars.

Section 4 describes estimates taken in 1996 and 2016 of U.S. passenger car fleet makeup.

Section 5 describes side impact assessment strategies in other modes of transportation.

Section 6 describes simplified sidewall and rollover analyses conducted during this research program.

Section 7 contains discussion and conclusions from the research in this report.

Section 8 contains a list of references cited in this report.

Appendix A includes a tabular description of the U.S. passenger rolling stock car count, with references.

Appendix B provides details on how the section modulus calculations were carried out.

2. Existing Regulations and Standards on Sidewalls

Existing design and performance criteria are described throughout this report as specified in either a regulation or a standard. A regulation refers to a requirement promulgated through a Federal rulemaking process required to be met for rail vehicles operating under the particular conditions applicable to the equipment class, e.g., Tier I, Tier II, or Tier III[2] service. In this report, a standard refers to industry-adopted criteria and/or procedures that are generally non-compulsory, but may be required by a car buyer or railroad operator.[3]

Conventional U.S. practice for passenger car design was formalized as a set of criteria and evaluation procedures first adopted by the Association of American Railroads (AAR) as recommended practices in 1939 [3]. Those practices were upgraded to a standard in 1945 (AAR S-034), last revised in 1969 (AAR-S-034-69), and discontinued in 1989.

As a longstanding design practice, the approaches used in AAR S-034-69 were largely adopted into subsequent regulations and standards. In 1999, both FRA and the railroad industry, through the American Public Transportation Association (APTA) [4], published design standards of their own. A timeline of side structure standards and regulations development is shown in Figure 1.

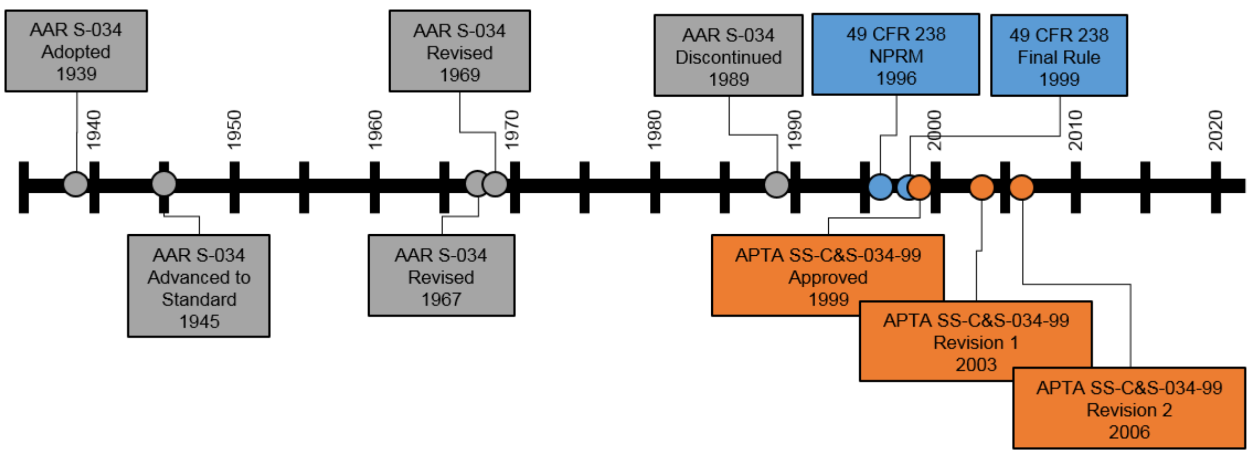

Figure 1. Timeline of Standards and Regulations Applicable to U.S. Cars that Include Side Structure Criteria

A summary of performance and design criteria contained in passenger rail equipment side structure integrity regulations and standards discussed in this section is presented in Table 4.

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[2] *Tier II* means operating at speeds exceeding 125 mph but not exceeding 160 mph. *Tier III* means operating in a shared right-of-way (ROW) at speeds not exceeding 125 mph and in an exclusive ROW without grade crossings at speeds exceeding 125 mph but not exceeding 220 mph (49 CFR 238.5).

[3] In other areas of passenger railcar design, industry standards may be incorporated into regulations by reference and thus become compulsory.

Table 1. Summary of Side Structure Performance and Design Criteria

Applicability	Regulation or Standard	Title	Performance or Design Criteria
Tier I, III Regulation	49 CFR 238.215	Rollover Strength	Rest on (a) side or (b) roof with $\sigma < \frac{\sigma_Y}{2}$ and $\sigma < \frac{\sigma_{CR}}{2}$ in frame
	49 CFR 238.217	Side Structure	Minimum section modulus / thickness and material allowance
Tier II Regulation	49 CFR 238.415	Rollover Strength	Rest on (a) side or (b) roof with $\sigma < \frac{\sigma_Y}{2}$ and $\sigma < \frac{\sigma_{CR}}{2}$ in frame
	49 CFR 238.417	Side Loads	Static load 80,000 lbf to side sill and 10,000 lbf to belt rail over 8ft with $\sigma < \sigma_Y$ and $\sigma < \sigma_{CR}$ in frame
Historical Industry Standard	AAR S-034-69	Side Posts and Bracing	Minimum section modulus and material allowance
		Sheathing	Minimum thickness and material allowance
Current Industry Standard	APTA PR-SS-C&S-034-99, Rev. 2	Rollover Integrity	Rest on side or roof with $\sigma < \frac{\sigma_Y}{2}$ and $\sigma < \frac{\sigma_{CR}}{2}$ in frame
		Side Structure Framing & Sheathing	Minimum section modulus/thickness and material allowance
		Side Impact	Static load 40,000 lbf to side sill and 7,000 lbf to belt rail with $\sigma < \sigma_Y$ and $\sigma < \sigma_{CR}$ in frame

σ_Y = Yield Stress; σ_{CR} = Critical Buckling Stress

In general, the performance and design criteria shown in Table 1 consist of a static loading scenario (i.e., load cases) applied to specific structural elements. Schematics of the structural members in the sidewalls of exemplar single-level and multi-level passenger cars are shown in Figure 2 and Figure 3, respectively. The longitudinal support members include, from top to bottom, the roof rail, intermediate floor rail (multi-level), belt rail, and side sill. The vertical support members include the side posts and corner posts. The static side load cases are applied to the side sill and belt rail (longitudinal members) while the longstanding stress-based design criteria are applied to the side posts and corner posts (vertical members) as well as the sheathing (outer skin).

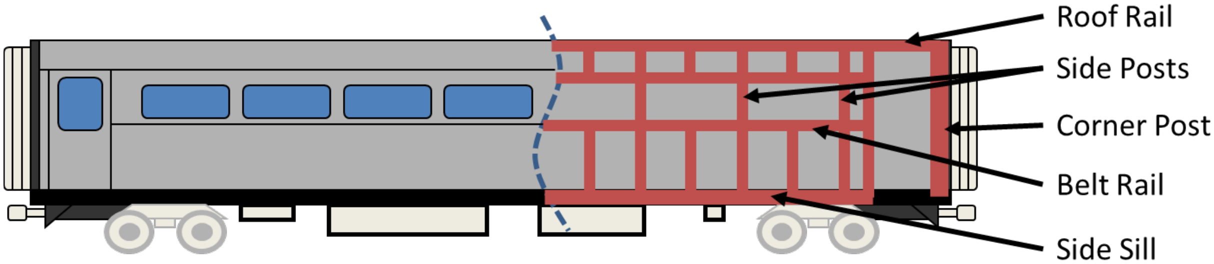

Figure 2. Schematic of Structural Members in Sidewall of Single-level Passenger Car

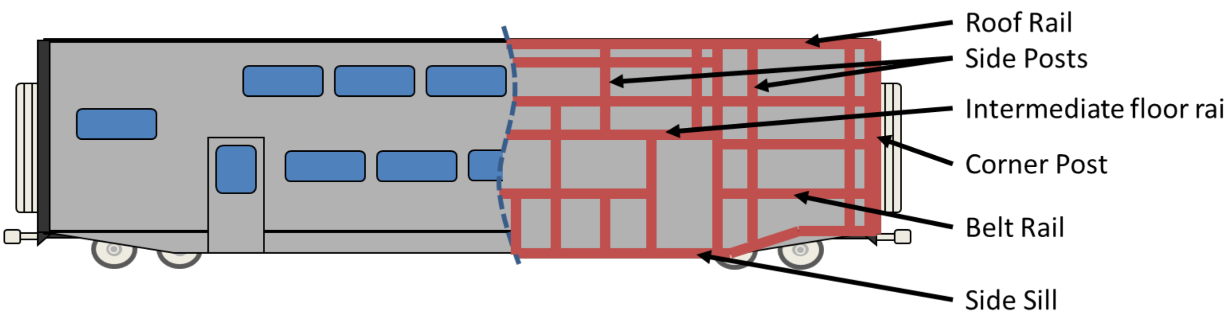

Figure 3. Schematic of Structural Members in Side Wall of Multi-level Passenger Car

2.1 Side Structure Framing and Sheathing

AAR S-034-69 contained a design criterion that affected sidewall stiffness. The sum of the section moduli of the sidewall posts at the weakest location in the sidewall was required to exceed a factor determined by multiplying the length of the sidewall by a constant. The requirement was applied to the section moduli calculated about a longitudinal and a transverse axis. Current Tier I equipment regulations (§238.217) and standards (APTA S-034-99) also contain similar requirements for vertical structural members. The existing design requirements essentially represent a global stiffness requirement for the entire side wall intended to prevent the side wall from flexing excessively under aerodynamic service loads.

In its 1999 rulemaking, FRA stated:

> *This section §238.217 was originally entitled ''Side impact strength'' in the NPRM [Notice of Proposed Rulemaking]. FRA has changed the section title because the requirements in this section principally refer to the stiffness of a car's side panel, rather than the panel's strength. That is, these provisions principally focus on preventing the side panel from flexing excessively under service loads. The greatest service loads acting on the sidewalls of a passenger car probably result from the aerodynamic loads of a train entering or exiting a tunnel, and from two trains passing each other at speed. Residually, these requirements will provide some protection in the event the passenger car's side panel is struck by an outside object.* [1]

Demonstrating compliance with the side structure stiffness requirement requires simple calculations based on the geometry of the side posts and sheathing as well as the materials of construction. With respect to crashworthiness, a major limitation of this global sidewall stiffness approach is that it is not directly apparent what measure of intrusion protection is provided by a sidewall designed to meet this requirement.

2.2 Rollover Strength

A passenger car resting on its side is a load case that was not included in AAR S-034, but has been included in the FRA Tier I and Tier III regulations (§238.215, §238.715), FRA Tier II regulations (§238.415), and APTA S-034-99. The requirements of these three current rollover regulations and standards are similar for passenger rail equipment. They specify the car should be able to resist twice its weight while resting on its side or roof as could occur after a derailment (shown schematically in Figure 4). For single-level cars, the car is supported at the longitudinal support members located at the roof (roof rail) and the bottom (side sill) when resting on its side. For multi-level cars, the car is supported at an additional longitudinal support member located at the intermediate floor.

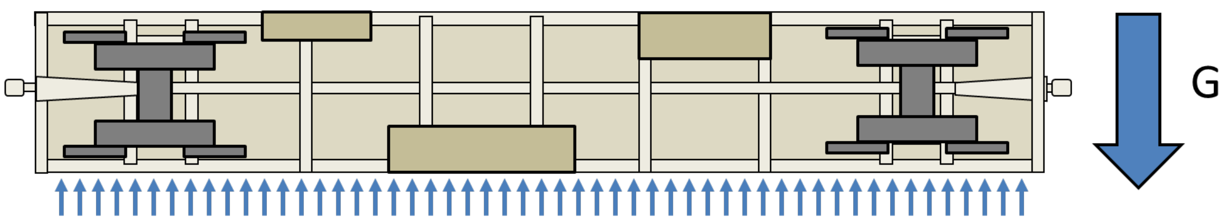

Figure 4. Schematic of Rollover Load Case, Carbody-on-Side

Stresses in the structural support members must not exceed either half the yield strength (σ_Y) or half the critical buckling strength (σ_{CR}). This approach is equivalent to requiring the structural members to be able to withstand twice the weight of the car without exceeding a critical stress value. The factor of 2 is an important safety factor since a dynamic rollover scenario, where a train is moving, would likely result in greater stresses than a rollover case with a stopped train. Local yielding of the outer skin (sheathing) is allowed but not if it results in intrusion into the occupied volume of the car.

This requirement is relevant to crashworthiness, as the rollover of a car during an accident is not a rare occurrence [5], [6], [7], [8]. While this load case does not evaluate a side impact scenario, designing a car with the capability to resist twice its weight would likely have an indirect benefit in a side impact scenario, especially in a case where the longitudinal support members are involved.

2.3 Side Loads

Local static side load requirements are specified in the APTA S-034-99 standard that applies to Tier I equipment and in regulations for Tier II equipment (§238.417). Local static side load requirements were not specified in AAR S-034-69, and were not adopted in FRA's Tier I regulations.

2.3.1 Tier I - APTA S-034

APTA S-034-99, which applies only to Tier I passenger equipment, prescribes two static side load the car must be able to resist without exceeding the critical stress value (either σ_Y or σ_{CR}):

40,000 lbf applied to the side sill and 7,000 lbf applied to the belt rail (the longitudinal support member in the side wall located near the bottom of the windows).

Each load is applied separately over an 8-ft length, and it is required that the structure withstand the loads regardless of where they are applied along the length of the carbody, as seen in Figure 5. Note that while this figure shows multiple loads applied simultaneously, in practice each 8-ft section of belt rail or side sill would be evaluated individually.

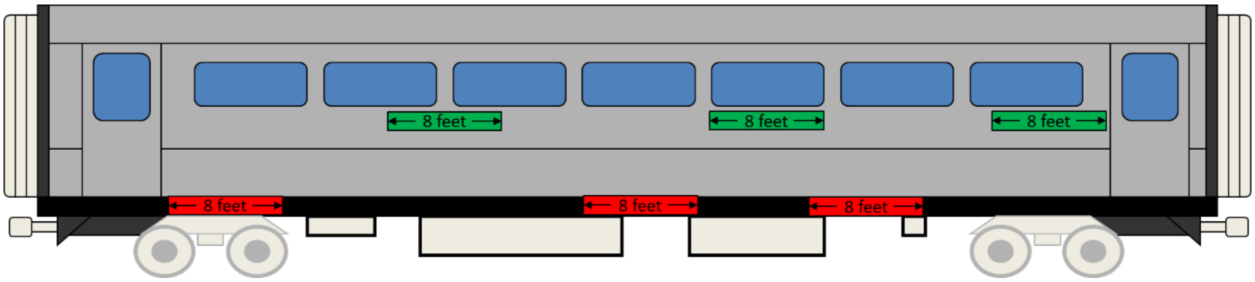

Figure 5. Schematic of 8-ft Side Sill and Belt Rail Loads, Showing Multiple Loading Positions

Annex A.2.7 of APTA S-034-99, Rev. 2 states the static side load cases were developed because it was observed that the side sill and belt rail could buckle in sideswiping accidents due to inadequate connections between the longitudinal structural members and either transverse or vertical structural members. Annex A.2.7 also states FRA had originally asked APTA to develop performance criteria intended to address an accident scenario involving a side impact from a heavy-duty truck, but the APTA Construction and Structural Subgroup[4] could not reach consensus on performance criteria for that accident scenario. The APTA Annex also states that "for the future, the APTA Construction and Structural Subgroup has committed to a more thorough investigation of the feasibility of designing rail vehicles for the FRA side impact scenario."

2.3.2 Tier II – §238.417

The Tier II side load requirements specify the car structure should resist an inward transverse load of 80,000 lbf applied to the side sill and 10,000 lbf applied to the belt rail (longitudinal support member at the bottom of the window opening in the side frame) without exceeding either σ_Y or σ_{CR}. The requirements are similar to what is specified in APTA S-034-99, except the loads are greater.

In the 1999 PESS section analysis on §238.417, FRA stated:

> *This section contains the requirements intended to resist penetration of the side structure of a passenger car by a highway or rail vehicle. The objective is to make the side of the passenger car strong enough so that the car derails rather than collapses when struck in the side by a highway or rail vehicle. If the passenger car can move sideways (derail), less structural damage and potential to injure train occupants will result.*

[4] This group is currently named the Construction and Structural Working Group.

And in the 1999 PESS section analysis on §238.217, FRA stated the following with respect to the Tier II requirements:

> *As noted above, the side strength of a passenger car is also highly pertinent to its crashworthiness in a side or raking collision with other railroad rolling stock. Examples could include a freight car rolling out of a siding or industrial spur into the side of a passenger train, or a locomotive moving in a terminal area passing through a switch and into the side of a passenger train. Recognizing these concerns, the Tier II provision on side strength does attempt to address the identified need. This provision was derived from discussions with Amtrak concerning development of specifications for its high-speed trainsets for the Northeast Corridor.*

From the two discussions in the section analysis, it is clear that the side loads are intended to address impacts from other rail vehicles and from highway vehicles. It is unclear how the static load cases compare to the dynamic loading conditions in side impact accidents with rail vehicles and highway vehicles.

3. Accident History

Two accident surveys were conducted to analyze the history of side impact incidents involving passenger trains. The FRA Highway-Rail Accidents Database [9] (6180.57) was used to compile incidents of grade crossing accidents (see Section 3.1) from 1986 to 2015. A less comprehensive but more focused survey was also conducted on side impact accidents which resulted in a large amount of structural damage to the side structure of passenger cars (see Section 3.2). Two accidents were selected from the focused accident survey for a summary of the sequence of events and discussion of findings related to side structure integrity.

3.1 Grade Crossing Accident Survey

In the PESS NPRM [10] and Final Rulemaking [1], the FRA summarized rail-highway grade crossing (GX) accidents using the publicly available Highway-Rail Accidents Database (6180.57) from 1986 to 1995. While the exact figures reported at that time could not be replicated by the authors over the same time period when accessing the database approximately 20 years later, the results were similar for 1986–1995, and two subsequent decades (1996–2005 and 2006–2015) of accident history are presented.

Three categories of accidents are defined by filtering the grade crossing accident database:

1. **All Motor Vehicle GX Accidents** category refers to grade crossing accidents involving a “passenger train” (TYPEQ = 2) and a highway motor vehicle (TYPVEH = A – J).
2. **Side Impact from Motor Vehicle** category adds an additional filter for rail equipment struck by highway user (TYPACC = 2).
3. **Side Impact from Heavy-Duty Truck** category narrows the motor vehicle type filter to only include “truck” and “truck-trailer” (TYPVEH = B – C). Note that “pick-up truck” (TYPVEH = D) was excluded from the last category to focus on “Heavy-Duty Trucks” such as a dump truck or semi-trailer truck weighing over 33,000 lbs.

Table 2 presents the counts of accidents after categorizing and filtering the grade crossing accidents involving passenger trains for 1986–1995, 1996–2005, and 2006–2015.

Table 2. Highway-Rail Grade Crossing Accidents Involving Passenger Trains and Highway Vehicles

Years	All Motor Vehicle GX Accidents	Side Impact from Motor Vehicle	Side Impact from Heavy-Duty Truck
1986 – 1995	2,781	424 (15.2%)	107 (3.8%)
1996 – 2005	2,287	262 (11.5%)	42 (1.8%)
2006 – 2015	1,656	168 (10.1%)	21 (1.3%)
Total	6,724	854	170

Figure 6 presents the data contained in Table 2 graphically. The category for *All Motor Vehicle GX Accidents* was changed to *All Other Motor Vehicle GX Accidents* because it now excludes counts from *Side Impacts from Motor Vehicles* and *Side Impacts from Heavy-Duty Trucks*.

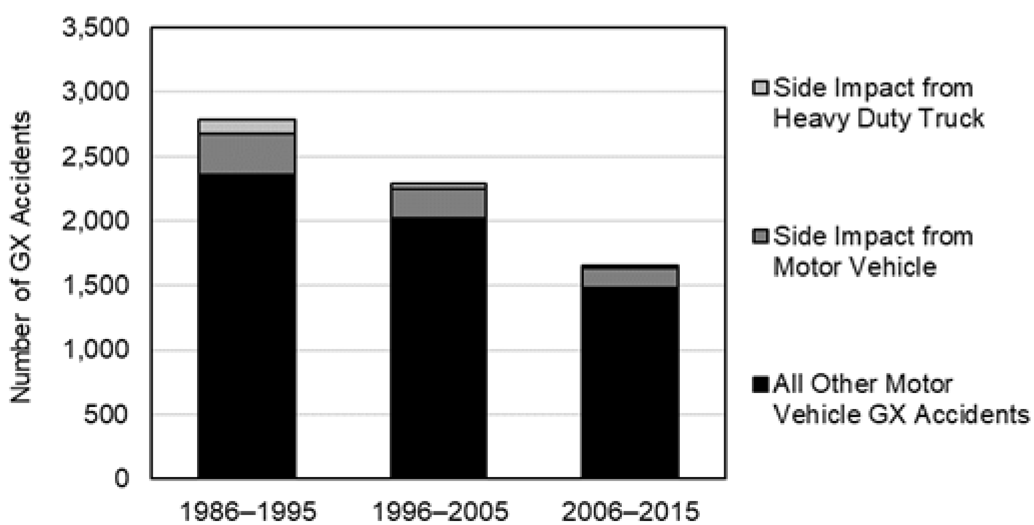

Figure 6. Highway-Rail Grade Crossing Accidents Involving Passenger Trains and Highway Vehicles

The frequency of reported grade crossing accidents involving passenger rail equipment decreased over the three decades included in the survey for every category. This decline in accident frequency is consistent with an overall trend for grade crossing accidents. The percentage of passenger train grade crossing accidents where the train was impacted by a "truck" or "truck-trailer" was also relatively low (2.5%). Also note that only one accident (Miriam, NV) was reported between 1986 and 2015 where either railroad employees or passengers on a passenger train were killed in a side impact collision at a grade crossing.

3.2 Focused Study of Side Impact Accidents

A focused accident study on side impacts to rail vehicles as a major source of passenger equipment damage was also performed as a part of this research program. This study only included accidents where the side impact was the primary event, such as a highway vehicle striking the side of a train at a grade crossing, as well as accidents where side impact occurred during a derailment subsequent to another primary incident.

The accident study is a useful tool for characterizing what types of impact scenarios tend to compromise the integrity of different car designs, i.e., single-level or multi-level. The results of the accident study also provide insight into the consequences of a side impact beyond localized side damage (e.g., tendency to derail, tendency to roll over, etc.). Train derailments and rollovers tend to result in a large number of injuries, as passengers experience a lateral acceleration relative to their surroundings, and suffer secondary impacts with the car interior; it is important to consider the potential for such an outcome during a side impact event.

The survey includes incidents in the US and Canada. Canadian incidents were included in the survey because railroad equipment operating on the general railroad system in Canada is structurally similar to equipment operated in the U.S. Indeed, in one incident cited in Table 3, Amtrak equipment was involved in an incident while operating in Canada.

It is worth noting that relatively few incidents are included in this survey. This survey focused on accidents in which an impact to the side structure of one or more passenger cars occurred, either as the primary collision or as a result of the collision or derailment scenario. This list does *not* include incidents where a passenger car came to rest on its side as a result of a collision or derailment, as that situation is being considered separately from side impacts (see Section 2.2 Rollover Strength). In general, reports by NTSB or the Transportation Safety Board (TSB) of Canada have been the primary information sources on side impact incidents. NTSB and TSB do not investigate every incident involving passenger rail equipment; thus, the results of the survey may be skewed toward more severe incidents which were investigated by either of the two bodies. Minor incidents, where the side structure was loaded but did not have its integrity seriously challenged, are not represented in this survey, as those incidents would not likely warrant a major investigation. For example, the survey does not include incidents where a highway passenger vehicle (e.g., car, pickup truck, SUV, etc.) struck the side of a passenger train. The survey does contain numerous reports from incidents involving a heavy highway vehicle (semi-truck) striking the side of a passenger train.

Table 3. Summary of Incidents Involving Side Impact of Passenger Cars

Year	Location	Type of Passenger Equipment	Incident Description	Reference
1975	Elwood, IL	Amtrak Turboliner single-level coaches	Highway truck into passenger train	[11]
1999	Hornepayne, Ontario	VIA Rail single-level coaches	Highway truck into passenger train	[12]
1999	Limehouse, Ontario	Amtrak Superliner multi-level coaches	Highway truck into passenger train	[13]
2006	Franklin, MA	MBTA multi-level coaches	Passenger train into highway truck	[14]
2007	Woburn, MA	MBTA single-level coaches	Passenger train into maintenance-of-way (MOW) equipment	[15]
2011	Miriam, NV	Amtrak Superliner multi-level coaches	Highway truck into passenger train	[2]
2016	Chester, PA	Amtrak Amfleet coaches	Passenger train into MOW equipment	[16]

3.2.1 Elwood, IL

In 1975, a highway dump truck traveling at approximately 35 mph (while braking) struck the side of an Amtrak Turboliner train traveling at approximately 71 mph in Elwood, Illinois [11]. The dump truck skidded and overturned during the impact event. A combination of the impact force and debris from the dump truck caused 4 out of 5 single-level coach cars to derail, leading to 45 passenger injuries but no fatalities. The collision is illustrated schematically in Figure 7.

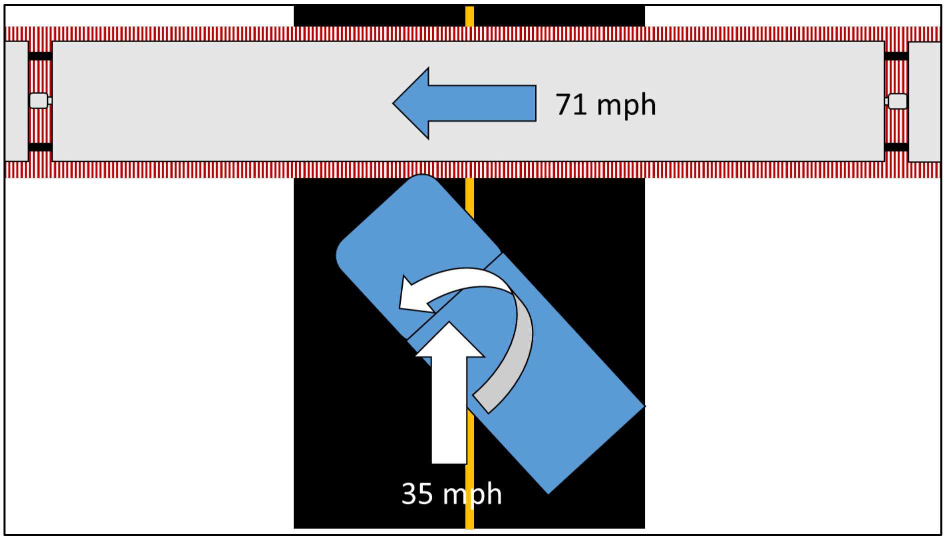

Figure 7. Schematic of Elwood, IL, Highway-Rail Accident

According to the National Transportation Safety Board (NTSB) report, the damage to the train cars was described as:

> *[i]mpact damage to the second car was restricted to the left rear side of the car… The damaged area was 24 feet 6 inches long, about 6 feet high, and about 8 inches deep at its deepest point. Two double-pane windows were shattered completely and a third had only its outer pane shattered. In the area of impact, the floor was deformed slightly, a pair of seats had rotated partially, and a folding tray was deformed to the right. The floor and seats were littered with broken window glass. There were no signs of side or roof panel buckling or deformation of the overhead baggage racks.*
>
> *The third car was damaged at its left front corner. At that point, the lower-outside paneling had been crinkled and had been marked with horizontal striations, and the window was broken. The left front corner of the car was crushed beginning about 8 feet above the top of rail and extending upward for 21 feet. Some additional deformation occurred just above that crushed area.*

3.2.2 Miriam, Nevada

In a similar accident in 2011, the sidewalls of two, multi-level, Amtrak Superliner cars were breached in a highway-railroad grade crossing collision in Miriam, Nevada [2]. A semi-trailer truck pulling two unloaded side-dump trailers, traveling at an estimated 26–30 mph (while braking), impacted the side of the train, which was traveling at 77 mph. The impact is illustrated schematically in Figure 8.

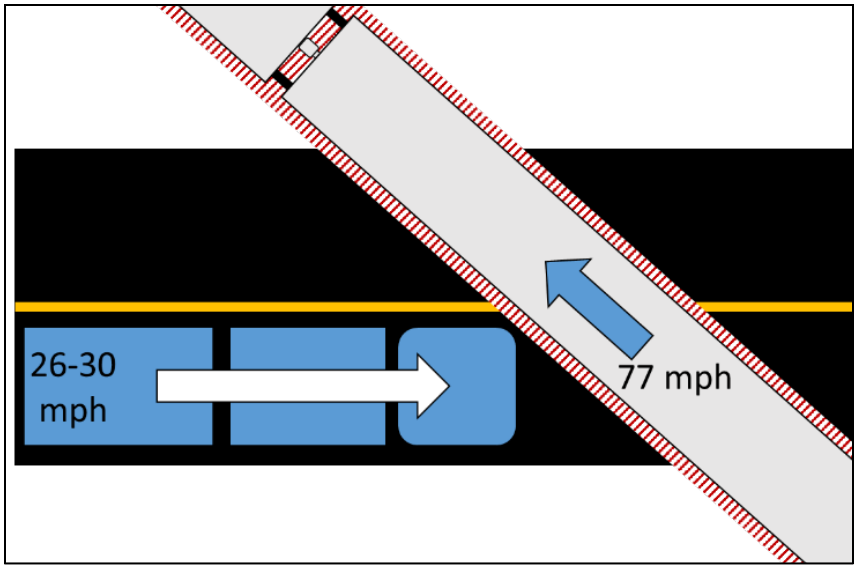

Figure 8. Schematic of Miriam, NV, Highway-Rail Accident

The highway vehicle impacted Amtrak Superliner Crew Sleeper Car 39013 at its lower level, and struck Coach Car 34033 on its upper level. The accident killed the driver of the semi-trailer truck, the train conductor, and 4 train passengers; 15 train passengers and 1 train crewmember were injured.

Figure 9 shows the sleeper car impacted first by the semi-tractor. The low floor of the passenger car was overridden, resulting in a large loss of occupant volume space. Figure 10 shows the coach car that was impacted second by the first side-dump trailer of the highway vehicle, which also resulted in a large loss of occupant volume space. A fire also developed after the impact, damaging the two passenger cars shown below and a third car, which is not shown. The NTSB report claimed the side-dump trailer was able to reach the upper level of the second impacted car because the trailer impacted the rear of the tractor unit and "ramped over" it, causing raking damage to the upper level of the passenger car.

Figure 9. Sleeper Car 39013 from Miriam, NV, Accident Showing Damage from Highway Tractor Unit (FRA Photo)

Figure 10. Coach Car 34033 from Miriam, NV, Accident Showing Damage from Highway Trailer (FRA Photo)

While there was nothing remarkable about the design of the semi-tractor which was crushed during the incident, the side-dump trailers, used for mining, were fairly rigid and largely intact after the accident. Figure 11 shows the second side-dump trailer after the accident.

Figure 11. Second Side-dump Trailer from Highway Vehicle (FRA Photo)

3.2.3 Discussion

The passenger train did not derail in the Miriam accident, and the multi-level cars suffered a significant loss of occupant survival space, leading to cases of fatal blunt force trauma. Passengers outside these impact zones suffered only minor injuries. In the Elwood accident, the train did derail, did not lose a large amount of occupant survival space, but had a larger number of non-life-threatening passenger injuries.

While these two accidents occurred under similar circumstances involving highway vehicles of similar masses impacting the trains at similar speeds, the outcomes were quite different. These accidents indicate the need to consider both the structural arrangement of the sidewall, including the height of the side sill or other major longitudinal members, and the post-accident kinematics of the struck car (e.g., tendency to derail or roll over) in evaluating potential improvements to overall occupant safety during side impact events.

The high speed (70+ mph) and relative direction of travel contributed to the severity of the Miriam, Nevada, accident. Figure 8 shows the heavy-duty truck was traveling obliquely against the direction of travel of the passenger train. This likely contributed to the truck overriding the lower floor and the trailer ramping into the upper floor. If the truck and passenger train were traveling obliquely in the same direction of travel, the effective closing speed would have been reduced, and the impact could have pushed the truck out of the way of the passenger train. In the case of the Elwood accident, the truck and passenger train were traveling obliquely in the same direction at the time of impact and the truck was pushed sideways, away from the train. The Miriam accident was a realization of a concern raised during the 1999 PESS rulemaking that a heavy-duty truck could override the low floor of a multi-level passenger car. However, the *trailer* of the highway vehicle *also* caused a loss of occupant survival space in the upper level of the passenger car – which was not discussed in the rulemaking.

The severity of the heavy-duty truck side impact in the Miriam accident should not be considered commonplace. The grade crossing accident survey (Table 2) found a total of 170 side impact accidents from heavy-duty trucks over the entire 30 year span examined, and Miriam was the only accident which resulted in a fatality on board a passenger train.

4. Passenger Car Fleet Estimates

The current standards and regulations that address side structure integrity were issued in 1999. At the time of the rulemaking, FRA stated, "most of the passenger cars in the United States possess floor structures similar to the Amfleet rail car, positioned at a similar height above the rail." [1] The Amfleet is a single-level railcar of conventional construction; thus, the fleet in 1999 was believed to be made up of mostly single-level cars of conventional construction.

In the time since the 1999 rulemaking, new commuter rail operation start-ups have begun using new equipment designs, and railroads that existed at the time of the 1999 rulemaking have updated their rolling stock rosters. Therefore, it is important to understand whether the fleet makeup has changed significantly since 1999.

In particular, this study sought to determine whether the fleet was still comprised mostly of conventional, single-level coaches, as described in the 1999 rulemaking, or whether multi-level or alternative designs had since become more prevalent. A 1996 report on passenger rail equipment suspension characteristics [17] included a car count as of January 1, 1994. Data from that car count were reviewed and, where necessary, adjusted based on current information. These data were used as a baseline and assumed to approximately represent the U.S. passenger car fleet at the time of the 1999 rulemaking.

In 2016, the authors performed a car count (see Appendix A) to reflect the state-of-the-fleet using publicly available rolling stock information from numerous sources. No railroads were contacted during this phase of the study, so these figures should be considered an approximate count of the entire fleet.

This count only included Tier I (operations at or below 125 mph) passenger cars operating on the general railroad system of the U.S. It did not include Tier II (operations between 125 and 150 mph) vehicles, privately-owned passenger cars, or Port Authority Trans-Hudson (PATH) equipment (PATH had been excluded from the 1994 car count). The cars identified in this count were grouped into three broad categories: (1) single-level cars, (2) multi-level cars, and (3) alternatively designed vehicles.

The 2016 car count identified 29 different railroad operators of passenger equipment in the U.S. The 1994 car count identified 14 railroads operating passenger equipment at that time. The estimated passenger car fleet is broken down by car type in Table 4 and Figure 12.

Table 4. Estimated Passenger Car Fleet in the U.S.

Car Type	Count in 1994	Count in 2016
Single-level	4,472 (70%)	4,367 (56%)
Multi-level	1,875 (29%)	3,254 (42%)
Alternatively-designed	45 (1%)	122 (2%)
Total	6,392	7,743

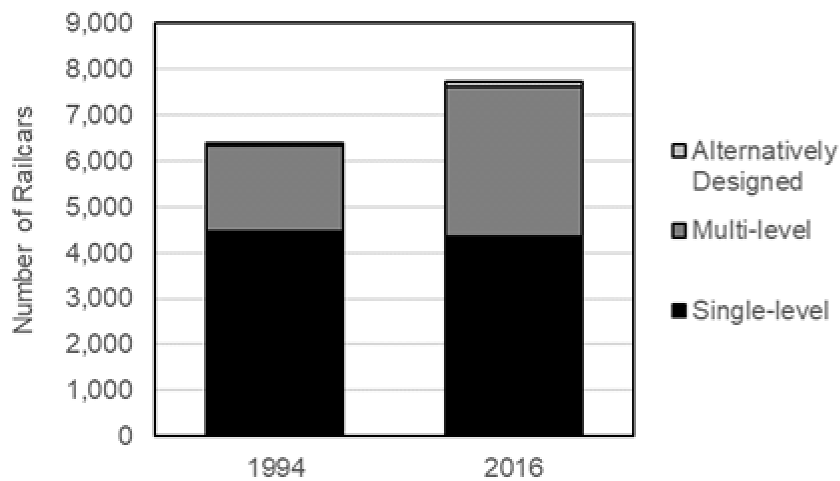

Figure 12. Estimated Passenger Car Fleet in the U.S.

These results indicate that since 1994, the passenger car fleet has grown by approximately 1,350 cars, or 21 percent. While the majority of the passenger fleet is still made up of single-level cars, the number of multi-level cars has nearly doubled since 1994 and now compromise approximately 42 percent of the passenger fleet. The increase in the number of multi-level cars indicates a need to ensure that current standards and regulations, some of which are based on longstanding design practice, remain relevant to the entire fleet. If new or modified criteria or evaluation procedures for side structure integrity are considered, they should be relevant and applicable to the full range of equipment in the fleet. Additionally, because of the inherent structural differences between single- and multi-level passenger cars, it is also important to consider whether a side impact presents the same hazard to each design.

5. Relevant Evaluation Loads for Other Transportation Applications

This study considered existing side structure integrity evaluations for passenger vehicles used in other modes of transportation. This analysis sought to understand the working experience developed in the automobile industry in developing and applying side-impact criteria and evaluation procedures that could be of benefit in evaluating passenger railcars under side impact conditions. In some ways, the framework of standards and regulations for passenger railcars parallels those for passenger highway vehicles. The Insurance Institute for Highway Safety (IIHS) is an industry group, similar to APTA, which develops structural safety standards for automobiles. Similar to the FRA, NHTSA is a USDOT agency that promulgates mode-specific side structure integrity regulations.

This study also considered existing regulations and standards for side impact loads applicable to non-passenger-carrying rail vehicles. Several current standards for locomotive fuel containers (diesel tanks and natural gas fuel tenders) include a requirement to consider a side impact load. While not directly applicable to passenger rail vehicles, unless such a vehicle features a fuel tank (e.g., a diesel multiple unit), these load cases represent an impact that could occur within the railroad operating environment. Since locomotives and passenger cars operate in the same environment, a similar side impact could occur to either a fuel tank or to a passenger railcar. Thus, the side impact threats applicable to locomotive fuel tanks, natural gas fuel tenders, and passenger railcars in a railroad environment could be expected to be similar.

Finally, this study considered the results of full-scale impact tests and companion FE modeling, assessing the impact response to fixed infrastructure (e.g., highway bridge piers) when struck by a heavy highway vehicle. This research was included in the present study to understand the impact load environment presented by a heavy highway vehicle, such as the impact force and vertical position of the load. By better understanding the load environment presented by a highway vehicle impacting a fixed, relatively rigid barrier, the effects of side impact loading on a passenger rail vehicle's sidewall could be extrapolated.

5.1 Side Impact – IIHS – Side Impact Test Protocol

IIHS has standardized crash test protocols for evaluating side impacts. Its test protocols are not requirements for any new vehicles. Rather, IIHS performs its array of crash tests to calculate safety ratings for different passenger vehicle designs to inform consumers and encourage manufacturers to produce safer vehicles to remain competitive.

The IIHS side impact test protocol involves striking a stationary passenger car, light truck, or SUV with a specially-designed moving deformable barrier (MDB) ram cart weighing 3,300 lbs, at a speed of 31.1 mph [18]. This combination of mass and speed results in an impact with approximately 106,000 ft-lbf of kinetic energy. In recognition of the tendency of the struck vehicle to overturn, pickup trucks and SUVs may have an "outrigger" added to the passenger side of the vehicle to limit the amount of roll the vehicle can undergo during the test.

The stationary car is instrumented, and two specialized side-impact anthropomorphic test devices (ATDs), also known as crash test dummies, are positioned within the vehicle. IIHS determines its vehicle rating using a combination of injury criteria derived from ATD measurements and from measurements of the intrusion of the side pillar of the vehicle into the occupant volume [19].

5.2 Side Impact – NHTSA – Side Impact Protection Regulation

NHTSA's Federal Motor Vehicle Safety Standards (FMVSS) contain requirements for side impact testing to be performed on new passenger vehicles that meet particular criteria. These requirements are codified at 49 CFR 571.214 and apply to relevant highway vehicles. The side impact requirements include quasi-static door crush resistance requirements, a dynamic side impact test using an MDB and side-impact ATDs, and a side impact into a rigid pole by a vehicle with side-impact ATDs inside.

The quasi-static door crush resistance test specifies an 18-inch crush distance at a specific location on the door. The pass/fail criteria for these tests specify minimum average crush forces over the first 6 inches, over the first 12 inches, and over the entire crush distance.

The dynamic impact test uses an MDB vehicle weighing 3,015 lbs at a speed of 33.5 mph. This combination of mass and speed results in an impact with approximately 113,000 ft-lbf of kinetic energy. The dynamic side impact test does not include any requirements or limitations on intrusion into the occupied volume; however, door separation is evaluated. This test's pass-fail criteria are based upon ATD measurements. The test protocol defines upper limits on various injury criteria, and the measurements from the ATDs must be shown to not exceed these criteria.

The 16–20 mph side impact pole test does not include requirements or limitations on intrusion into the occupied volume. The criteria do include limitations on door separation. This test's pass-fail criteria are based upon side-impact ATD measurements. The test protocol defines upper limits on various injury criteria, and the measurements from the ATDs must be shown to not exceed these criteria.

The NHTSA and IIHS approaches differ in that IIHS uses a single test to examine both the injury criteria obtained through ATD measurements as well as the structural response through intrusion measurements. NHTSA measures resistance to intrusion through its door crush test, and measures ATD response in the moving deformable barrier side impact test and the pole test. While both NHTSA and the IIHS evaluate relevant passenger vehicles by performing dynamic side impact tests, the specific test vehicles, their orientations, and the test protocols are not identical.

No direct comparison can be made between passenger highway vehicles and passenger rail equipment with respect to side structure design and performance criteria. However, the approach taken in implementing quasi-static and dynamic side structure test protocols while quantifying intrusion into the occupied volume is informative for planning the analyses (see Section 6) in the next phase of this study.

5.3 Side Impact – Locomotive Fuel Tanks

The industry standards AAR S-5506 [20], APTA SS-C&S-007-98 [21], and Federal Regulations at 49 CFR 238 Appendix D [22] prescribe loads cases for diesel fuel tanks used on locomotives in the U.S. Each of these regulations or standards contains a "side impact" load case that places a lateral load on the side of the fuel tank, as might be encountered during a side impact involving the locomotive's fuel tank. The specific requirements of each standard or regulation are summarized in Table 5, adapted from a previously published study on locomotive fuel tanks [23].

Table 5. Summary of Side Impact Load Cases for Locomotive Fuel Tanks

	AAR S-5506	APTA SS-C&S-007-98	49 CFR 238 App. D
Load Location	Longitudinal center of the fuel tank, 30 in. above the rail	Any location along fuel tank, 30 in. above the rail	Longitudinal center of the fuel tank, 30 in. above the rail
Load Magnitude	200,000 lbs, distributed over a 6-in. x 48-in. area.	200,000 lbs, distributed over a 6-in. x 48-in. area.	200,000 lbs, distributed over a 6-in. x 48-in. area.
Pass/Fail Criterion	Without exceeding the ultimate strength	Fuel tank must avert a rupture and fuel release.	Without exceeding the ultimate strength

While the wording differs slightly from one standard or regulation to another, the critical similarities are that the load magnitude is 200,000 lbs, distributed over a 6-inch high by 48-inch wide area, applied 30 inches above top of rail (ATOR). Appendix D to 49 CFR Part 238 says, in part, "In a side impact collision by an 80,000 pound Gross Vehicle Weight tractor/trailer at the longitudinal center of the fuel tank, the fuel tank shall withstand, without exceeding the ultimate strength, a 200,000 pound load (2.5g) distributed over an area of six inches by forty-eight inches (half the bumper area) at a height of thirty inches above the rail (standard DOT bumper height)." Thus, it is apparent that the "side impact" load cases are specifically intended to address an impact from a heavy highway vehicle into the side of the fuel tank. As both Appendix D and APTA SS-C&S-007-98 apply to diesel locomotives in passenger rail service, it is reasonable to assume that if a fuel tank on a passenger locomotive is threatened by a side impact from a heavy highway vehicle, so too would the coaches hauled by that locomotive.

5.4 Side Impact – AAR M-1004 Standard for Natural Gas Fuel Tenders

AAR has a technical advisory group working to develop standard M-1004, currently in draft form as of this writing [24]. This standard contains design requirements for fuel tenders used to carry and supply either compressed natural gas (CNG) or liquefied natural gas (LNG) as a locomotive fuel. This standard contains a load case intended to demonstrate the ability of the protective housing around the piping and valves to withstand an impact from a heavy highway vehicle, as could occur at a highway-rail grade crossing. The standard allows the housing to be evaluated using one of two methods. In the first, a dynamic test or simulation subjects the tender to a side impact from an 80,000-lb highway vehicle traveling at 40 mph. After this impact, the tender must not be breached.[5] The standard contains no requirement for the tender to remain

[5] M-1004 contains more specific required results for various types of fuel tender designs, such as intermodal-style tenders, tank-car-style tenders, etc.

upright or on the rails following this prescribed impact, but does contain separate load cases to address tender rollover.

As an alternative to this dynamic evaluation, M-1004 contains a prescriptive load case in which a 400,000-lbf load is applied to the protective housing. This 400,000-lbf load is applied over an area measuring 6 inches high by 48 inches wide, centered 33 inches ATOR. The load must be supported without exceeding the ultimate tensile strength of any material in the tender, and without causing buckling. Further, the prescriptive load case contains additional requirements on the thickness and strength of material used to construct the protective housing's doors.

The placement and distribution of this load is similar to the side loading cases contained within the various diesel fuel tank standards discussed in Section 5.3. The load magnitude for fuel tenders has been increased to 400,000 lbf, compared to the 200,000 lbs required by diesel fuel tanks. The load area of 6 inches by 48 inches is identical across the fuel tank and tender requirements. The load location is similar, but in the fuel tank requirements the load is centered 30 inches ATOR, and in M-1004 the load is centered 33 inches ATOR. No explanation is given in M-1004 for the increase in load magnitude and load application height compared to the diesel fuel tank requirements.

However, in a separate report the load cases contained in the draft M-1004 standard were evaluated using FE analyses [25]. This report provides insight into the load placement and magnitude used in M-1004. This report states the initial evaluation of the natural gas tender loads sought to use the same load magnitude and location as required for a diesel fuel tank. The report states the modelers "initially evaluated this loading condition at the 200,000 lb load level for the protective housing on the Legacy Tender Design 1 model. The interpretation of this rule is that the load should start at a height of 30 in. from the top of the rail…" [25] Since the height of the diesel fuel tank load is distributed over a 6-inch vertical distance, a lower edge placed at 30 inches ATOR would result in a load centered 33 inches ATOR.

The load magnitude was increased from 200,000 lbs to 400,000 lbs based on the initial results of simulating both the dynamic collision scenario and a 200,000-lb static load:

> *A comparison to the grade crossing collision scenario determined that the initial 200,000 lbs prescriptive load is much easier to pass and would not provide for a comparable level of protection. The simulation shows that this proposed requirement could probably be met with a protective housing structure design that would not be sufficient to protect in the more detailed collision simulation. Based on a comparison of the analyses, the prescriptive loading condition is less severe than the performance-based grade crossing scenario.*
>
> *A further evaluation of the appropriate loading for the grade crossing was determined by a simplified analysis of the physics of the collision. The average force required to stop an 80,000 lbs vehicle from 40 mph over a 0.4-second collision duration is 366,000 lbs. Therefore, a final analysis was performed to ensure that the reinforced protective housing could withstand a 400,000 lbs prescriptive load in the same configuration.* [25]

The discussion contained in the analysis report of the M-1004 load cases provide several insights into the development of the load scenario and its relevance to passenger equipment sidewall loading. In particular, the 400,000-lb load magnitude was chosen based on a simple physics calculation of kinetic energy and average deceleration. Recall from Section 5.3 that the 200,000-

lb load applied to a diesel fuel tank was also derived from an 80,000-lb vehicle weight and an assumed deceleration of 2.5g. Decelerating the tractor-trailer from 40 mph to a stop over 0.4 second, as was done in the LNG tender side impact analysis report, corresponds to an average deceleration of approximately 4.6g.

The deceleration behavior of the highway vehicle depends not only on its characteristics, but also on the compliance of the object it is striking. An impact between a 40-mph tractor-trailer and a rigid, immovable wall will result in a higher average deceleration than an impact between the same tractor-trailer and a deformable or movable object.

5.5 Passenger Railcar Superstructure Impact – End Frame Loads

For passenger railcars, current regulations at 49 CFR 238.211 ("Collision posts") and 238.213 ("Corner posts") and APTA S-034 [4] require an evaluation of loading to the end structure of the railcar above the level of the floor. While not strictly a side structure evaluation, the end frame loads are included in this report as relevant loads already applicable to passenger railcars. The existing end frame regulations differ slightly if the railcar undergoing evaluation is a cab car, multiple-unit (MU) locomotive, or a trailing coach. In the case of a cab car or MU locomotive, the leading end of the train could be the car's end frame, leaving it susceptible to a direct longitudinal impact. Thus, the load requirements are more demanding for leading ends of cab cars and MU locomotives. For trailing coaches, end loads can still develop due to car-to-car interactions following a collision or derailment.

The basic approach of evaluating the end structures of passenger cars for an impact above the level of the floor has been a longstanding U.S. practice, with AAR S-034 containing requirements for the section modulus and shear value for the collision posts at each end of the car [3]. The end structures of conventionally designed U.S. passenger cars typically consist of vertical posts at the corners of the car ("corner posts"), and vertical collision posts located at approximately 1/3 the width from each corner of the car. In recognition of modern railcar engineering taking advantage of aerodynamic leading ends and/or crash energy management (CEM) features, in 2010 FRA promulgated alternative, performance-based regulations to evaluate the dynamic performance of the end frames of cab cars and MU locomotives. By moving to a scenario-based evaluation, FRA intended to make the regulations design-neutral and more widely applicable to a variety of railcar designs while maintaining a level of safety equivalent to that provided by the conventional regulations. The conventional regulations remain in place to permit conventional end frame designs to be evaluated using the traditional combinations of load magnitudes and locations that include corner and collision posts as design features.

The conventional corner post regulations applicable to all passenger railcars require an end frame to be evaluated by applying, individually, several forces of varying magnitude at different heights on the post. Each load magnitude and location is paired with a pass/fail criterion, setting a limit on the stress that can develop in the post as a result of the applied load. Further, all load cases require the post to be loaded at any angle ranging from longitudinal inward (i.e., perpendicular to the end frame) to lateral inward. (i.e., perpendicular to the sidewall) for each load magnitude and location.

Cab cars and MU locomotives must meet additional corner post load requirements, including one that each post be able to absorb a prescribed amount of energy when loaded in the longitudinal direction at a specific location by a loading fixture having prescribed dimensions. The energy-absorption requirement must be met without resulting in more than 10 inches of permanent deformation into the occupied volume and without the post or its connecting structure experiencing "complete separation." This "large deformation" load case is not applied in the lateral direction.

The conventional collision post requirements applicable to all passenger cars are similar to those for corner posts, with a series of paired load magnitudes and heights applied to each post. Cab cars and MU locomotives must meet additional requirements for their collision posts. The collision post loads applicable to cab cars and MU locomotives are applied in the longitudinal direction, and within ±15 degrees of the longitudinal direction. An energy-absorption requirement evaluation using a static load on MU and cab car collision posts is similar to that applicable to cab car corner posts.

For cab cars and MU locomotives, a dynamic performance-based evaluation may be used in lieu of both the conventional corner and collision post load cases. The dynamic impact scenarios use a proxy object (a rigid cylinder of prescribed diameter and length) at a defined height above the floor of the car to apply load to the post. The velocity of the proxy object, or the cab car, may be chosen to fulfill the energy-absorption requirement. As the alternative performance-based requirements do not make mention of "posts" at specified locations, they are more widely applicable to passenger car end structures of varied shapes and design methodologies. The pass/fail criteria for both the corner and collision post dynamic scenarios include a minimum amount of energy absorption, a maximum amount of intrusion into the occupied volume, and a restriction of "no complete separation" of the post or its connections to the carbody.

5.6 Heavy Highway Vehicle Impacts to Bridge Piers

During the course of this study, the research team became aware of research conducted to investigate dynamic impacts of heavy highway vehicles into highway bridge piers [26, 27, 28]. While not directly relevant to the strength requirements of passenger railcar sidewall structures, the bridge pier research could provide relevant information on the magnitude and location of impact forces resulting from a heavy highway vehicle running into the side of a relatively stiff structure. These forces and their locations could then be considered in the context of the fuel tank and fuel tender load cases and their overall applicability to side impacts on passenger railcars.

The first phase of the bridge pier research was conducted entirely using FE simulations of different single-unit and tractor-trailer vehicles into simulated bridge piers [26]. Various approaches to modeling the highway vehicle ballast were examined as well as the effects of impact speed and bridge pier diameter. Of most relevance to passenger railcar side impacts are the force-time, force-displacement, and force-versus-height results. This prior study demonstrated that for both a single-unit dump truck and an articulated tractor-trailer impacting a rigid bridge pier there are two distinct peak forces that occur. The first peak force is typically the lower of the two. This peak force corresponds to the engine block (refer to Figure 13) impacting the crushed components between it and the bridge pier. As crush progresses, the second peak force occurs when the dump body or trailer, depending on the vehicle configuration, loads the pier through the crushed structure at the front end of the vehicle. For high-speed impacts, the peak force associated with deceleration of the dump body or trailer is typically higher than the peak force associated with the engine block's initial deceleration.

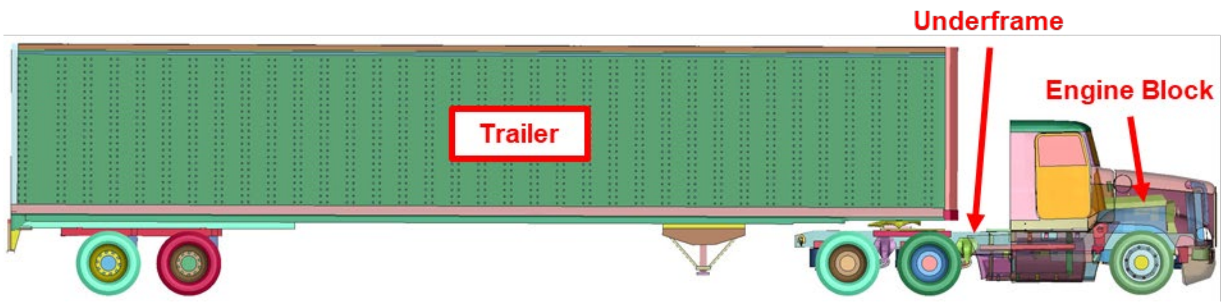

Figure 13. Annotated Tractor-trailer Model with 181-inch Wheelbase [29]

Published in 2011, the second phase of the bridge pier impact research included full-scale testing of highway tractor-trailers impacting an instrumented, simulated pier [27]. Full-scale testing indicated that during a 50 mph collision between a 79,640-lb tractor-trailer and a 36-inch-diameter, concrete-filled pipe simulating a highway pier, the peak truck force acting on the pier was approximately 700 kips (using a 10 ms moving average). The pier was supported on two load cells aligned with the direction of impact, and thus the time-averaged height of the centroid of force could also be calculated for this test. The load position was found to vary throughout the course of the impact event, but remained greater than 48 inches above ground for a significant portion of the impact event.

Subsequently, a separate research effort proposed performance-based loading definitions for bridge piers based on simulations of heavy highway vehicles striking bridge piers. That work discussed the existing static load recommendation for bridge piers, stating "[t]he current AASHTO-LRFD (2012) specifications recommend designing a bridge pier vulnerable to vehicular impacts for an equivalent static force of 600 kips (2,670 kN) applied in a horizontal plane at a distance of 5.0 feet above the ground level." [28]

6. Side Impact Performance Criteria and Modeling

NTSB has recommended that new side impact criteria proposed by FRA should provide “measurable improvement compared to the current regulation for minimizing encroachment to and loss of car occupant survival space.” [2] To be able to provide measurable improvement, FRA would first need to establish the baseline performance of cars designed to meet the current longstanding design criteria, codified in §238.217 for Tier I equipment.

Since the current side structure requirement for Tier I equipment is based on design criteria, it is difficult to “translate” from a design that meets the material and geometric requirements to the expected performance of such a design in an impact scenario, as there are many different designs that meet the design criteria. It is likely that the baseline performance of the existing fleet of passenger cars that are compliant with the existing regulations varies greatly.

FRA stated in its 1999 PESS rulemaking that it is preferable for the side structure of a passenger car to be strong enough to result in derailment when impacted by heavy-duty truck at high speed as opposed to losing occupant survival space. The NTSB’s recommendation also focuses on preventing the loss of occupant volume through the crushing of the side structure. However, in the extreme case where a passenger car has an infinitely stiff sidewall, the car would have an increased tendency to roll over or push sideways if struck with sufficient force. While the goal of a side-impact performance requirement is to improve passenger safety by reducing the risk of loss of occupant volume at the impact site, tipping the car onto its side may introduce additional risks. Indeed, NTSB has also recommended that FRA “[c]onduct research to evaluate the causes of passenger injuries in passenger railcar derailments and overturns and evaluate potential methods for mitigating those injuries, such as installing seat belts in railcars and securing potential projectiles.” [6] NTSB has also recommended that FRA “[d]evelop a performance standard to ensure that windows (e.g., glazing, gaskets, and any retention hardware) are retained in the window opening structure during an accident and incorporate the standard into 49 Code of Federal Regulations (CFR) 238.221 and 49 CFR 238.421 to require that passenger railcars meet this standard.” [7] The level of risk to which passengers are exposed must be considered when comparing occupant space preservation and rollover tendency in determining the baseline performance criteria.

To characterize rollover tendency, design information on a variety of passenger cars is required. At a minimum, it is likely that such information includes data on mass and moments of inertia for the carbody, center of gravity (CG) position, and details on the suspension system to evaluate the likelihood of rollover.

To develop a performance requirement, impact conditions must be prescribed against which sidewalls would be evaluated. This will require establishing not only a particular scenario or multiple scenarios, but also justifying that choice with a particular impact condition that could be encountered in rail operations. Based on the focused study of accident data presented in Section 3.2, several side-impact scenarios have occurred in passenger rail operations:

Scenario 1: Side impact from heavy-duty truck (e.g., Miriam, NV, June, 2011) [2]

Scenario 2: Heavy-duty truck struck by passenger train, resulting in truck swinging around and impacting the side of a passenger car (e.g., Franklin, MA, October 2006) [14]

Scenario 3: Side swipe (raking) from other train (e.g., Glendale, CA, January 2005) [30]

Scenario 4: Passenger train derailment and pile-up (e.g., Bourbonnais, IL, March 1999) [31]

The accident scenarios described above are depicted schematically in Figure 14.

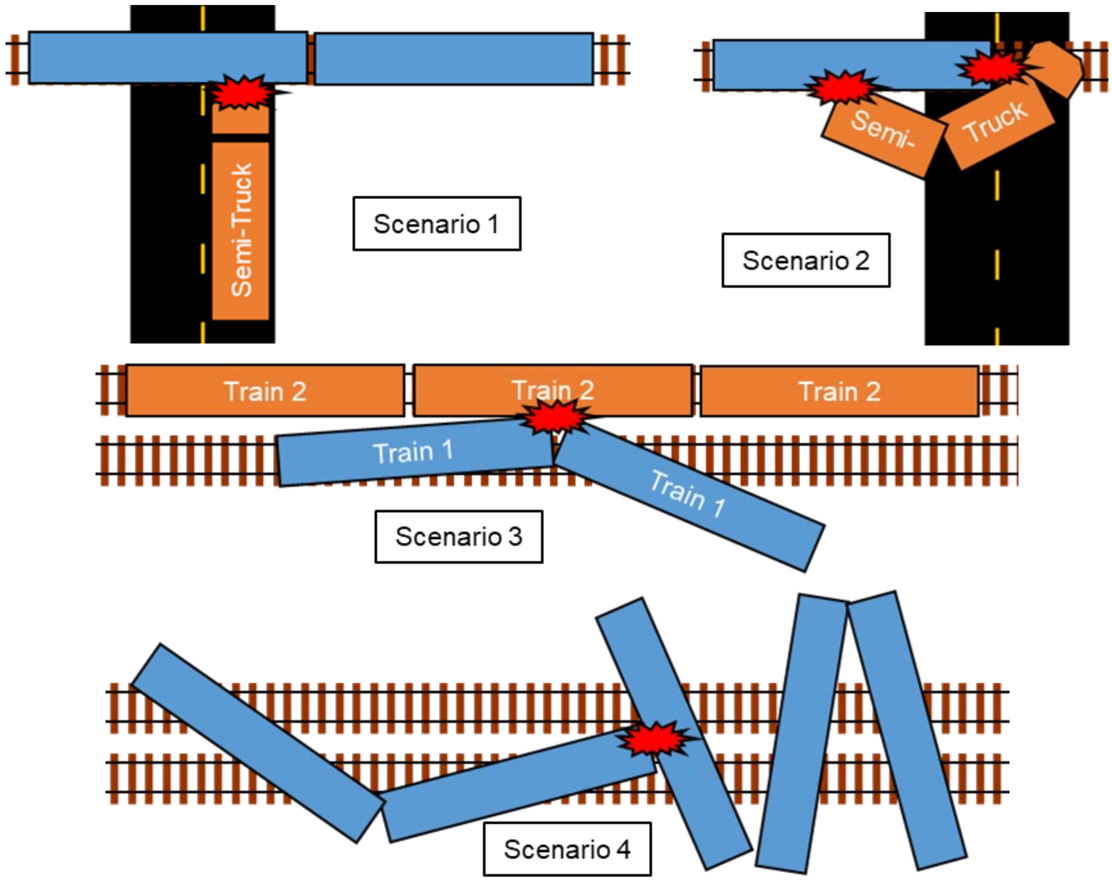

Figure 14. Side-Impact Scenarios Involving (1) Side Impact from Heavy-duty Truck, (2) Struck Heavy-duty Truck Swinging Around to Impact Side of Passenger Car, (3) Sideswipe (raking) from Other Train, (4) Passenger Car Derailment and Pile-Up

While much of the published discussions from the FRA, NTSB, and APTA have focused on Scenario 1 (side impact from heavy-duty truck), it is not apparent which of the above scenarios is either most likely to be encountered nor which scenario presents the greatest challenge to side structure integrity. While distinct from one another, these scenarios do have certain similarities. In each case, the side of the impacted railcar experiences a localized loading. In Scenarios 1–3, the struck train may be traveling along the rails at the time of impact, and thus may be loaded along the length of the car during the course of the impact. However, at each point in time the loading is localized. This condition is an important distinction, as the current regulations and standards require a carbody-on-side load case in which the entire length of the carbody is loaded simultaneously.

In Scenarios 1–3, the struck railcar is on its rails at the time of impact. Thus, derailment as a result of a side impact is an undesirable effect that should be avoided if possible. However, in Scenario 4, the struck railcar may have already derailed and become part of a pileup. While further rollover of the derailed car is undesirable, as a practical concern rollover cannot be evaluated with any confidence, as the support condition under a derailed car will vary greatly from the support provided by the wheels and trucks of a car on the rails.

Should an appropriate alternative side structure evaluation scenario be developed, it would logically be based on the accident history and the need to apply the scenario to existing equipment initially. At the same time, the scenario should be general enough to be readily applied to alternatively designed equipment or future equipment whose configuration is not represented by the current fleet. A performance standard is typically more readily applied to a variety of designs than a prescriptive design standard; however, care must be taken to ensure that alternative designs (e.g., double-walled extruded aluminum carbodies, vehicles with non-conventional underframes, etc.) can be evaluated in a manner that is both reasonable and consistent with the intent of the potential standards.

Several simplified analyses were performed as a part of this study and are described in this section. While future work could include detailed modeling (e.g., dynamic impact simulations, detailed stress and deflection FE analyses), simplified models were employed as a first step of examining several behaviors of sidewall structures. These simplified analyses made use of publicly available information on existing passenger railcars to consider generalized sidewall behaviors; i.e., the analyses are not examining the performance of any specific carbody design.

Based on the review of Scenarios 1–3, several undesirable outcomes were identified that could result from an impact to the sidewall when the struck railcar is upright and on the rails. These underscore the importance of considering the railcar as a system, and not focusing solely on the sidewall as an isolated structure. The undesirable outcomes identified in this study are presented approximately in the order of the load path from the point of impact to ground:

1) The sidewall structure is breached, allowing intrusion into occupied volume.
2) The attachments of the sidewall to either the roof or floor structures fail, allowing intrusion into occupied volume.
3) The sidewall and its attachments do not fail, but are flexible enough to allow unacceptable intrusion into occupied volume.
4) The underlying floor or roof structures supporting the sidewall fail, allowing intrusion into occupied volume.
5) The sidewall does not deform excessively, but the carbody derails and rolls over, resulting in lateral accelerations and secondary impacts.
6) The sidewall does not deform excessively, and the carbody does not derail, but the rail or track structure fails as a result of the lateral impact loads, resulting in lateral accelerations and secondary impacts.

An initial set of simplified analyses was performed to examine the relative positions of the heights of the lateral load applications from existing standards with the positions of typical longitudinal sidewall members in passenger railcar sidewalls. A second set of simplified analyses included simplified elastic stress, deflection, and stiffness calculations for sidewall posts to estimate their typical load-carrying capabilities. Separate simplified models examining lateral impact force versus rollover were also executed.

6.1 Height of Typical Design Features and Impact Forces

In its 1999 PESS rulemaking, FRA mentioned that passenger cars with a low floor could be more susceptible to occupant space intrusion from a heavy-duty truck. The passenger car count from Section 4, Passenger Car Fleet, revealed that the number of multi-level (low floor) passenger cars has increased since the time of the PESS final rule, while the number of single-level passenger cars has remained fairly constant. The number of alternatively designed railcars has also increased over the period reviewed. Additionally, several different alternatively designed railcars feature low floors, either as part of a multi-level vehicle or as part of a vehicle featuring a full or partial low-floor in a single-level design. Establishing the range of equipment susceptible to a side impact is a first step in determining the baseline level of performance of passenger rail equipment in service today.

As an example, Figure 15 shows the floor heights of three rail vehicles. Using drawings available from NTSB's accident dockets for accidents in Miriam, Nevada (HWY-11-MH-012), Glendale, California (DCA-05-MR-009), and Bridgeport, Connecticut (DCA-13-MR-003), two multi-level and one single-level car floors are represented schematically. Additionally, using design information on a manufacturer's publicly available website, floor heights of an exemplar, partial low-floor, alternatively designed passenger railcar are also shown [32]. The solid bars represent the floor heights as estimated from the information available in the NTSB dockets. To the left of each floor schematic is a shape representing the front end of a highway semi-tractor (Scenario 1). Again, using data available in NTSB's docket for the Miriam accident, the truck is assumed to have a bumper height that spans 18 inches to 31 inches above ground level, and a front-end height of 79 inches. Recall that for a passenger locomotive fuel tank (Section 5.3) the impact from a heavy highway truck is assumed to be distributed over a 6-inch height, centered at 30 inches ATOR. Thus, the fuel tank side impact load spans a height of 27 inches to 33 inches ATOR. Similarly, for a natural gas fuel tender (Section 5.4) the bumper height spans 30 inches to 36 inches ATOR. It is assumed that the height of ground is at the same height as the top of the rail, for simplicity.

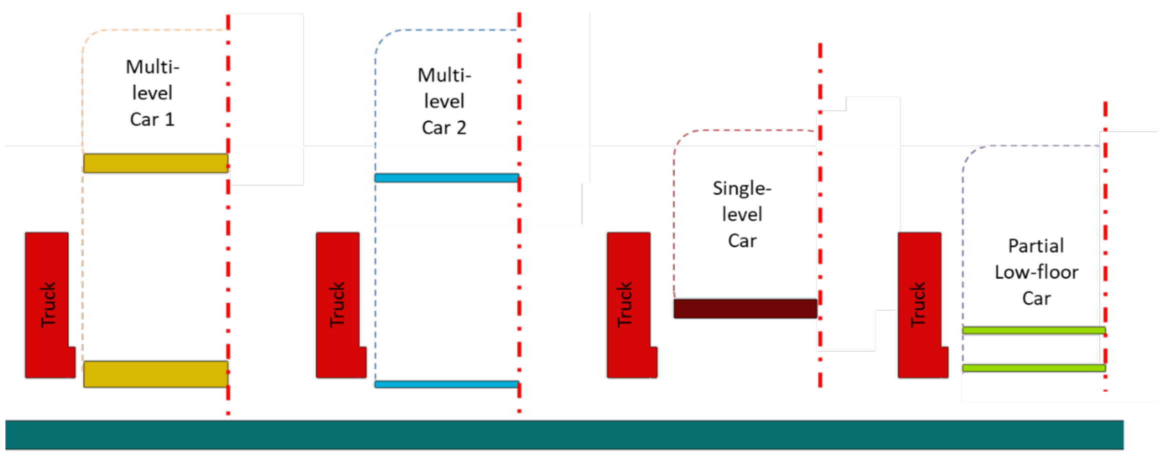

Figure 15. Approximate Floor Heights and Heavy-duty Truck Front-End Height

Note that the example shown in Figure 15 is merely for illustration of one potential accident scenario with only one carbody design variable between single-level and multi-level equipment considered, i.e., floor height. The other accident scenarios shown in Figure 14 would also require considerations of relative floor height. Also, there are numerous other differences in carbody designs besides floor height that could greatly affect performance in any side impact accident scenario, such as sidewall material strength, reinforcement spacing, and the spacing and sizes of the windows.

In Scenario 1 (side impact from heavy-duty truck), additional studies would be required to evaluate the trade-off between intrusion prevention and likelihood of rollover. The kinetic energy of an impacting highway vehicle must be dissipated during an impact. This kinetic energy will result in some combination of deformation of the heavy-duty truck, deformation of the side structure of the passenger car, and displacement of the car in the direction of travel of the heavy-duty truck. If the passenger car were infinitely strong (i.e., no deformation occurs in the side structure), all of the energy imparted to the car would be used to displace the car (i.e., roll over). Depending on the design parameters, CG height and suspension characteristics, a carbody may exhibit more of a tendency to roll over in certain impact scenarios. While it may be preferable to allow a car to derail as opposed to lose occupant survival space, it is not clear which outcome would present a greater hazard to occupants.

Figure 16 contains an image of the 194-inch-wheelbase, publicly available, LS-DYNA FE tractor model [29], with dashed lines indicating the lower (~2.3 ft) and upper (~5.1 ft) limits of the engine block height. This single component – a solid, massive object – is believed to represent a substantial threat to any struck object. While the frame rails are typically also a structural component below the engine block, they may buckle during an impact, limiting the amount of force they can transmit.

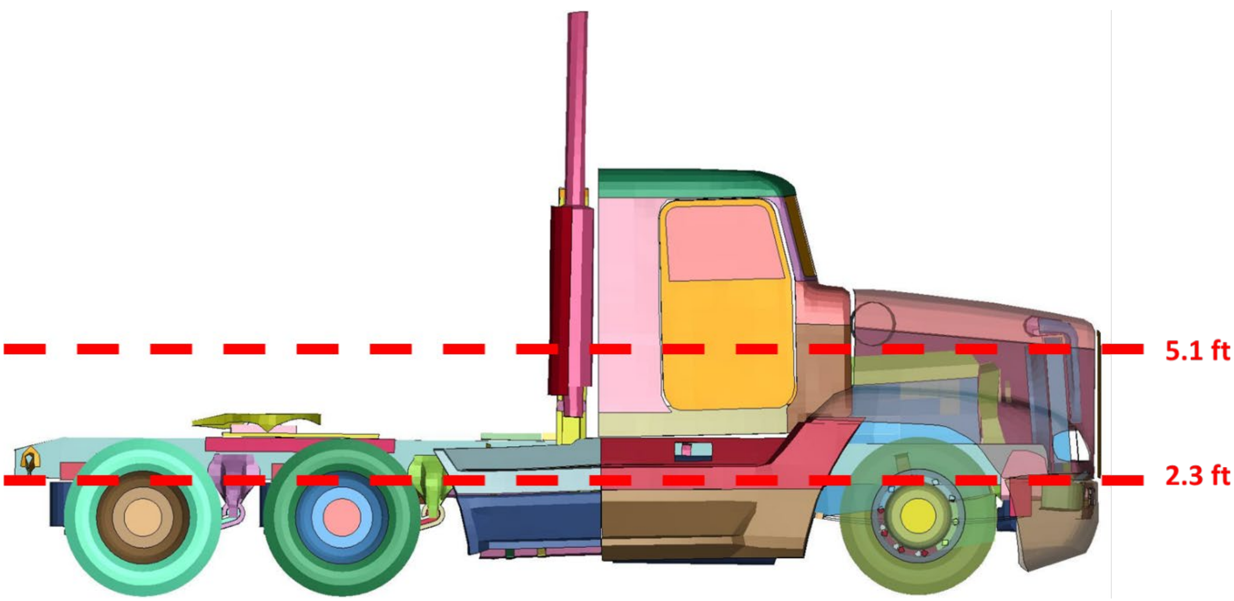

Figure 16. Annotated Semi-tractor Model with 194-inch Wheelbase [29]

Figure 17 shows a combination of the schematic floor heights from Figure 15 and the semi-tractor model from Figure 16. This figure demonstrates that the low-floor sections of the multi-level and partial low-floor alternatively designed passenger cars are below the bottom of the engine block. The alternative high-floor and single-level high floor are both located above the bottom of the engine block, but below its upper limit. Thus, some portion of the engine block can bear directly on the sidewall at the height of floor attachment, likely engaging the floor members without relying on the sidewall to transmit impact loads down into the floor.[6] Note that for the multi-level car, the upper and lower floors exist within the same cross-section in the center of the car, while the partial low-floor car has a high-floor section at the end and a low-floor section in its center. While not shown in this figure, some multi-level cars may also feature occupied volume on an intermediate level (i.e., above the lower level but below the upper level) at its ends.

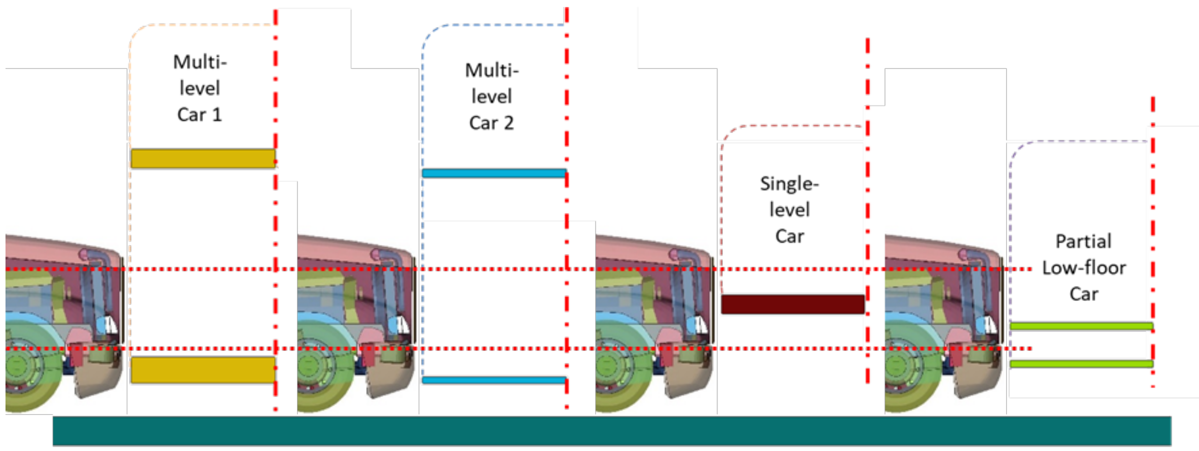

Figure 17. Approximate Floor Heights and Semi-tractor Model Components

6.2 Estimated Stiffness and Intrusion Limits

As described in Section 5.1, IIHS includes in its side impact ratings a measure of the permanent deformation of the side pillar of the vehicle into the passenger compartment. The distance from the interior of the B-pillar is measured relative to the centerline of the driver's seat. A longer distance after the impact test corresponds to a higher rating. IIHS rates vehicles according to four categories with corresponding clearance distances, as summarized in Table 6. These post-crash distances are measured over a vertical span from the base of the B-pillar to a point 54 cm (21.26 in.) above the H-point[7] measurement with the seat in the full-rear and full-down position [19].

[6] Impact with the upper portion of the engine block could allow the highway vehicle to "underride" the side of the coach, leading the coach to roll over. Evaluation of this behavior is beyond the scope of this report, as underride is not a direct loading of the sidewall.

[7] The H-point (or hip-point) is a theoretical point corresponding to the pivot point between the torso and upper leg of the ATD used in the crash test.

Table 6. Post-crash Clearance Distances from IIHS Side Impact Test Rating Guidelines [19]

	Upper Limit of Post-crash Distance cm (in.)	Lower Limit of Post-crash Distance cm (in.)
Good	Pre-crash distance	12.5 (4.92)
Acceptable	12.5 (4.92)	5.0 (1.97)
Marginal	5.0 (1.97)	0.0
Poor	0.0	< 0.0

The lateral loads identified in previous regulations and standards for passenger railcar side structures (Section 2.3) or other relevant transportation standards (Sections 5.3 through 5.5) can be used to estimate intrusion distances for comparison with the guidelines in Table 6. The ratio of a prescribed lateral load and an intrusion limit provides an estimate of the stiffness required by a sidewall to support that load without exceeding that intrusion limit. However, the limits shown in Table 6 are the residual clearances between the interior B-pillar and the centerline of the driver's seat. A more practical measurement for estimating sidewall stiffness is the intrusion distance, not the residual clearance. Thus, before the values in Table 6 can be used, the initial distance between the centerline of a window-side seat and the interior sidewall of a passenger railcar must be estimated. A value of 25 cm (9.8 in.) was used in these calculations, which assumes a 50-cm (19.7 in.)-wide seat attached directly to the interior wall [33]. Thus, the allowable intrusion is the difference between 25 cm and the residual distance reported in Table 6. A second set of calculations was performed using a 33-cm (13 in.) sidewall-to-seat centerline clearance, which assumes a 66-cm (26 in.)-wide seat attached directly to the interior wall.

The stiffness calculations presented in this section assume the seats do not translate with the sidewall, a conservative assumption for intrusion. In reality, deformation of the wall will result in the seat being pushed with the deforming wall. For loading above the position of the seat attachment, the sidewall may deform inward faster than the base of the seat can be pushed sideways, leading to intrusion into the seating space. This situation is complex, as passengers may be injured either by loss of occupant space owing to intrusion of the space above or below the seat, by rapid lateral acceleration as the seat is moved by the deforming sidewall but the passenger remains compartmentalized within his/her seat, or by secondary impacts if the passenger is thrown sideways as a result of the lateral acceleration of the seat.

Table 7 contains the estimated stiffness that a structure would be need to possess for various combinations of reference standard loads and allowable intrusion based on the IIHS rating criteria for an initial sidewall-to-seat centerline distance of 25 cm.

Table 8 contains similar stiffnesses for an initial sidewall-to-seat centerline distance of 33 cm. A smaller intrusion limit corresponds to a higher rating. Thus, for a given applied load the stiffness must increase to limit the amount of intrusion. Similarly, as the lateral load magnitude becomes larger the sidewall must be stiffer if a given intrusion limit is to be maintained.

Table 7. Estimated Stiffnesses for Various Load and Deflection Combinations

(25-cm seat centerline)

Reference Standard	Lateral Load Magnitude in Reference Standard (kips)	Stiffness Range for Intrusion Limit "Good" (kips/in.)	Stiffness Range for Intrusion Limit "Acceptable" (kips/in.)	Stiffness Range for Intrusion Limit "Marginal" (kips/in.)	Stiffness Range for Intrusion Limit "Poor" (kips/in.)
APTA – Belt Rail	**7**	> 1.4	0.9 – 1.4	0.7 – 0.9	< 0.7
CFR Tier II – Belt Rail	**10**	> 2.0	1.3 – 2.0	1.0 – 1.3	< 1.0
CFR Tier I – Corner Post (coach, at roof attachment)	**20**	> 4.1	2.5 – 4.1	2.0 – 2.5	< 2.0
CFR Tier I – Corner Post (coach, 18 in. above underframe)	**30**	> 6.1	3.8 – 6.1	3.0 – 3.8	< 3.0
APTA – Side Sill	**40**	> 8.1	5.1 – 8.1	4.1 – 5.1	< 4.1
CFR Tier I – Corner Post (cab, any height)	**45**	> 9.1	5.7 – 9.1	4.6 – 5.7	< 4.6
CFR Tier II – Side Sill	**80**	> 16.3	10.2 – 16.3	8.1 – 10.2	< 8.1
CFR Tier I – Corner Post (cab, 18 in. above underframe)	**100**	> 20.3	12.7 – 20.3	10.2 – 12.7	< 10.2
CFR Tier I – Corner Post (coach, top of underframe)	**150**	> 30.5	19.0 – 30.5	15.2 – 19.0	< 15.2
Locomotive Fuel Tanks (30 in. ATOR)	**200**	> 40.6	25.4 – 40.6	20.3 – 25.4	< 20.3
CFR Tier I – Corner Post (cab, top of underframe)	**300**	> 61.0	38.1 – 61.0	30.5 – 38.1	< 30.5
AAR M-1004 Natural Gas Fuel Tender (centered 33 in. ATOR)	**400**	> 81.3	50.8 – 81.3	40.6 – 50.8	< 40.6
AASHTO-LRFD (2012) Bridge Piers (60 in. above ground)	**600**	> 121.9	76.2 – 121.9	61.0 – 76.2	< 61.0

Table 8. Estimated Stiffnesses for Various Load and Deflection Combinations (33-cm seat centerline)

Reference Standard	Lateral Load Magnitude in Reference Standard (kips)	Stiffness Range for Intrusion Limit "Good" (kips/in.)	Stiffness Range for Intrusion Limit "Acceptable" (kips/in.)	Stiffness Range for Intrusion Limit "Marginal" (kips/in.)	Stiffness Range for Intrusion Limit "Poor" (kips/in.)
APTA – Belt Rail	**7**	> 0.87	0.63 – 0.87	0.54 – 0.63	< 0.54
CFR Tier II – Belt Rail	**10**	> 1.2	0.91 – 1.2	0.77 – 0.91	< 0.77
CFR Tier I – Corner Post (coach, at roof attachment)	**20**	> 2.5	1.8 – 2.5	1.5 – 1.8	< 1.5
CFR Tier I – Corner Post (coach, 18 in. above underframe)	**30**	> 3.7	2.7 – 3.7	2.3 – 2.7	< 2.3
APTA – Side Sill	**40**	> 5.0	3.6 – 5.0	3.1 – 3.6	< 3.1
CFR Tier I – Corner Post (cab, any height)	**45**	> 5.6	4.1 – 5.6	3.5 – 4.1	< 3.5
CFR Tier II – Side Sill	**80**	> 9.9	7.3 – 9.9	6.2 – 7.3	< 6.2
CFR Tier I – Corner Post (cab, 18 in. above underframe)	**100**	> 12.4	9.1 – 12.4	7.7 – 9.1	< 7.7
CFR Tier I – Corner Post (coach, top of underframe)	**150**	> 18.6	13.6 – 18.6	11.5 – 13.6	< 11.5
Locomotive Fuel Tanks (30 in. ATOR)	**200**	> 24.8	18.1 – 24.8	15.4 – 18.1	< 15.4
CFR Tier I – Corner Post (cab, top of underframe)	**300**	> 37.1	27.2 – 37.1	23.1 – 27.2	< 23.1
AAR M-1004 Natural Gas Fuel Tender (centered 33 in. ATOR)	**400**	> 49.5	36.3 – 49.5	30.8 – 36.3	< 30.8
AASHTO-LRFD (2012) Bridge Piers (60 in. above ground)	**600**	> 74.3	54.4 – 74.3	46.2 – 54.4	< 46.2

The simplified stiffness calculations show a wide range of sidewall stiffness targets are possible, depending on the desired intrusion limit and lateral force to be resisted. Additionally, a target stiffness is only one part of any criteria for evaluating sidewall intrusion. The example loads shown in Table 7 and Table 8 may be applied at different heights on the carbody. A prescribed location above either top-of-rail, the floor of the car, or another convenient reference point would also need to be prescribed. This can be defined as an absolute value (e.g., 30 in. ATOR, such as the locomotive fuel tank load) or defined with respect to a particular structural member on the carbody (e.g., acting over the full height of the belt rail).

Both approaches have benefits and drawbacks. By prescribing an absolute height, any load requirement assumes the railcar will have a structure at that height. This may or may not be the case, particularly if a loading condition is meant to be applicable to a wide variety of carbody designs. Referring to a specific structure on the carbody allows the absolute position to vary based on the specifics of the design undergoing evaluation, but also presumes that the design will have such a member. This may be a challenge in future designs, as an alternatively designed railcar may not feature the same arrangement of posts and beams that conventional railcars have had. It may also be appropriate to consider different load magnitudes acting at different heights, similar to the approach already used in the APTA and CFR Tier II side sill and belt rail loads.

The area over which the load is applied would also need to be defined in any future evaluation criteria. This area will affect the way the load is distributed across the sidewall structure, and may affect localized behaviors in the vicinity of the area of load application.

Additionally, it is highly desirable to include a criterion or criteria limiting the allowable stresses that may develop in the carbody under the applied loading. A stiffer sidewall may develop higher stresses than a softer sidewall for a given load, as the carbody is experiencing less deflection. However, if the stresses exceed some critical value (e.g., buckling stress or ultimate tensile strength), the structure may experience a failure that allows for uncontrolled loss of occupied volume.

Finally, it may be appropriate to consider whether there are other undesirable outcomes to any loading scenario that would require additional criteria to define. For example, a large lateral load applied high on the sidewall can create a large moment. This moment will tend to cause the carbody to roll in response to the lateral load. Several adverse outcomes may be possible, including rollover of the car or derailment if the loads transmitted through the suspension into the rail are sufficiently large.

6.3 Exemplar Calculations of Single-post Stress, Deflection, and Stiffness

As a simplified means of investigating the practical load-carrying capacity of typical sidewall posts, a series of stress and deflection calculations were performed. These calculations assumed a conventional sidewall made up of identical posts uniformly spaced along the length of the carbody. This concept is illustrated schematically in Figure 18. While Section A-A passes through the corner posts, these posts are not included in either the section modulus requirements in the current Tier I regulations and APTA Standard, nor in the simplified post calculations presented in this report.

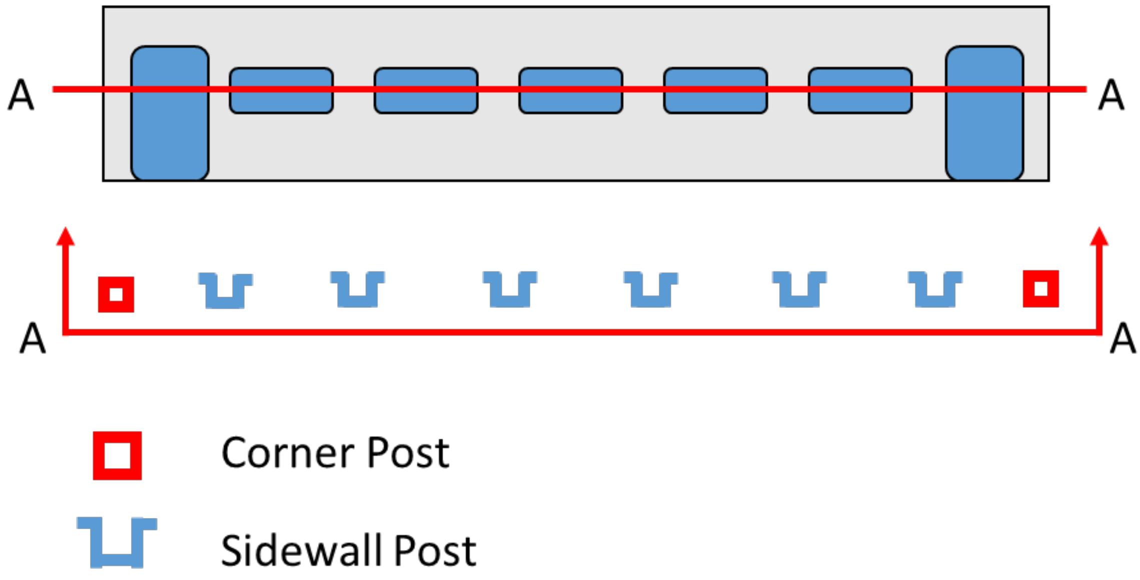

Figure 18. Generalized Conventional Passenger Railcar Sidewall Post Arrangement

6.3.1 Properties of Generalized Sidewall

The carbody and sidewall parameters used in the simplified calculations are shown in Table 9. These values are intended to represent a generalized, conventional single-level passenger railcar in operation in the U.S. and do not represent any particular railcar design.

Table 9. Carbody and Sidewall Parameters Used in Simplified Calculations

Parameter	Value	Units
Length Over Couplers	85	ft
Distance between End Panel Centers on Sidewall	81	ft
Height of Sidewall Posts (side sill to roof rail)[8]	65	in
Number of Sidewall Posts	15	-
Sidewall Post Material	Elastic Steel	-
Yield Strength of Sidewall Steel	60/80/100	ksi

The profile of each post used in these simplified calculations is shown in Figure 19. The dimensions from this figure are defined in Table 10.

[8]This simplified design assumes the lateral members above the height of the roof rail have an arched shape, leading to increased roof height toward the centerline of the car.

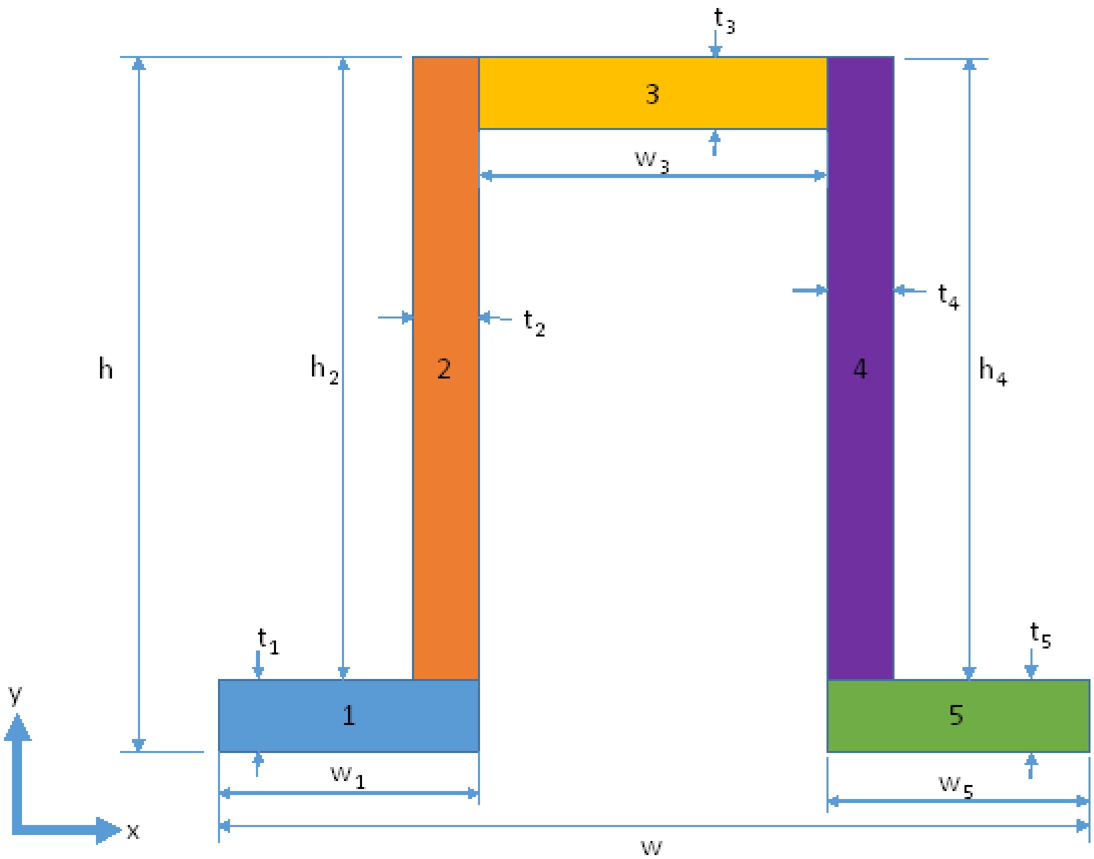

Figure 19. Beam Profile for Sidewall Posts Used in Calculations

Table 10. Dimensions of Beam Profile Used in Calculations

Label	Dimension (in.)
t_1	0.125
w_1	1.75
h_2	2.625
t_2	0.125
t_3	0.125
w_3	1.75
h_4	2.625
t_4	0.125
t_5	0.125
w_5	1.75
h	2.75
w	5.25

6.3.2 Verification of Generalized Sidewall Section Moduli

The simplified sidewall was compared against the section moduli requirements given in 49 CFR 238.217(a) and (b) to show it meets existing regulations. As discussed previously, the regulations require the total section moduli of all sidewall posts on each side of the car for loading about a lateral and a longitudinal axis to exceed a minimum value. The minimum value for each loading direction is a function of the distance between end panels at each end of the sidewall and the yield strength of the sidewall post material. The calculations used to establish the minimum moduli about these two axes are shown in Equation 1 and Equation 2.

Equation 1. Minimum Required Total Section Modulus for Bending about X-axis

$$RequiredModulus_{xaxis} = \frac{0.3 \cdot End\ Panel\ Center\ Distance}{Strength\ Factor}$$

Equation 2. Minimum Required Total Section Modulus for Bending about Y-axis

$$RequiredModulus_{yaxis} = \frac{0.2 \cdot End\ Panel\ Center\ Distance}{Strength\ Factor}$$

The requirements given in 49 CFR 238.217(a)(4) allow the required modulus in each direction to be adjusted based on the ratio of the yield strength of the material used in the sidewall post to the yield strength of mild, open-hearth steel. The CFR does not provide a set value for the yield strength of mild, open-hearth steel. Section 5.2.2.1.1 of APTA SS-C&S-034-99, Revision 2, gives a value of 32,000 psi for the yield strength of mild, open-hearth steel. This value was used throughout these calculations. The strength factor is calculated according to Equation 3.

Equation 3. Strength Factor

$$Strength\ Factor = \frac{Sidewall\ Post\ Yield\ Strength}{Mild\ Open\ Hearth\ Steel\ Yield\ Strength}$$

Since three different values of sidewall post yield strength were assumed in these example calculations, three different strength factors were calculated. The values of strength factor and the resulting minimum required modulus for each assumed value of yield strength are shown in Table 11.

Table 11. Yield Strength, Strength Factors, and Minimum Required Moduli for Simplified Sidewall Calculations

Sidewall Post Yield Strength (psi)	Strength Factor (unitless)	Minimum Required Modulus for Bending about X-axis (in^3)	Minimum Required Modulus for Bending about Y-axis (in^3)
60,000	1.875	12.96	8.64
80,000	2.5	9.72	6.48
100,000	3.125	7.776	5.184

The total section modulus of the sidewall is simply the section modulus of each post multiplied by the number of posts contained in the weakest horizontal section of the sidewall (e.g., the section passing through the window openings). Note that the section modulus calculation is based entirely on the geometry of the cross-section of the post; neither the height of the post nor its material strength appear in this calculation. Thus, the total section modulus per car sidewall is independent of the assumed yield strength. While a typical sidewall also includes an outer metallic skin, any structural contribution of such skin is excluded in the section modulus calculations. Further, note that if a sidewall post is asymmetric, the section modulus for an inward-applied load may differ from the section modulus for an outward-applied load. While not stated explicitly in the regulation or standard, a thorough evaluation should verify that the lesser of these two moduli still meet the minimum requirements established by the regulations.

Exemplar section modulus calculations for the generalized post are shown in Appendix B. The generalized post shown in Figure 19 had a minimum section modulus about the X-axis of 0.94 in^3 and a minimum section modulus about the Y-axis of 0.79 in^3. Each generalized sidewall contained 15 posts. The total section modulus for each generalized sidewall about the X-axis was 14.06 in^3. The total section modulus for each sidewall about the Y-axis was 11.91 in^3. Thus the generalized sidewall met the minimum moduli requirements of 49 CFR 238.217 for each assumed value of yield strength used in these calculations. Note that in a practical design, using a higher-strength material would allow a sidewall to meet the requirements with fewer posts, or with each post having a lower section modulus (i.e., made of thinner material).

6.3.3 Deflection, Stress, and Stiffness Calculations

Having established that the generalized sidewall would meet the section moduli requirements, a series of deflection and stress calculations were performed. The post was treated as either a pinned-pinned or a fixed-fixed beam with an intermediate point load. These end conditions represented upper- and lower-bound estimates of the attachments between the sidewall post and the side sill or roof rail. A pinned-pinned connection corresponds to a highly flexible connection between post and rail, while a fixed-fixed connection corresponds to a rigid connection between post and rail. In reality, a welded connection between post and rail possesses some flexibility but can transmit moments.[9] The actual elastic behavior of the post would be expected somewhere between the pinned-pinned and fixed-fixed cases examined in these simplified calculations.

For each combination of end conditions and yield strength, a series of point loads representing lateral loads were applied to a sidewall post. In each analysis, a single point load was applied to the post at a particular height. The magnitude of each load was chosen so that the magnitude of the absolute maximum bending stress in the post was equal to the assumed yield strength of the material. The height of load application was varied in 5-inch increments over the height of the post, with the elastic limit load re-calculated at each position.

Figure 20 contains a plot of the lateral deflection of a single post at its elastic limit load for each height of load application. These results were obtained assuming a simply supported post having a 60 ksi yield strength. Each data series corresponds to a different height of load application. Note that even for loads applied very close to the bottom or top of the post, the maximum lateral deflection occurs toward the center of the post.

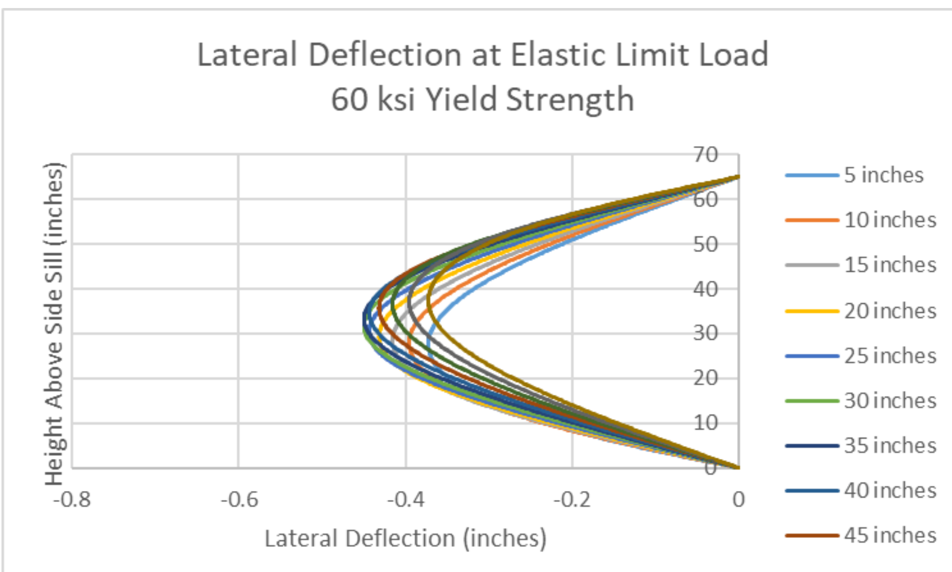

Figure 20. Lateral Deflection at Elastic Load Limit for Varied Load Heights (single post, simply supported at ends, 60 ksi yield strength)

[9] These calculations are focused on the behavior of the post, and do not attempt to estimate whether a post-to-sill connection would actually be capable of carrying the loads at the reaction locations, or whether such a load would cause collapse of the floor or roof structures.

Figure 21 contains a similar plot for an assumed yield strength of 80 ksi. Figure 22 contains a corresponding plot for an assumed yield strength of 100 ksi. Regardless of yield strength, a single post behaves similarly (qualitatively) for each position of load application. From these figures, the largest inward deflection always occurs for a load applied at the center of the post.

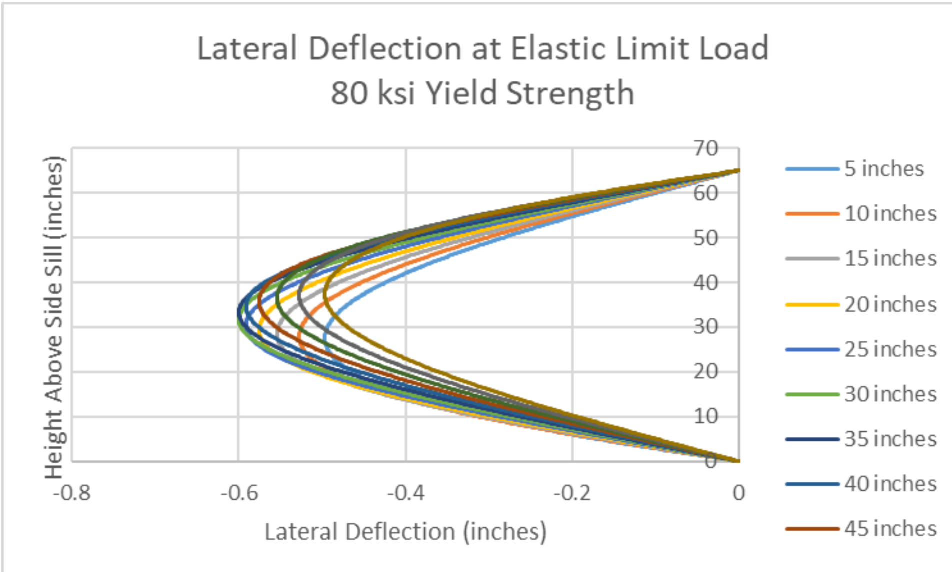

Figure 21. Lateral Deflection at Elastic Load Limit for Varied Load Heights (single post, simply supported at ends, 80 ksi yield strength)

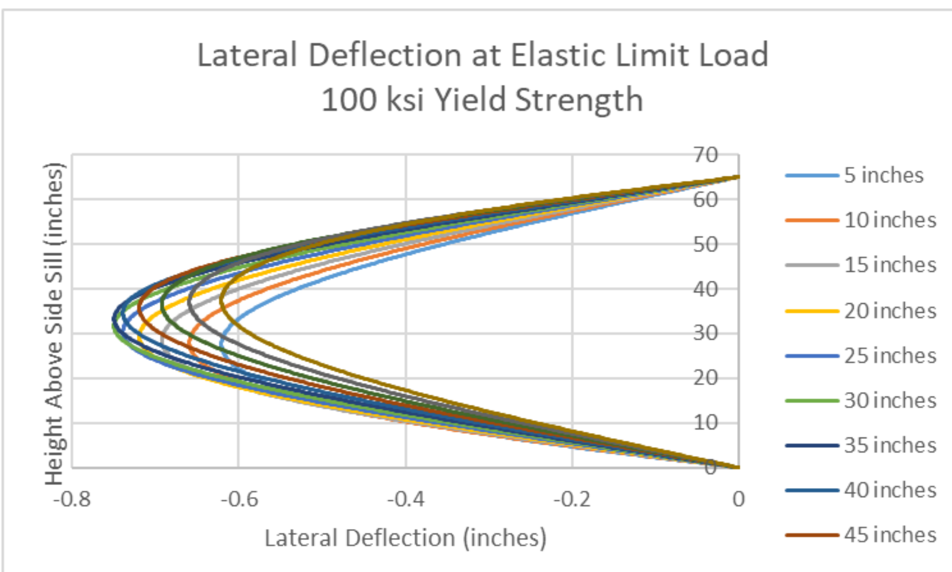

Figure 22. Lateral Deflection at Elastic Load Limit for Varied Load Heights (single post, simply supported at ends, 100 ksi yield strength)

The inward deflection of a single, simply-supported post increases as the assumed yield strength increases, which appears counterintuitive. However, recall that the magnitude of the point load was chosen for each combination of position and assumed yield strength such that the maximum bending stress in the post was equal to the assumed yield strength. Thus, the applied forces tended to increase as the yield strength increased since the geometry of the post remained the same for all loads.

Similar plots of lateral deflection versus post height for varied heights of point load application are shown for the fixed-fixed boundary conditions in Figure 23 through Figure 25. Each of these figures used a different value for the assumed yield strength.

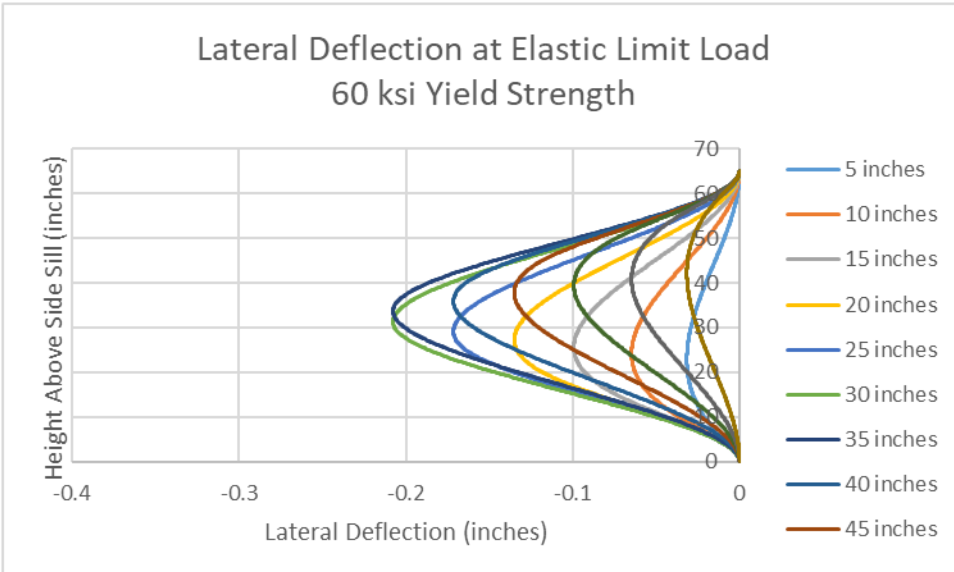

Figure 23. Lateral Deflection at Elastic Load Limit for Varied Load Heights (single post, fixed at ends, 60 ksi yield strength)

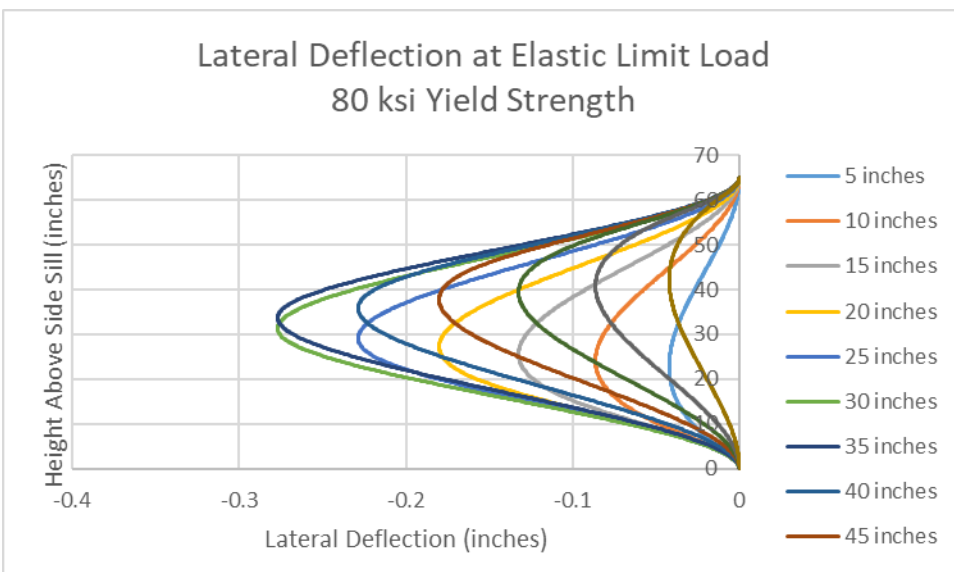

Figure 24. Lateral Deflection at Elastic Load Limit for Varied Load Heights (single post, fixed at ends, 80 ksi yield strength)

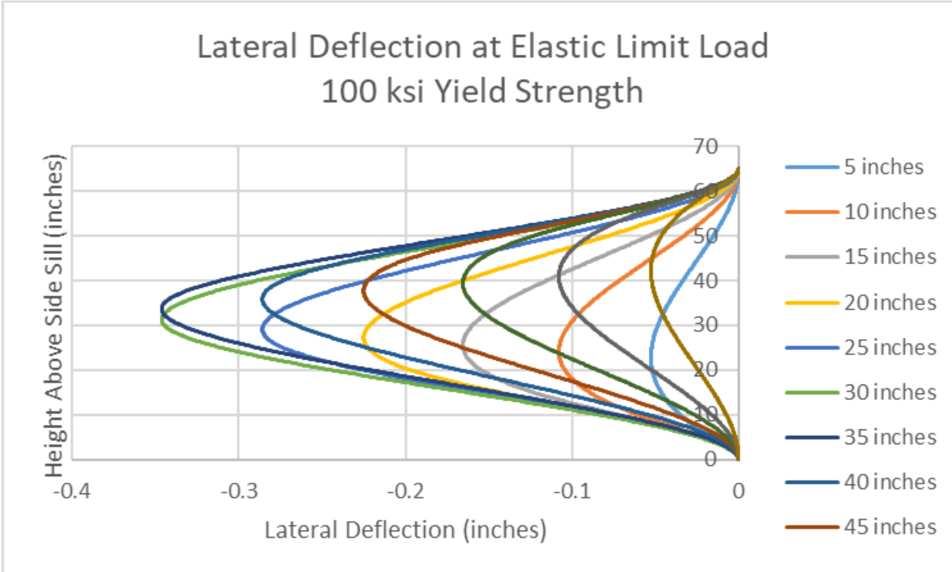

Figure 25. Lateral Deflection at Elastic Load Limit for Varied Load Heights (single post, fixed at ends, 100 ksi yield strength)

The smallest elastic limit load for an entire sidewall would result from a focused lateral load that engages only one sidewall post. For a load to be focused entirely on one post, two conditions must be met. First, the impacting object must be small, such that its width does not span the distance between any two posts. Second, the load-carrying contributions from the sidewall skin and any longitudinal members connecting posts to one another would have to be insignificant to prevent a single post from sharing any load with the adjacent posts. Thus, a single post load can be thought of as the lower-bound case for the entire sidewall as a system.

Figure 26 shows a plot of the single-post elastic load limit versus the height of load application above the side sill for both the simply supported and fixed-fixed end conditions, assuming the yield strength is 60 ksi. At every load application height, the fixed-fixed end conditions require a larger lateral load to reach the 60 ksi yield strength of the material. Additionally, the simply supported end conditions result in the smallest elastic limit loads occurring for a load applied at the center of the post, while the fixed-fixed end conditions have a minimum elastic limit load at roughly the one-third points.

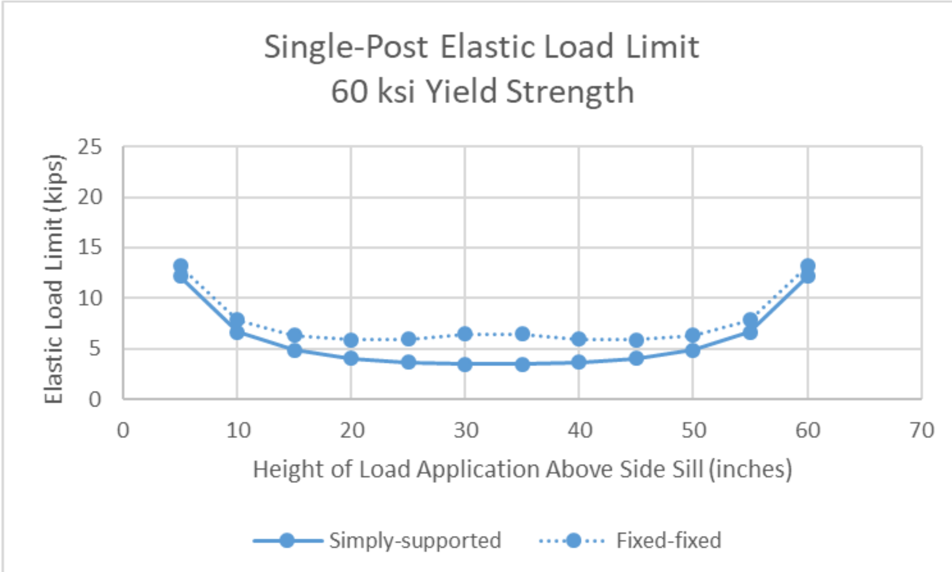

Figure 26. Elastic Load Limit versus Height of Applied Load above Side Sill for Simply Supported and Fixed-fixed Sidewall Post (load on one post, 60 ksi yield)

Alternatively, the total force could be shared equally among all the posts making up the sidewall on one side of the railcar. This situation would represent a sidewall that has a significantly stiff outer skin and/or longitudinal members attaching the vertical posts to one another to allow a point load to be shed outward across all posts. This situation could also represent a long, horizontal object applying load across all sidewall posts simultaneously (e.g., a railcar rolling over and coming to rest supported by a single rail).

Assuming the load is applied to each post at the same height, the total elastic limit of the sidewall is simply the single-post elastic load limit multiplied by the total number of posts. The all-post elastic load limit for the simply-supported and fixed-fixed connection cases are shown in Figure 27 for an assumed yield strength of 60 ksi.

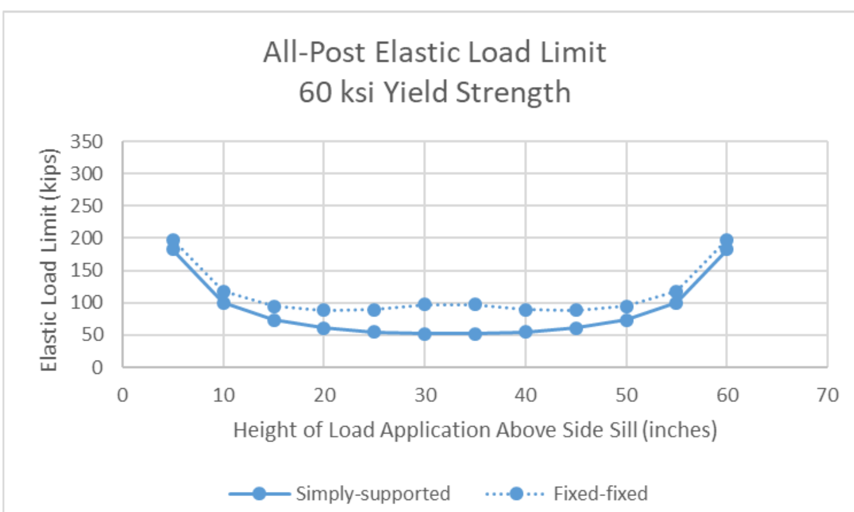

Figure 27. Elastic Load Limit versus Height of Applied Load above Side Sill for Simply Supported and Fixed-fixed Sidewall Post (load shared across all posts, 60 ksi yield)

Using the same approach as above, the single-post and all-post elastic load limits were calculated for assumed yield strengths of 80 and 100 ksi. Figure 28 shows a plot of the single-post elastic load limit versus the height for an 80 ksi assumed yield strength. Figure 29 shows a plot of the all-post elastic load limit for an 80 ksi assumed yield strength. Figure 30 shows a plot of the single-post elastic load limit versus the height for a 100 ksi assumed yield strength. Figure 31 shows a plot of the all-post elastic load limit for a 1,000 ksi assumed yield strength.

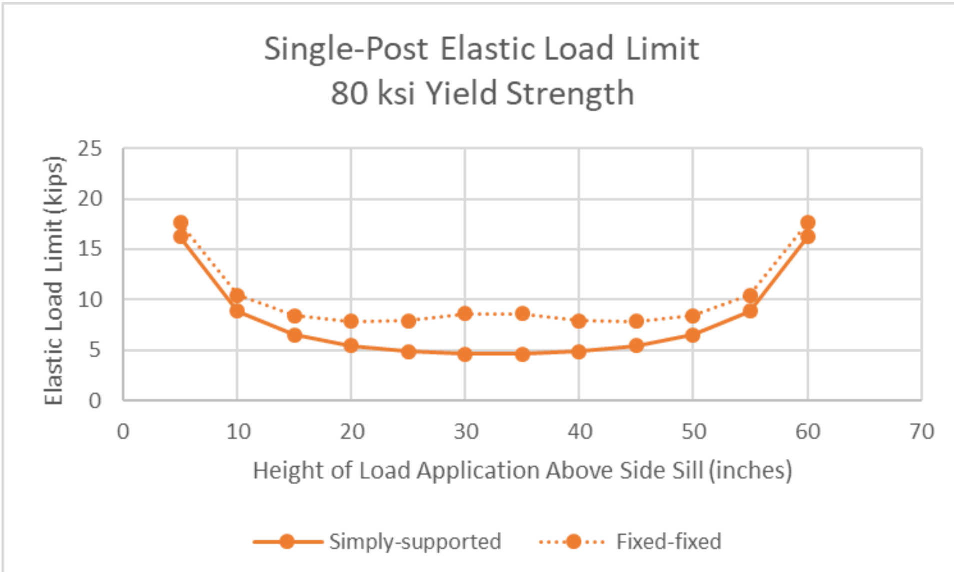

Figure 28. Elastic Load Limit versus Height of Applied Load above Side Sill for Simply Supported and Fixed-fixed Sidewall Post (load on one post, 80 ksi yield)

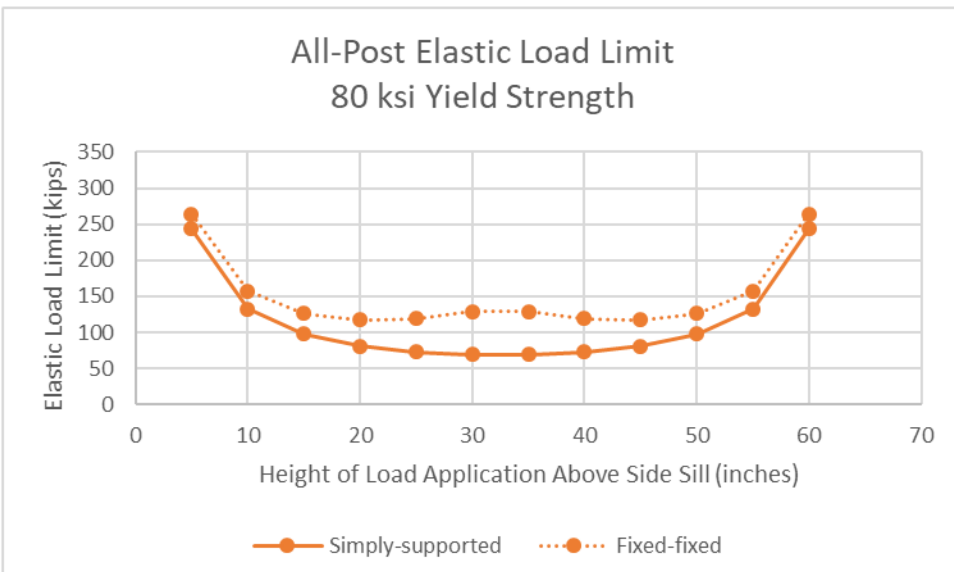

Figure 29. Elastic Load Limit versus Height of Applied Load above Side Sill for Simply Supported and Fixed-fixed Sidewall Post (load shared across all posts, 80 ksi yield)

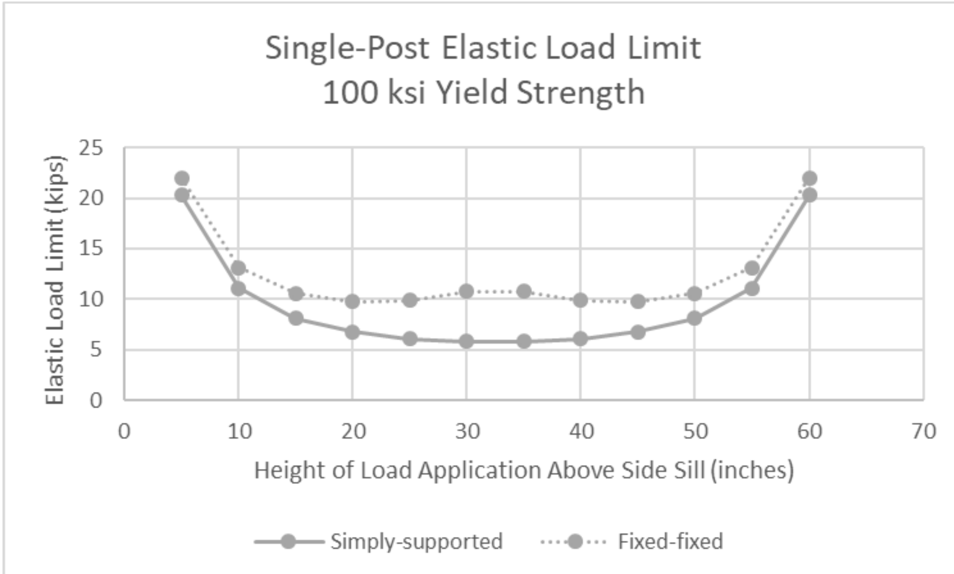

Figure 30. Elastic Load Limit versus Height of Applied Load above Side Sill for Simply Supported and Fixed-fixed Sidewall Post (load on one post, 100 ksi yield)

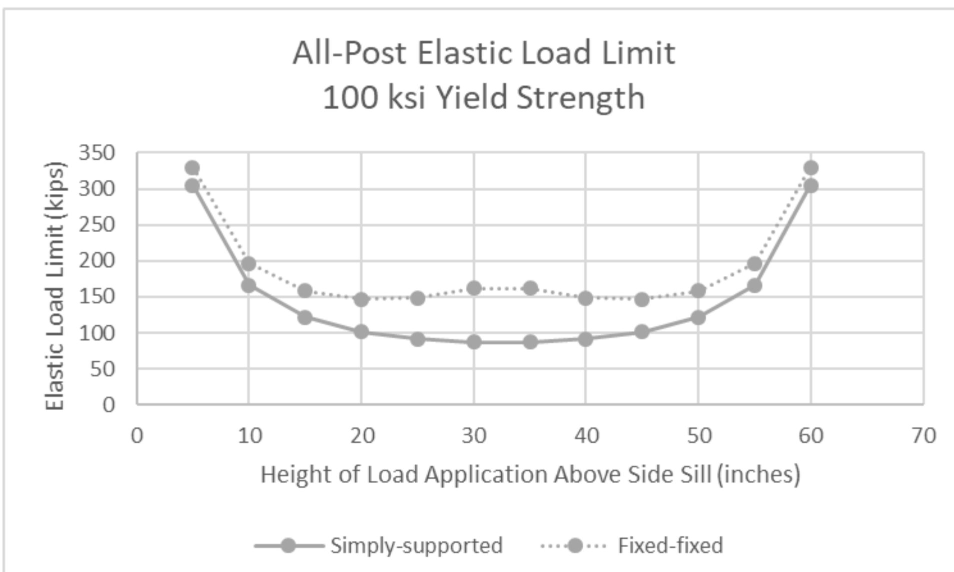

Figure 31. Elastic Load Limit versus Height of Applied Load above Side Sill for Simply Supported and Fixed-fixed Sidewall Post (load shared across all posts, 100 ksi yield)

The section modulus requirement in the current regulations and standards requires consideration of the minimum section modulus along the height of the sidewall. Typically, this height occurs at the center of the windows, as the posts are the only structural members at such locations. For these calculations, a height of 30 inches above the top of the side sill (assumed to correspond to the height of the floor) was assumed to correspond with a plane passing through the windows. Examining the elastic load limit at such a height would provide a rough estimate of the elastic load carrying capacity of the sidewall based on the position typically used in the section modulus calculations. The elastic limit loads for all single- and all-post cases are summarized in Table 12.

Table 12. Elastic Limit Load 30 inches above Side Sill, All Cases

Yield Strength	Simply Supported Single Post (lbf)	Fixed-fixed Single Post (lbf)	Simply Supported All Posts (lbf)	Fixed-Fixed All Posts (lbf)
60 ksi	3,481.6	6,465.8	52,223.4	96,986.3
80 ksi	4,642.1	8,621.0	69,631.3	129,315.1
100 ksi	5,802.6	10,776.3	87,039.1	161,643.9

The maximum indentation of each post for each value of assumed yield strength and end support condition resulting from the elastic limit load applied at 30 inches above the side sill is shown in Table 13. For a given assumed yield strength, the maximum indentation is the same for the single post and the all-post loading cases. This is a result of the assumption that the load is applied equally to all posts at a height of 30 inches above the side sill. The elastic limit load is reached at all posts simultaneously, with the same indentation in each post.

Table 13. Maximum Lateral (Inward) Displacement 30 inches above Side Sill, All Cases

Yield Strength	Simply Supported Single Post (in.)	Fixed-Fixed Single Post (in.)	Simply Supported All Posts (in.)	Fixed-Fixed All Posts (in.)
60 ksi	0.45	0.21	0.45	0.21
80 ksi	0.6	0.28	0.6	0.28
100 ksi	0.75	0.35	0.75	0.35

The forces from Table 12 can be divided by the displacements in Table 13 to estimate the elastic stiffness of each post when loaded at a height of 30 inches above the top of the side sill. These estimated elastic stiffness values are shown in Table 14. As expected, the elastic stiffness of either a single post or all the posts together was independent of the yield strength assumed for the steel.

Table 14. Estimated Elastic Post Stiffness 30 inches above Side Sill, All Cases

Yield Strength	Simply Supported Single Post (kips/in.)	Fixed-Fixed Single Post (kips/in.)	Simply Supported All Posts (kips/in.)	Fixed-Fixed All Posts (kips/in.)
60 ksi	7.74	31.1	116.1	466.9
80 ksi	7.74	31.1	116.1	466.9
100 ksi	7.74	31.1	116.1	466.9

Finally, as a simple estimate of the elastic energy required to deform either the single post or entire sidewall to its maximum intrusion, the estimated stiffness values shown in Table 14 were combined with the maximum lateral displacement values shown in Table 13. Equation 4 was used to calculate energy from stiffness and displacement. The results of these calculations are shown in Table 15.

Equation 4. Energy Required for Elastic Deformation of Posts

$$Energy = \frac{1}{2} stiffness \times displacement^2$$

Table 15. Elastic Energy Absorbed 30 inches above Side Sill, All Cases

Yield Strength	Simply Supported Single Post (ft-lbf)	Fixed-Fixed Single Post (ft-lbf)	Simply Supported All Posts (ft-lbf)	Fixed-Fixed All Posts (ft-lbf)
60 ksi	65.3	56.0	978.8	839.4
80 ksi	116.0	99.5	1,740.0	1,492.3
100 ksi	181.3	155.4	2,718.8	2,331.7

6.3.4 Estimated Side Sill and Roof Rail Load Capacities

The analyses above assume the post-sill connections at both the top and bottom of the sidewall post are capable of carrying the elastic limit load. These analyses also assume the collapse of the roof or floor does not occur before the elastic load limit is reached. As a means of evaluating whether this is a reasonable assumption, recall from Section 2.2 that Tier I passenger equipment is required to demonstrate its ability to support the loads that may be encountered following a rollover, with the carbody resting on its side. In the case of a single-level passenger car, the regulations state the loads are to be supported by only the side sill and roof rail. The requirement places a 1g load (acting on the weight of the railcar) on the side sill and roof rail, with the allowable stresses limited to one-half either the yield strength or buckling strength of the carbody. This is equivalent to a 2g load shared by the side sill and belt rail, without exceeding the yield strength or buckling strength.

Thus, a simple way to estimate the minimum capacity of the roof rail or side sill of an existing Tier I passenger railcar is to assume an equal sharing of this 2g load along the length of each member (i.e., each member carries 1g uniformly along its length without either yielding or buckling). The actual proportion carried by each longitudinal member will vary with the details of construction of each car, as the roof and floor structures may not be equally stiff, and the position of the CG of the car on its side. However, the total load carried by both members must equal twice the weight of the car, without exceeding the yield or critical buckling stresses.

The highest estimated elastic limit loads correspond to loads shared equally across fixed-fixed posts. Table 16 shows the three highest elastic limit loads alongside the weights of several single-level passenger coaches. For an elastic limit load at a height of 30 inches above the side sill, the load will be roughly equally shared between the side sill and roof rail. Since each member is assumed to be capable of carrying the weight of the car (for a total load of 2g), there is a reasonable assumption that the sidewall will yield before the side sill or roof rail begin to yield or buckle. Thus, if the side sill and roof rail are individually capable of supporting a uniform 1g load, the elastic load limit from loading all side posts simultaneously would have to exceed 2g before the side sill or roof rail would be expected to buckle or yield first. While this assumption would have to be confirmed for the specific carbody undergoing evaluation, this rough estimate suggests the sidewall or its connections should yield before the side sill or roof rail yields or buckles. Note that this simplified analysis does not consider a locally-applied load, as the rollover case assumes a uniformly distributed load along the length of the carbody.

Table 16. Elastic Limit Loads and Single-level Car Weights

	Load (lbf)	Reference
Fixed-fixed, all posts (60 ksi)	96,986.3	Table 12
Fixed-fixed, all posts (80 ksi)	129,315.1	Table 12
Fixed-fixed, all posts (100 ksi)	161,643.9	Table 12
MBTA single-level	89,000-95,000	[17]
NJTransit Comet V	100,000	[34]
Budd Amfleet	104,300	[17]
MARC single-level	102,000-111,500	[17]
LIRR M3	112,400	[17]

6.3.5 Additional Sidewall Loading Concerns

During a side impact to a passenger car, lateral loads acting on the carbody will act both to deform (indent) the side of the car, and to displace the center of gravity of the car in the direction the impacting object is traveling. Depending on the height of the impact, the structural details of the car's design (including mass distribution), and the car's suspension characteristics, a lateral force can result in both a tendency to shift the carbody laterally and to cause the carbody to roll about its longitudinal axis.

How a given lateral load is reacted by some combination of wheel-rail interaction or the coupling mechanism will depend on the duration of the impact event, the location of the impact (both the height and the position along the length of the car), the speed of the moving train, the structural design of the carbody, the suspension design, and the details of the car-to-car connection.

In general, the energy absorbed through deformation of a body is a function of the applied force and the amount of deformation. In the case of a side impact, the kinetic energy of the impacting object will be partially dissipated through the crush of the sidewall structure. The energy-absorbing capacity of a structure, such as the sidewall, may be improved by increasing the average force required to crush that structure by a prescribed distance, increasing the crushable distance for a fixed force, or simultaneously increasing both the force and the crush distance.

However, there are practical limits to each of these approaches. If a sidewall structure is constructed such that it allows a very small amount of inward deformation (relatively stiff) and can sustain a higher force without structural failure, the energy absorbing capacity of the sidewall will be increased. However, the higher lateral force applied to the carbody may result in an increased tendency toward derailment and/or rollover. While the occupied volume would be maintained during the initial impact, the resulting derailment and/or rollover introduces additional hazards to the occupants of the car, such as non-compartmentalized impacts with the interior, free-flying objects or debris within the car, and potential threats to the non-struck side of the coach associated with it rolling over (e.g., rolling down an embankment, rolling onto a hazardous structure, etc.). This research program plans to investigate the lateral forces necessary to cause rollover for different generalized carbody designs and suspension designs to estimate reasonable bounds for the lateral forces that could be supported by a sidewall before derailment and/or rollover becomes likely.

Energy absorption can also be increased by designing a structure that has a modest crush force and increasing the allowable crush distance over which that force may act. By limiting the laterally applied force, the risk of derailment or rollover is also limited. However, the allowable space for crushing the sidewall of the car is also limited. From the earliest stages of FRA's passenger equipment research, the primary objective of crashworthy design "is to preserve a sufficient occupant volume for the occupants to ride out the collision without being crushed, thrown from the train, or directly struck from something outside the train." [35] This concern for maintaining sufficient survival space is extremely relevant in the event of side impacts, as seats are typically attached directly to the sidewall of the carbody. This offers a very limited amount of crushable space before the occupied volume of the car begins to reduce. While the seats may also deflect along with the sidewall, reducing the sidewall's intrusion into the seating space, the lateral acceleration of a moving seat can cause injuries to occupants or create lateral secondary impact hazards.

The challenge of limiting occupied volume intrusion is not unique to protecting rail passengers during side impacts. In describing its side impact testing program, IIHS states, "[p]rotecting people in side crashes is challenging because the sides of vehicles have relatively little space to absorb energy and shield occupants, unlike the fronts and rears, which have substantial crumple zones." [36] IIHS bases its side impact safety ratings of passenger vehicles on a series of injury criteria derived from ATDs as well as the residual deformation of the side of the vehicle into the occupied volume in a standardized impact scenario. Thus, the IIHS approach considers both the intrusion into the occupied volume as well as the injuries sustained by the occupants during the impact.

6.4 Simplified Rollover Models

In this section, the authors used simplified 2D models of a side impact scenario to estimate the tendency of a railcar to displace, derail, and roll over during a side impact. In these models the side structure of the railcar was assumed to be perfectly rigid – which the authors believed would be a worst-case scenario for derailment and rollover.

The authors studied a 1994 Volpe Center internal memo about a simplified model for determining the speed of a proxy highway vehicle necessary to derail a passenger railcar and the resulting impact forces. The inertias, suspension parameters, and support conditions from this (legacy) model were used to perform additional analysis on passenger railcar rollover in the Abaqus/Explicit FE software [37].

6.4.1 Legacy Model

Figure 32 shows a diagram of the simplified 1994 model. The model made the following simplifications:

- The model lumped both of the railcars' trucks into one – with equivalent springs and dampers.
- The vertical springs were nonlinear, with a primary and secondary stiffness.
- The equivalent lateral spring was also nonlinear, but the secondary stiffness additionally accounted for the lateral stiffness of the trucks and rail.
- A single car was modeled, so the resistance from the couplers was neglected.
- The crush spring stiffness between the impacting highway vehicle and railcar was calculated assuming a 0.5-second duration impact.
- The lumped train truck remained static; however, if $V_1 = 0$ (wheel-lift) then the corresponding vertical suspension springs were neglected and the inertia of the lumped truck was included in the dynamic analysis of the carbody.

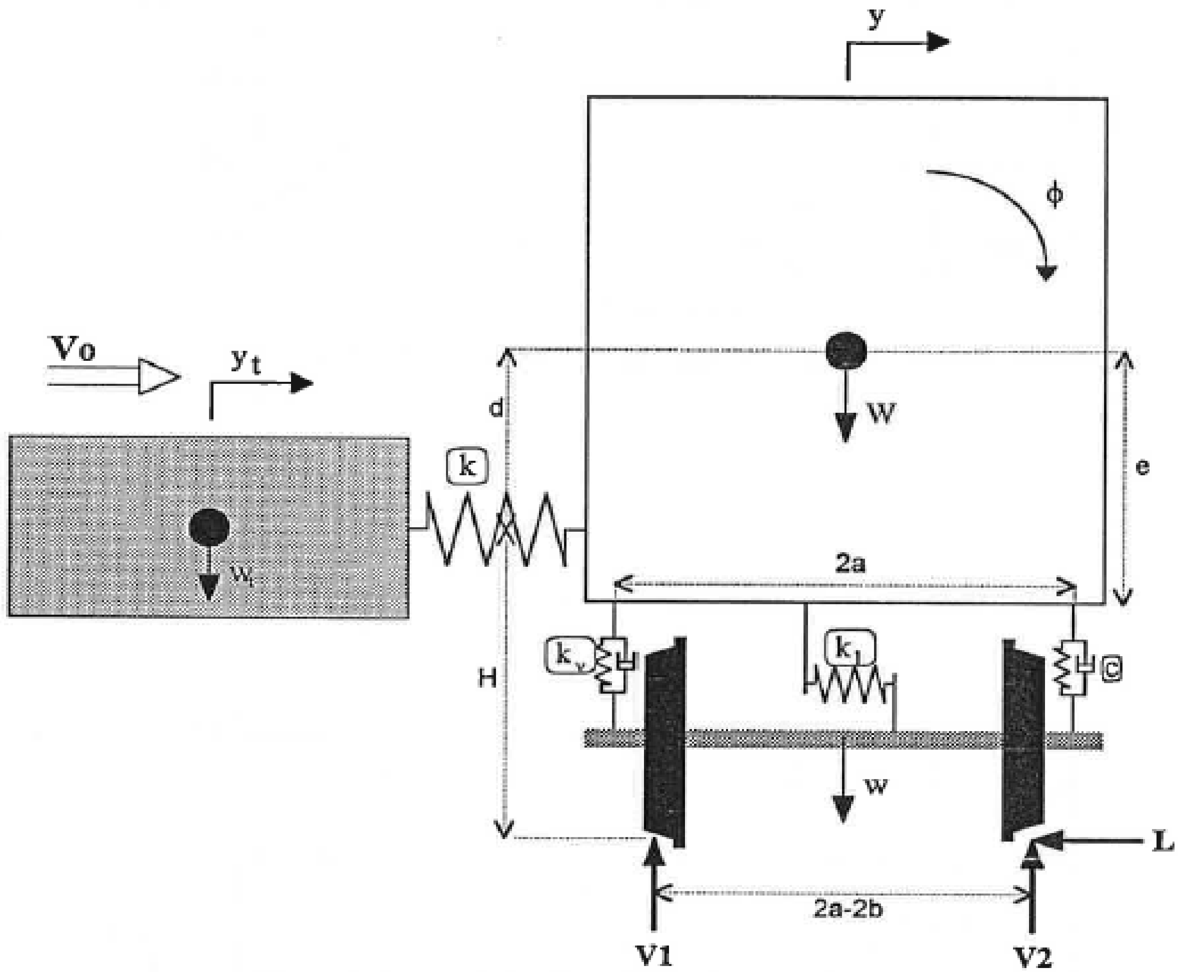

Figure 32. Highway Vehicle Side Impact Model

Table 17 provides the parameters of the legacy model and the updated parameters in the Abaqus/Explicit model. The suspension parameters were updated using values reported by Bing et al. [17] in Appendix A1.1 of that report.

Table 17. Parameters of Highway Vehicle Side Impact Model

Parameter Description	Legacy Value	Updated Value
Car Body Weight, W	77,188 lbf	-
Total Truck Weight, w	27,410 lbf	-
Highway Vehicle Weight, w_t	80,000 lbf	-
Vertical Suspension Springs, k_v Primary Stiffness k_{vp} if $\Delta > 1.496$" Secondary Stiffness k_{vs} if $\Delta \leq 1.496$"	 $7.74 \cdot 10^6$ lbf/ft $4.44 \cdot 10^4$ lbf/ft	 $4.944 \cdot 10^7$ lbf/ft -
Lateral Suspension Spring, k_l Primary Stiffness k_{lp} if $\Delta > 1.496$" Secondary Stiffness k_{ls} if $\Delta \leq 1.496$"	 $1.172 \cdot 10^6$ lbf/ft $9.6 \cdot 10^4$ lbf/ft	 $7.728 \cdot 10^6$ lbf/ft† -
Crush Spring, k	$9.808 \cdot 10^4$ lbf/ft	$8.0 \cdot 10^5$ lbf/ft
Vertical Damping Constant, c	$9.768 \cdot 10^4$ lbf-s/ft	$5.76 \cdot 10^3$ lbf-s/ft
Lateral Damping Constant, c_l	-	$9.6 \cdot 10^3$ lbf-s/ft†
Impact Height, H	3.5 ft	-
a	3 ft	3.75 ft
b	0.5 ft	-
d	2.776 ft	-
e	2.943 ft if $k_l = k_{ls}$ 6.276 ft if $k_l = k_{lp}$	- -
Moment of Inertia of Car Body, I_{CB}	$3.71 \cdot 10^4$ lbf·s²·ft	-
Total Truck Moment of Inertia, I_W	$1.294 \cdot 10^3$ lbf-s²-ft	-

† Reported lateral suspension parameters are the totals for the railcar as depicted in Figure 32. These values were evenly split between two suspension springs in the Abaqus model as depicted in Figure 33.

The legacy analysis was performed in 1994 in MathCAD and estimated that an impact speed of 5 mph would make derailment a likely outcome for an exemplar, single-level coach car. While it was not explicitly stated in the memo, the authors believe the model parameters were derived from an Amfleet II car using Budd Pioneer III trucks, based on the suspension parameters reported by Bing et al. [17] The 5-mph impact resulted in a peak impact force of approximately 100,000 lbf, and it was determined that derailment was a likely outcome due to a high lateral load relative to the vertical load on the wheels. Note that this legacy model was designed to study the impact scenario likely to cause wheel lift, not to determine whether the carbody would recover (i.e., land back on its wheels) or continue to roll and come to rest on its side.

6.4.2 Abaqus Rollover Model

The authors recreated the legacy model in Abaqus/Explicit to perform subsequent analyses. Several updates were made to the 2D model:

- The lateral spring (k_l) was divided into two equivalent springs positioned in the same locations as the vertical suspension springs.
- The vertical suspension was no longer neglected when wheel-lift occurred, meaning the center pin was not considered in this analysis.
- The lateral secondary suspension stiffness was corrected and rail stiffness was neglected, i.e., the rail was assumed to be rigid.
- The vertical secondary suspension damping was changed.
- The lateral secondary suspension damping was added.
- The lateral spacing of the suspension was changed.
- The crush spring was updated based on FEA results from crush of an 80-kip dump truck into a rigid wall and the stiffness of the side structure was neglected, i.e., the side sill was assumed to be rigid.

Figure 33 shows the simplified 2D rollover model in Abaqus/Explicit. The carbody and trucks were constrained to translate only in the X and Y directions and rotate only about the Z axis. The highway vehicle was only allowed to translate in the X direction and was given an initial velocity. Cartesian connector elements were used to represent the suspension springs, crush spring, and rigid stops on the wheels. The wheel on the struck side was allowed to move in the positive X and positive Y directions, while the wheel opposite the struck side was allowed to move in the negative X and positive Y directions. The parts were meshed with surface (SFM3D4R) elements and assigned tied rigid body constraints so that all nodal degrees of freedom were tied to the reference points (RPs). The solver used a time increment of $1 \cdot 10^{-4}$ second.

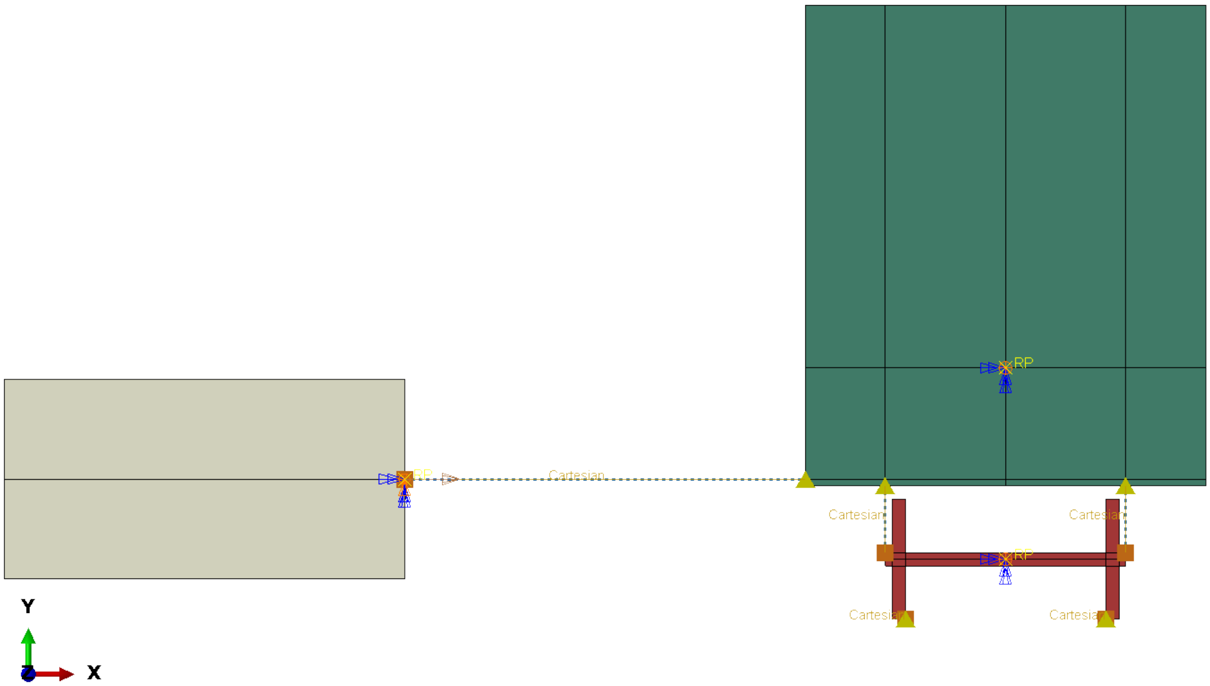

Figure 33. Simplified 2D Rollover Model in Abaqus/Explicit

Figure 34 shows the applied loads in the 2D rollover model. Gravity was applied in the negative Y direction as depicted by the downward yellow arrow, and inertias were assigned to the RPs on the highway vehicle, carbody, and truck. The black vertical double arrows depict connector forces on the vertical suspension connectors which were applied to balance the gravitational force on the carbody so that it was initially at steady-state.

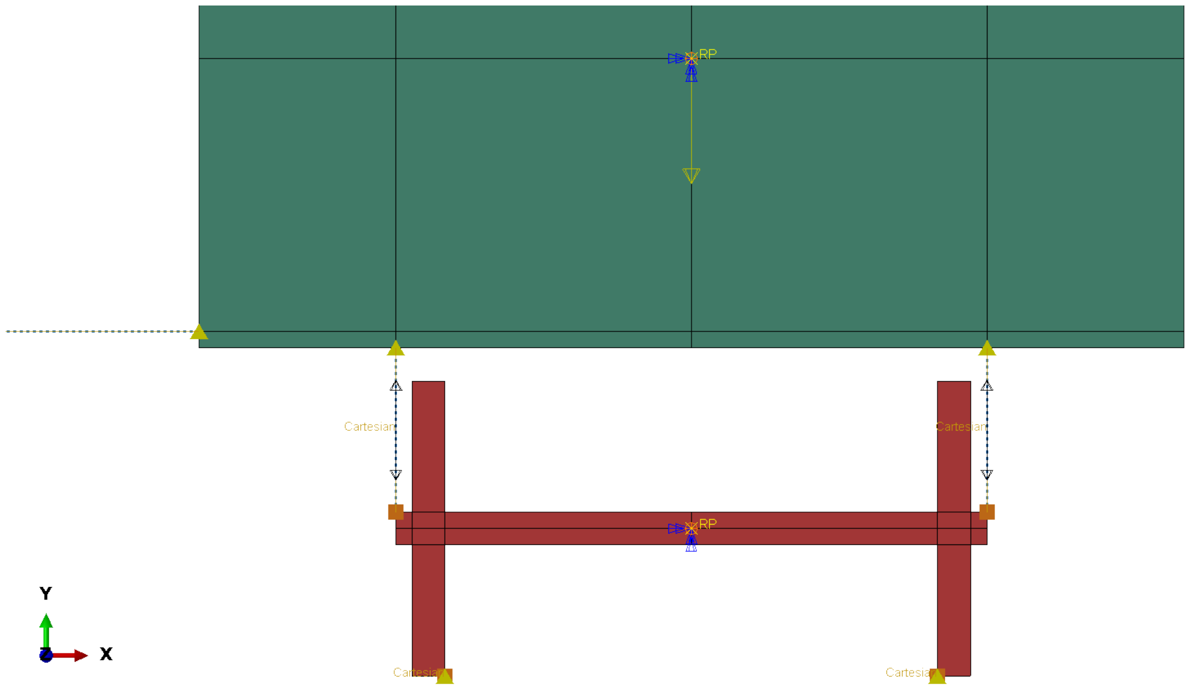

Figure 34. Loads in 2D Rollover Model in Abaqus/Explicit

The authors determined that as impact height increased, car body rollover became a more likely outcome. When impact height decreased, derailment became a more likely outcome.

The impact vehicle spring was defined in Abaqus using a Cartesian connector element with non-linear, elastic behavior and non-linear, plastic, isotropic hardening behavior in the X direction. This was done so the spring only acted plastically in compression (negative force and negative displacement) and unloaded quickly. Using the characteristics shown in Table 18, the spring yielded at an infinitesimally small force (10^{-6} lbf), had a piecewise linear plastic response, and unloaded nearly rigidly, with a stiffness of 10^{8} lbf/in.

Table 18. Impact Vehicle Cartesian Connector Behavior

Elastic Motion *in.*	**Elastic Force** *lbf*
-1	-10^{8}
0	0
1	10^{-8}

Plastic Motion *in.*	**Plastic Force** *lbf*
0	10^{-6}
5.5	$1.5 \cdot 10^{4}$
8.7	$4.1 \cdot 10^{5}$

Figure 35 shows the plastic force-crush behaviors of the highway vehicle used in the rollover models. The legacy model used a plastic spring with a stiffness of $9.808 \cdot 10^{4}$ lbf/ft, while the Abaqus model used a bilinear plastic spring with an initial of stiffness of $3.273 \cdot 10^{4}$ lbf/ft and a final stiffness of $1.481 \cdot 10^{6}$ lbf/ft. The force-crush behavior from the legacy model was estimated assuming a simple mass-spring system with a natural frequency of 2 Hz, while the

Abaqus behavior was estimated from a detailed dump truck FE model[10] weighing 80 kips, impacting a 1-foot-tall rigid wall centered 3.5 feet above ground at 5 mph. Additional discussion on the origins and development of the dump truck model can be found in [38]. The initial soft portion of the response corresponds to the crush of components in front of the engine block, and the secondary stiff portion of the response corresponds to the hard impact of the engine block into the 1-foot-tall rigid wall.

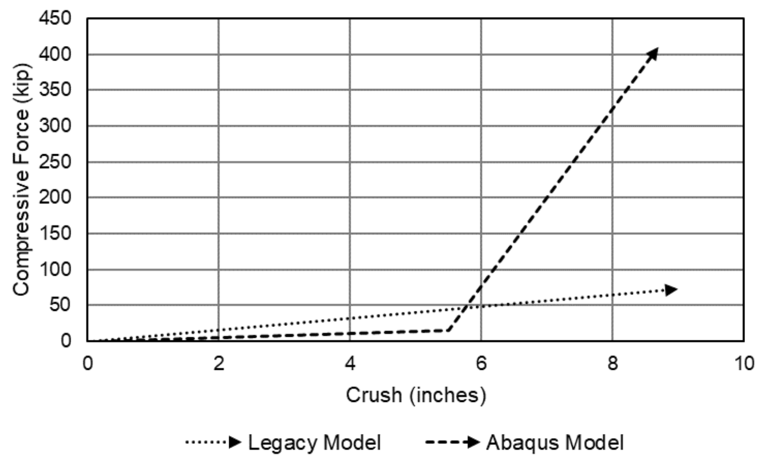

Figure 35. Highway Vehicle Compressive Force versus Crush Behavior

Figure 36 shows the vertical and lateral suspension behaviors used in the legacy and Abaqus models. The secondary suspension remained unchanged in the updated Abaqus model; however, the primary suspension was stiffer for both the vertical and lateral suspension based on reported values from Bing et al. [17]

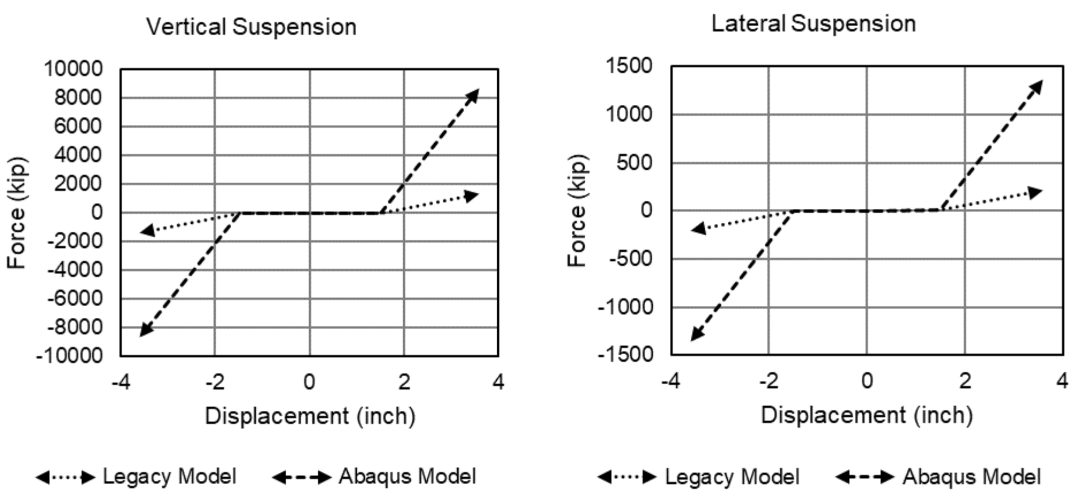

Figure 36. Railcar Vertical and Lateral Suspension Behaviors

Figure 37 shows the impact sequence at 5 mph in time increments of 75 ms with a 5x scale factor to visualize the displacement and rotation of the railcar. Early in the impact sequence, the carbody rolled toward the highway vehicle because the highway vehicle impacted it below its CG. Subsequently, the truck rolled away from the highway vehicle along with the carbody. The

[10] The dump truck FE model is similar to the tractor-trailer FE modeled referenced in Section 5.4 but modified to represent a single-unit dump truck prescribed in the AAR M-1004 side impact scenario.

roll angle resulting from this impact was small enough that the carbody could recover and began to roll back toward the highway vehicle. Finally, the railcar returned to rest, and a secondary impact with the highway vehicle occurred.

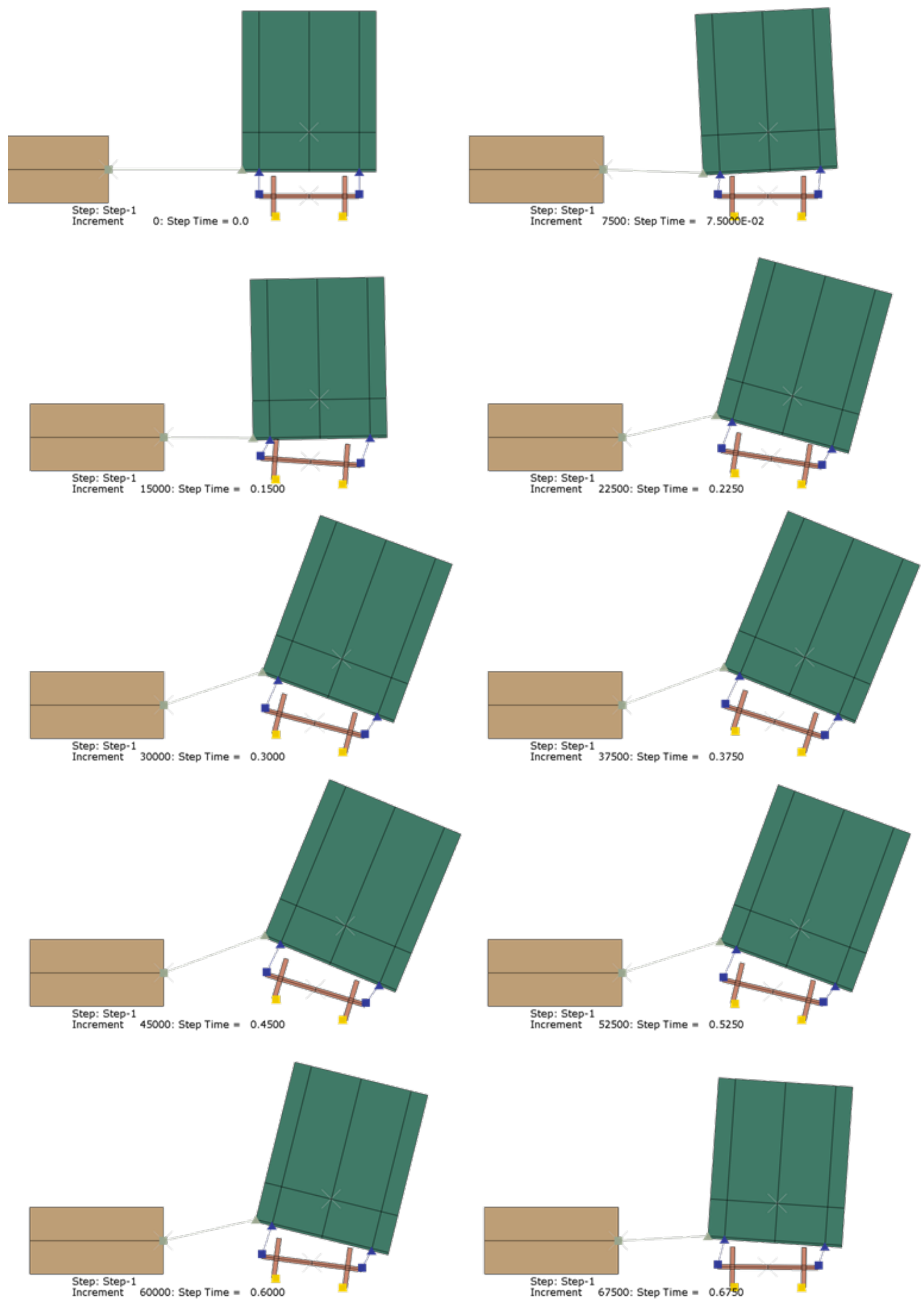

Figure 37. Impact Sequence at 5 mph (5x displacement scale factor)

Figure 38 shows the time histories of the vertical and lateral reaction forces from the rigid rails and the impact force. The wheel opposite the struck side (V_2) unloaded (wheel-lift) at 0.085 second due to roll of the carbody toward the highway vehicle when the suspension and impact crush springs reached the stiff portion of their bilinear behaviors. At 0.109 second, the wheel opposite the struck side returned to its initial position and hit a hard stop, resulting in non-physical spikes in both V_2 and the lateral force on the wheel opposite the struck side exerted by the rail (L). Subsequently, the wheel on the struck side (V_1) unloaded as the truck rolled away from the highway vehicle. Derailment appears to have been a likely outcome due to wheel-lift of the wheel opposite the struck side. The impact force (F) of the highway vehicle is also plotted against time.

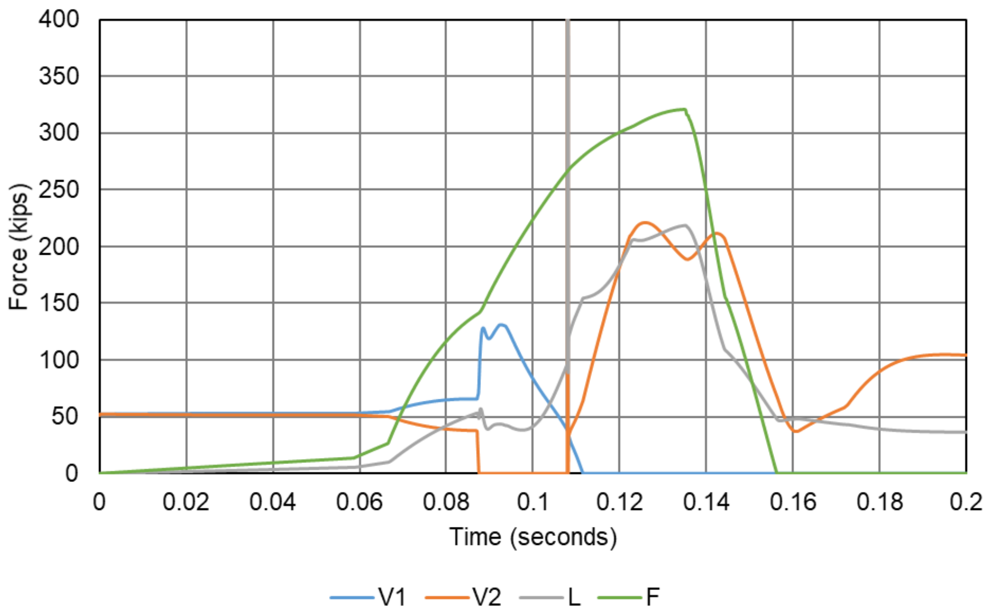

Figure 38. Rail Reaction Forces and Impact Force versus Time at 5 mph

The legacy analysis used an assumed soft linear force-crush response for the highway vehicle and only resulted in wheel-lift for the wheel on the struck side (V_1) – not the wheel opposite the struck side (V_2). The peak impact force was also considerably lower with the softer force-crush highway vehicle (100 kips) versus the updated behavior (320.9 kips). Derailment was considered a likely outcome in both models at 5 mph, but for different reasons. In the Abaqus model, the wheel opposite the struck side experienced wheel-lift akin to the wheel suddenly “jumping off” the rail. In the legacy model, the wheel opposite the struck side had a more gradual response corresponding to wheel climb derailment, where a high L/V_2 ratio was achieved when the peak lateral reaction force was reached. Section 6.4.3 provides further discussion on the relationship between the L/V_2 ratio and wheel climb derailment via the Nadal limit.

A summary of the model results with varying impact speed is shown in Table 19. The Abaqus rollover analysis presented here considered speeds from 1 to 10 mph. Impact speeds of 3 mph and greater could result in derailment because the wheel opposite the struck side lifts up (see Table 19) and/or buckling of the railcar’s side structure (based on an impact force of nearly 175 kips); thus, the results are difficult to interpret because the model assumptions are no longer valid. Additionally, impact forces in excess of 400 kips are expected to result in the buckling of the highway vehicle’s underframe. However, if the rails are assumed to be rigid, and derailment and buckling of both the carbody and the highway vehicle are neglected, then complete rollover of the railcar is estimated to occur at an impact speed of 10 mph. Rollover occurred at 10 mph in the Abaqus model whether the legacy or updated parameters from Table 17 were used.

Table 19. Summarized Results from 2D Rollover Model in Abaqus

Impact Speed	F	L	V_2	L/V_2	Wheel on Struck Side	Wheel opposite Struck Side
mph	*kips*	*kips*	*kips*	-	-	-
1	11.0	15.9	67.7	0.23	No wheel-lift	No wheel-lift
2	96.1	85.1	117.3	0.73	Slight wheel-lift	No wheel-lift
3	174.2	133.7	152.8	1.49	Wheel-lift	No wheel-lift
4	246.8	176.6	195.3	N/A†	Wheel-lift	Wheel-lift
5	320.9	218.7	221.2	N/A†	Wheel-lift	Wheel-lift
6	400.3	268.5	262.6	N/A†	Wheel-lift	Wheel-lift
7	479.5	321.2	300.3	N/A†	Wheel-lift	Wheel-lift
8	559.1	381.1	367.8	N/A†	Wheel-lift	Wheel-lift
9	636.8	420.9	400.1	N/A†	Near rollover	Wheel-lift
10	714.7	458.7	425.6	N/A†	Rollover	Rollover

† V_2 had a value of zero (wheel-lift) resulting in a divide by zero

Figure 39 shows impact force versus impact speed. A linear relationship between speed and force was observed using the model simplifications of a single car (i.e., the couplers are neglected), with the rails assumed to be perfectly rigid, wheel climb not allowed, and buckling not considered. However, a more detailed analysis would likely result in a non-linear relationship, as these behaviors begin to interact in a more complicated manner. As points of reference, the lateral loads applied to the side sill over an 8-foot width from APTA S-034 and 49 CFR 238.417 are shown on this figure. The simplified model estimates the higher of these two loads is exceeded from a 2-mph impact.

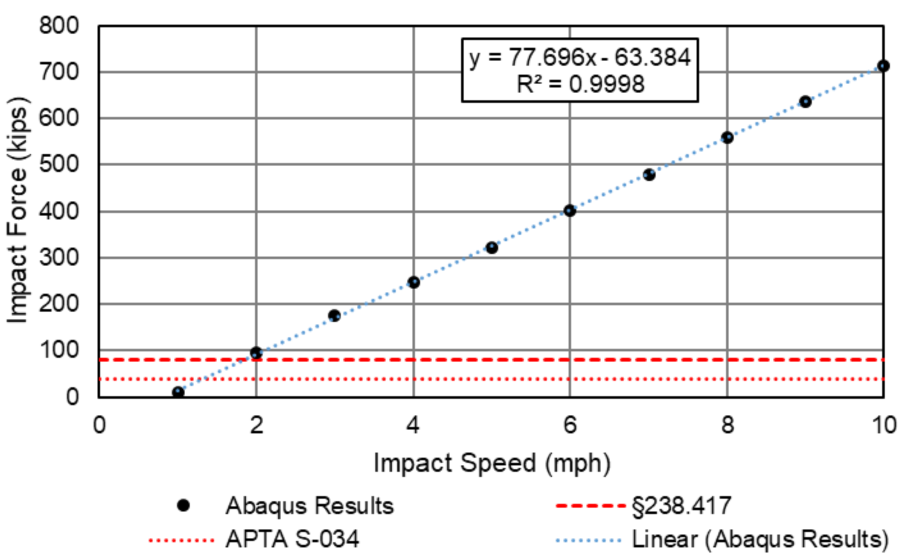

Figure 39. Impact Force (F) versus Speed

Figure 40 shows the lateral reaction force at the far-side, wheel-rail interface versus impact speed, and Figure 41 shows the vertical reaction force versus impact speed at the same location. As expected, both lateral and vertical reaction forces increased with speed. However, the realism of the reaction loads at higher speeds was limited by the simplifying assumptions of the model.

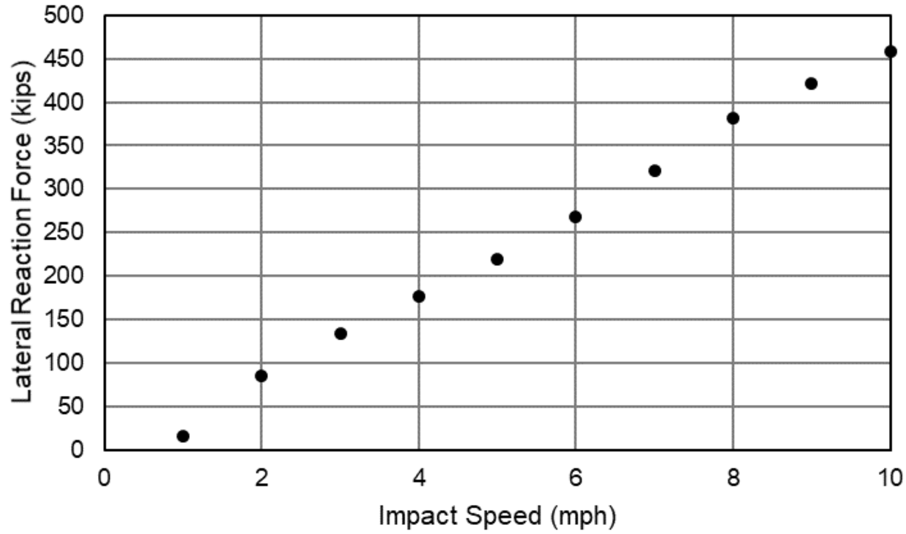

Figure 40. Lateral Reaction Force (L) versus Speed

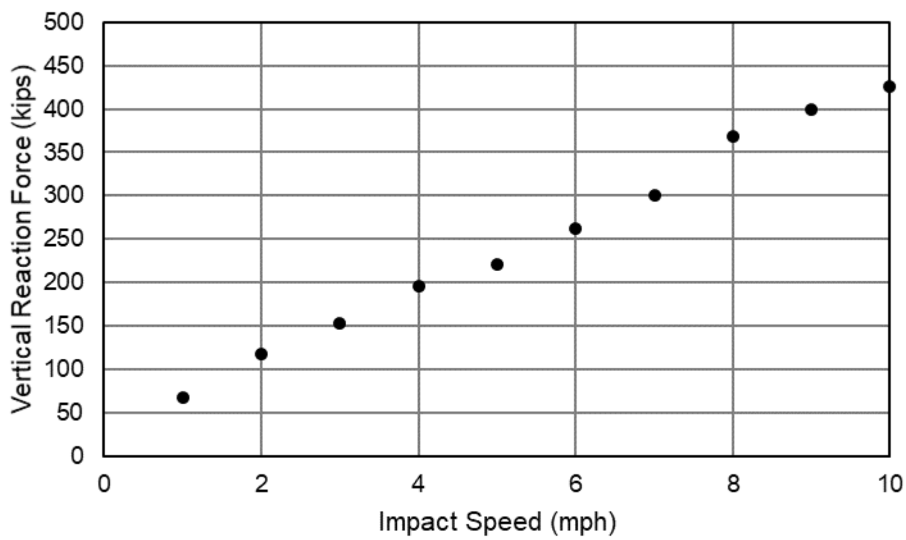

Figure 41. Vertical Reaction Force (V_2) versus Speed

6.4.3 Derailment Criteria

In an accident scenario where a railcar is impacted on its side by a heavy highway vehicle, there is a potential for a wheel flange climb derailment. The Nadal formula [37] relates the L/V ratio to the angle (δ) formed when the wheel flange contacts the rail gage and the coefficient of friction (μ) between the wheel and rail. The Nadal formula is an industry-accepted approach for low-speed wheel climb derailment [38]. Equation 5 gives the Nadal formula.

Equation 5. Nadal Formula

$$\frac{L}{V} = \frac{\tan(\delta) - \mu}{1 + \mu \tan(\delta)}$$

Figure 42 is a plot of the Nadal formula using various coefficients of friction. Since this formula considers a rolling wheel, as μ increases the L/V necessary to result in derailment decreases. In the case of a static wheel, this relationship does not hold true. While the 2D rollover models presented in Sections 6.4.1 and 6.4.2 simplify the equations of motion by assuming a standing car, this formula has been considered because it is a well-accepted industry standard, and impacts of stopped railcars at crossings were not observed in the accident history survey.

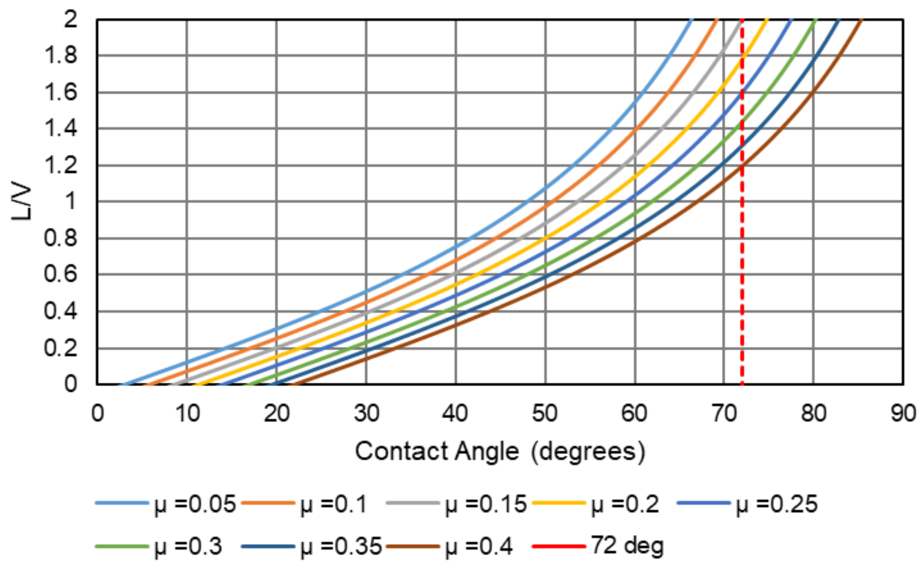

Figure 42. Nadal Formula for Various Coefficients of Friction

Based on the results of this simplified analysis and an assumed wheel flange angle δ of 72 degrees and $\mu = 0.4$, an impact speed of 3 mph could result in derailment from wheel climb because the Nadal limit is exceeded. At an impact speed of 4 mph or above, the wheel opposite the struck side lifts off, which would also likely result in a derailment. One complication is that δ changes once the wheel on the struck side (V_1) has lifted, i.e., it cannot be considered constant based on the wheel profile. This reduction to δ would naturally reduce the L/V ratio necessary to cause derailment; however, the change in angle was relatively low (< 1°) in cases where only the wheel on the struck side experienced wheel-lift and not the wheel opposite the struck side. Also, it is likely that adding torsional resistance from the couplers would inhibit roll of the carbody. Lastly, adding further details to the connections between the carbody, bolsters, truck frames, etc., would affect the resulting L/V ratio.

6.4.4 Future Rollover Modeling

The 2D rollover models presented in Sections 6.4.1 and 6.4.2 make several simplifying assumptions that limit the ability of the models to predict rollover at relatively low impact speeds. The main lesson learned from this effort at a simple 2D rollover model is that a more detailed model of passenger railcar rollover is needed to accurately determine impact conditions that would cause side structure deformation, derailment, and rollover. The detailed modeling should consider the struck railcar and its connections to other bodies (i.e., adjacent railcars and track structure) as a system. It may be appropriate to consider the influence of plastic deformation of the highway vehicle and carbody, coupled rail equipment and torsional resistance from the couplers, detailed connections between the carbody, bolsters, truck frames, and wheelsets, wheel-rail interactions, the rail fastening systems, etc.

7. Discussion

Research is underway to evaluate the side impact performance of passenger cars. In the first phase of this research program, the current state of passenger car side structure design was examined through: (1) a review of the current standards and regulations governing side structure, (2) a study of accidents involving side structures, and (3) an estimate of how the U.S. passenger car fleet has changed since the existing regulations were developed. Simplified engineering models were developed to investigate the elastic strength and deflection of sidewall members and the rollover behavior of an exemplar passenger railcar to a side impact. Additionally, comparisons were made among side impact load cases contained within existing railroad and highway standards that are not directly applicable to passenger railcar sidewalls.

Based on the work conducted in Phase I of this program, several alternative approaches to evaluating sidewall structural integrity could potentially be employed. These alternative approaches are described in broad terms below.

7.1 Alternative 1: Static Equivalent Load for Side Structure Evaluation

A static equivalent load case could be applied to evaluate side structure integrity. APTA has already developed this approach in Standard S-034, and it is in the CFR for Tier II passenger rail equipment. This approach is similar to the approaches currently used to evaluate locomotive fuel tank integrity, natural gas fuel tenders, and bridge piers.

A static equivalent load case is fairly straightforward to apply, but may be difficult to initially develop. At its core, the static equivalent load case requires one or more loads to be defined with corresponding acceptable behaviors in the passenger railcar as a result of the loads. For the load, a suitable magnitude must be chosen. As shown in Phase I research, the side load magnitudes currently applied to rail vehicles ranged from 7,000 lbs in the existing APTA Standard (applied on the sidewall at the belt rail) to 200,000 lbs applied laterally on a locomotive fuel tank (at a height of 30 in. ATOR). The current static equivalent load applicable to a fixed bridge pier subject to a highway vehicle impact is a 500,000-lb load (applied at a height of 60 in. above ground).

Along with a prescribed load magnitude, a static equivalent load case would need to describe the position of the applied load. The position should include both the height of the applied load and the extents over which the load is applied. Height could be expressed as an absolute position (i.e., measured ATOR or above ground) or a relative position (e.g., measured above the height of the floor of the equipment undergoing evaluation, measured relative to the weakest section of the sidewall, etc.). Similarly, the area over which the load acts can be defined as an absolute distance (similar to the 6 in. by 48 in. area given for fuel tank lateral loading) or as a relative measure (e.g., acting over the width of a single post, or acting over the width between two adjacent window cutouts in the sidewall).

Finally, a static equivalent load case would have to have a defined pass-fail criterion or a set of criteria. Based on Phase I of this sidewall research, two likely candidates for pass-fail criteria are limits on the stress allowed in the sidewall and its connections to the rest of the carbody structure, and limits on the allowable intrusion when the required load is applied.

Developing a static equivalent load presents several challenges. As evidenced by similar load requirements that use different load magnitudes seen in APTA Standard S-034 and CFR Tier II requirements, determining an appropriate load magnitude and location combination may prove challenging. For both the APTA and CFR Tier II requirements, the load amplitudes for sidewall and belt rail lateral loads are substantially lower than the side-impact load prescribed for a locomotive fuel tank, which is itself half of the side impact load proposed in AAR M-1004 for a fuel tender cabinet.

Determining a reasonable load magnitude for a static equivalent load case will first require a purpose of such a load to be determined. For example, is a new static equivalent load case intended to prevent loss of sidewall integrity against a particular threat, or is it intended as a means of demonstrating all sidewalls possess at least some amount of structural integrity? Establishing the purpose of such a load case will also help inform the load position and pass-fail criteria decisions that will have to be made.

In developing a static equivalent load case meant to evaluate sidewall integrity, care must be taken to ensure that the load case remains relevant and design-neutral for a variety of sidewalls that may be encountered. If a load case references a specific member, such as a side sill or belt rail, this load case may be difficult to apply to designs that do not feature such members. At the same time, prescribing that a load be applied at a certain absolute position may be irrelevant if a sidewall design does not have any structure at the prescribed height.

Finally, if a static equivalent load case is to be applied to a sidewall structure, such a load case may require certain assumptions about the ability of the carbody to support such loads through other structures. In this research program, simplified mathematical models treated the connections between the sidewall and roof rail and side sill as either fixed-fixed or pinned-pinned connections. While these acted as bounding cases for establishing deflection and stress distributions on the sidewall posts, they also implicitly assumed that the floor and roof structures were capable of supporting the sidewall loads before they themselves fail. Evaluation of an actual sidewall structure would also require some assumption of how much of the remainder of the carbody must be included in a model or in a test article to appropriately represent the support conditions and sidewall response from the static equivalent load.

7.2 Alternative 2: Dynamic Impact Scenario for Side Structure Evaluation

Another potential alternative approach to evaluating sidewall impact integrity is a dynamic impact scenario. This approach offers several positive aspects but also several challenges to implementation. A dynamic impact scenario involving simulation or testing of the particular scenario of concern is a direct way of evaluating the impact resistance of a particular sidewall structure with a minimal number of engineering simplifications or generalizations. If the concern for sidewall structures is a direct impact from a heavy highway vehicle, a dynamic impact scenario could be developed that addresses that particular concern directly. A dynamic impact scenario is an example of a performance requirement, which should be more design-neutral than requiring a railcar to support prescribed loads on prescribed design features.

If a scenario were to be developed, there are several criteria and procedures that would need to be defined to enable such a scenario to be evaluated. First, the scenario would have to be defined in terms of the impacting vehicle or category of vehicle, the target location or locations on the sidewall, and the desired energy, mass, or velocity (or some combination of these parameters) to describe the impacting vehicle. The scenario would also have to be defined in sufficient detail to allow either a full-scale impact test to be performed or a detailed computational model to be executed.

Whether a test or a model is being used to evaluate the scenario, some detail on the support conditions for the railcar undergoing evaluation would have to be established. For example, is the railcar standing on its trucks or on proxy supports? Is the support intended to allow the railcar to roll over in response to the impact, or is the support intended to fix the railcar's position? Is the railcar undergoing evaluation a single vehicle, or is it coupled to adjacent vehicles? Including such details in the definition of the scenario is important to giving the evaluation a clear purpose as well as minimizing uncertainty among those who are evaluating such a scenario.

Pass/fail criteria would also have to be defined for an impact scenario. Depending on whether testing, modeling, or a choice of either approach would be permissible to evaluate the scenario, different pass/fail criteria could be applicable. As a performance scenario, the desired outcomes are critical to determining whether the response of the railcar is acceptable under the prescribed impact conditions. Desired outcomes could include a limit on the intrusion into the occupied volume after the impact, similar to both the existing end frame requirements for passenger railcars and the IIHS criteria for side impacts to passenger automobiles. Desired outcomes could also include a limit on the allowable motion of the railcar, such as a prohibition on derailing, or a limit on the rollover angle that is permissible even if derailment occurs as a result of the impact. Desired outcomes could also include limits on the allowable stresses in the carbody structure.

A dynamic impact scenario presents many challenges to implementation. Any standard or regulation utilizing a dynamic impact scenario should make clear whether the scenario is to be implemented through full-scale impact testing, FE simulation, or if either approach would be acceptable. Full-scale testing would be costly, as such a scenario would result in both destruction of the railcar undergoing evaluation and the striking highway vehicle. A full-scale impact test of a highway vehicle into a standing railcar presents logistical challenges, such as the availability of facilities to perform such a test in a safe, consistent, and repeatable manner. While a new railcar design undergoing evaluation would be purpose-built for such a test, the highway vehicle would likely be procured as an existing vehicle. As there may be a considerable variation in vehicle availability and future designs, a standard would need to take into account what desired characteristics a vehicle should possess such that a variety of highway trucks could be used in the scenario, but still give equivalent performance regardless of the specific vehicle chosen for the impact. Alternatively, a "proxy object" representing the essential features of the highway vehicle could be developed and used for either testing or analysis. This poses an added challenge, as the geometry, mass, and desired level of deformation in a proxy object would have to be developed alongside the impact scenario itself.

If FE modeling is to be used in lieu of or in support of full-scale testing, many of the challenges of full-scale testing carry over into the model. A highly-detailed FE model of both the railcar and highway vehicle would be required, which may present cost challenges. Depending on the support requirements in the standard, the model may need to include not only the structural members of the railcar but also the suspension, trucks, couplers, adjacent railcars, and rails. Additional input properties would need to be defined in the FE model to account for these additional behaviors beyond the sidewall being evaluated, which will pose challenges to validating the model. This kind of model would also be expected to include highly-detailed material properties for the materials of construction, including elastic-plastic responses and some means of evaluating failure or fracture. These behaviors may require additional material testing and more specialized FE knowledge to implement in a credible manner.

8. Conclusion

This research program found the overall number of single-level passenger railcars in operation in the U.S. in 2014 was similar to that reported in 1996. The number of multi-level and alternatively designed passenger railcars have increased significantly since 1996. The researchers found that based on computer modeling and full-scale testing of impacts between heavy highway trucks and fixed pilings conducted by a separate group of researchers, multi-level and partial low-floor passenger railcars were more likely to have sidewalls spanning the heights that correspond to the position of the engine in a highway vehicle. The sidewalls of conventional single-level passenger railcars may experience less-severe intrusion from a heavy highway vehicle impact, as the floor of the single-level coach is positioned near the top of the engine block, potentially allowing a more direct load path between the engine and underframe of the railcar. The current research did not take into account any potential risk of rollover associated with “underride” of a heavy highway vehicle beneath a conventional single-level coach floor structure.

The researchers found side impacts between passenger rail vehicles and heavy highway vehicles at highway-rail grade crossings are relatively rare occurrences. In each 9-year period examined, the total number of grade crossing impacts reported to FRA decreased compared to the previous period. Additionally, the percentage of incidents involving a heavy highway vehicle striking the side of a train reported in each period decreased as a percentage of the total incidents occurring in the same time period. While rare, the potential for such an incident to have catastrophic consequences was observed in the Miriam, Nevada, incident – the only fatal incident involving a heavy highway vehicle striking the side of a passenger railcar reported to FRA between 1986 and 2015. While highway-rail grade crossing incidents have been declining over the period of time included in this study, these types of incidents cannot be eliminated entirely as long as highway-rail grade crossings exist.

The current design practice does not require an evaluation of sidewall resistance to intrusion when subjected to an inward load representative of an impact from a heavy highway vehicle. The researchers found that no existing domestic or international standard or regulation governing passenger railcar sidewall design is specifically intended to address a direct impact to the sidewall by a highway vehicle. Existing standards and regulations *do* address other aspects of sidewall design, such as the need for a sidewall to successfully support the weight of a railcar that has come to rest lying on its side. In the U.S., industry standards contain a requirement to evaluate static loading on the belt rail and side sill within the sidewall structure. However, these loads are not required by the CFR for Tier I passenger equipment. Additionally, the magnitude and placement of these loads are not directly derived from an analysis of side impact conditions.

The researchers also found that side impacts to railroad vehicles other than passenger coaches must be considered under existing U.S. regulations and industry standards. Side impact load cases specifically described as addressing impacts from heavy highway vehicles are required to be evaluated for locomotive fuel tanks and for natural gas fuel tenders. While the details of load application vary across the different standards and regulations examined, each includes a load magnitude, an area over which the load is to be applied, the position of the load relative to top-of-rail, and a prescribed pass/fail criterion relating to material stress.

Side impact loads intended to address highway vehicle strikes ranged from 200,000 lbs at 30 inches above top of rail for a locomotive fuel tank to 600,000 lbs at 60 inches above ground for fixed bridge piers. As seen in the simplified sidewall and rollover modeling, a passenger railcar is a complicated structure that behaves as a system (i.e., carbody, suspension, trucks, couplers, and track structure) when loaded laterally. Direct application of an existing load case may not be appropriate for a vehicle that will simultaneously deform and deflect when struck by an object that is itself deformable. Any load magnitude placed fairly high on the sidewall of a railcar may pose a substantial challenge for the sidewall to resist without exceeding a stress limit for the sidewall itself, or even the strength of the underframe or roof to which the sidewall is attached. The researchers note that a passenger railcar must resist an 800,000-lb longitudinal load along its line of draft (i.e., at the underframe-level), but the ability of the underframe to resist a substantial lateral load is not known. Highly simplified assumptions were applied to consider the global strength of the side sill and roof rail, but focused impact loads transmitted into the roof or floor may exceed the local load-carrying capacity of these structures. The lateral resistance of the underframe is expected to be lower than its longitudinal resistance, as the longitudinal load case is associated with longitudinal impacts as could arise during a train-to-train collision.

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Appendix A.
U.S. Passenger Rolling Stock Car Count

Table A1. U.S. Passenger Rolling Stock Car Count

Railroad	Car Manuf.	Car Name or Desc.	Type of Car	# in Fleet	Year(s) of Manuf.	Source
Altamont Corridor Express	Bombardier	Bi-level (VI)	Multi-level coach/Cab Car	30	2000	[1]
Amtrak	Talgo	Talgo V1	Alternatively designed	67	1998	[2]
Amtrak	Talgo	Talgo 8	Alternatively designed	26	2009	[3]
Amtrak	Budd	Amfleet I	Single-level coach	455	1975-??	[4]
Amtrak	Budd	Amfleet II	Single-level coach	145	1981-1983	[4]
Amtrak	Amerail	Viewliner I	Single-level coach	51	1995-1996	[4]
Amtrak	CAF	Viewliner II	Single-level coach	130	2012-present	[5]
Amtrak	Budd	Metroliner Cab Control Coach	Single-level coach	17	1969-present	[4]
Amtrak	Bombardier	Horizon	Single-level coach	92	1988-1989	[4]
Amtrak	Alstom	Surfliner	Multi-level coach	49	2000-2002	[4]
Amtrak	Morrison-Knudsen	California Car	Multi-level coach	91	1996	[4]
Amtrak	Pullman	Superliner I	Multi-level coach	245	1975-1981	[6]
Amtrak	Bombardier	Superliner II	Multi-level coach	184	1991-1996	[4]
Austin Capital Metro	Stadler	DMU	Alternatively designed	6	2005	[7]
CalTrain	Nippon-Sharyo	Gallery Trailer	Multi-level coach	26	1985	[8]
CalTrain	Nippon-Sharyo	Gallery Trailer	Multi-level coach	10	1985	[8]
CalTrain	Nippon-Sharyo	Gallery Trailer	Multi-level coach	6	1985	[8]
CalTrain	Nippon-Sharyo	Gallery Trailer	Multi-level coach	10	1986	[8]
CalTrain	Nippon-Sharyo	Gallery Trailer	Multi-level coach	14	2000	[8]
CalTrain	Nippon-Sharyo	Gallery Cab (Bike)	Multi-level coach	21	1985	[8]

Railroad	Car Manuf.	Car Name or Desc.	Type of Car	# in Fleet	Year(s) of Manuf.	Source
CalTrain	Nippon-Sharyo	Gallery Cab (Bike)	Multi-level coach	6	2000	[8]
CalTrain	Bombardier	Bi-level Cab (Bike)	Multi-level coach	7	2002	[8]
CalTrain	Bombardier	Bi-level Cab (Bike)	Multi-level coach	1	2002	[8]
CalTrain	Bombardier	Bi-level Trailer	Multi-level coach	9	2002	[8]
CalTrain	Bombardier	Bi-level Cab (Bike)	Multi-level coach	2	2008	[8]
CalTrain	Bombardier	Bi-level Trailer	Multi-level coach	6	2008	[8]
CalTrain	Bombardier	Bi-level Trailer	Multi-level coach	5	1997	[8]
Coaster (California)	Bombardier	Bi-level	Multi-level coach	28	1994, 1997, 2003	[8]
DCTA	Stadler	A-train	Alternatively designed	11	2010-2012	[9]
Denver RTD	Rotem	RTD	Single-level coach	66	2014	[10]
FrontRunner (Utah)	Pullman-Standard	Comet I	Single-level coach	25	1970-1973	[11]
FrontRunner (Utah)	Bombardier	Bi-level (VII)	Multi-level coach	20	2006-2007	[11]
LIRR	Kawasaki	C3	Multi-level coach	134	1997-1999	[12]
LIRR	Budd	M3	Single-level coach	170	1984-1986	[12]
LIRR	Bombardier	M7	Single-level coach	836	1999-2006	[12]
MARC	Kawasaki	MARC III	Multi-level coach	63	1999-2001	[13]
MARC	Sumitomo/Nippon-Sharyo	MARC IIB	Single-level coach	60	1985-1987; 1991-1993	[13]
MARC	Bombardier	MARC IV (MLV)	Multi-level coach	54	2014	[13]
MBTA	Pullman-Standard	BTC-1C	Single-level coach	57	1978-1979	[14]
MBTA	Bombardier	BTC-1A	Single-level coach	40	1987	[14]
MBTA	MBB	CTC/BTC-3	Single-level coach	32	1987-1988	[14]
MBTA	Bombardier	BTC-1B	Single-level coach	105	1989-1990	[14]
MBTA	Kawasaki	CTC/BTC-4	Multi-level coach	33	1990-1991	[14]

Railroad	Car Manuf.	Car Name or Desc.	Type of Car	# in Fleet	Year(s) of Manuf.	Source
MBTA	Kawasaki	BTC-4A	Multi-level coach	16	1997-1998	[14]
MBTA	Kawasaki	BTC-4B	Multi-level coach	14	2001-2002	[14]
MBTA	Rotem	CTC5/BTC-4D	Multi-level coach	74	2012-2014	[14]
MBTA	Kawasaki	BTC-4C	Multi-level coach	33	2005-2006	[14]
Metra	Nippon-Sharyo	Bi-level Cab Car	Multi-level coach	108	2002-2005	[15]
Metra	Pullman	Bi-level Cab Car	Multi-level coach	32	1956-1970	[15]
Metra	Amerail	Bi-level Cab Car	Multi-level coach	65	1995-1997	[15]
Metra	Morrison Knudsen	Bi-level Cab Car	Multi-level coach	14	1994-1995	[15]
Metra	Amerail	Bi-level Coach	Multi-level coach	97	1996-1998	[15]
Metra	Budd	Bi-level Coach	Multi-level coach	340	1953-1980	[15]
Metra	Nippon-Sharyo	Bi-level Coach	Multi-level coach	194	2002-2009	[15]
Metra	Bombardier	Bi-level EMU	Multi-level coach	9	1978-1979	[15]
Metra	St. Louis Car Co.	Bi-level EMU	Multi-level coach	19	1971-1972	[15]
Metra	Nippon-Sharyo	Bi-level EMU	Multi-level coach	168	2005-2015	[15]
Metrolink	Bombardier	Bi-level (I)	Multi-level coach	88	1992-1993	[16]
Metrolink	Bombardier	Bi-level (II)	Multi-level coach	23	1997	[16]
Metrolink	Bombardier	Bi-level (III)	Multi-level coach	26	2002	[16]
Metrolink	Rotem	Guardian	Multi-level coach	137	2010-2013	[16]
Metro-North	Bombardier	M7A	Single-level coach	336	2004-2005	[17]
Metro-North	Kawasaki	M8	Single-level coach	405	2009-Present	[17]
Metro-North	Bombardier	Shoreliner IV	Single-level coach	60	1996-1998	[17]
Metro-North	Bombardier	Shoreliner III	Single-level coach	49	1991	[17]
Metro-North	Bombardier	Shoreliner II	Single-level coach	36	1987	[17]
Metro-North	Bombardier	Shoreliner I	Single-level coach	39	1983	[17]
Music City Star (Tennessee)	Budd	Bi-level Coach	Multi-level coach	7	1950s	[18]

Railroad	Car Manuf.	Car Name or Desc.	Type of Car	# in Fleet	Year(s) of Manuf.	Source
New Mexico Rail Runner	Bombardier	Bi-level (VI)	Multi-level coach	22		[19]
NJ Transit	Bombardier	Comet II	Single-level coach	160	1982	[20]
NJ Transit	Bombardier	Comet IV	Single-level coach	99	1997	[20]
NJ Transit	Bombardier	Comet V	Single-level coach	265	2004	[20]
NJ Transit	Bombardier	MLV I	Multi-level coach	329	2007	[20]
NJ Transit	Bombardier	MLV II	Multi-level coach	100	2014	[20]
NJ Transit	GE	Arrow III	Single-level coach	160	1977	[20]
Northstar (Minnesota)	Bombardier	Bi-level (VII)	Multi-level coach	17		[20]
SEPTA	GE/Avco	Silverliner IV	Single-level coach	232	1973-1976	[21]
SEPTA	Rotem	Silverliner V	Single-level coach	120	2010-2013	[21]
Shore Line East (Connecticut)	Mafersa	Coaches	Single-level coach	33	1991-1992	[22]
SMART	Nippon-Sharyo	DMU	Single-level coach	18	2013-present	[23]
Sounder (Washington)	Bombardier	Bi-level (VIII)	Multi-level coach	58		[24]
South Shore Line (Chicago/Indiana)	Nippon-Sharyo	Single-level EMU	Single-level coach	41	1982-1983	[25]
South Shore Line (Chicago/Indiana)	Nippon-Sharyo	Single-level EMU	Single-level coach	7	1992	[25]
South Shore Line (Chicago/Indiana)	Nippon-Sharyo	Trailer	Single-level coach	10	1992	[25]
South Shore Line (Chicago/Indiana)	Nippon-Sharyo	Single-level EMU	Single-level coach	10	2001	[25]
South Shore Line (Chicago/Indiana)	Nippon-Sharyo	Bi-level EMU	Multi-level coach	14	2009	[25]
Sprinter (California)	Siemens	Sprinter DMU	Alternatively designed	12	2006	[26]

Railroad	Car Manuf.	Car Name or Desc.	Type of Car	# in Fleet	Year(s) of Manuf.	Source
Sunrail	Bombardier	Bi-level (VII)	Multi-level coach	20		[27]
Trinity Railway Express (Texas)	Bombardier	Bi-level (II)	Multi-level coach	25		[28]
Tri-Rail (Florida)	Rotem	Guardian	Multi-level coach	24		[29]
Tri-Rail (Florida)	Bombardier	Bi-level (III)	Multi-level coach	26		[30]
Tri-Rail (Florida)	Colorado Railcar	DMU	Multi-level coach	3		[30]
VRE	Pullman	Gallery I	Multi-level coach	5		[31]
VRE	Pullman	Gallery II	Multi-level coach	9		[31]
VRE	Sumitomo/Nippon-Sharyo	Gallery IV	Multi-level coach	84		[31]
WES Commuter Rail (Oregon)	Colorado Railcar	DMU	Single-level coach	4	2008	[32]
WES Commuter Rail (Oregon)	Budd	RDC	Single-level coach	2	1953	[32]

A1. Sources for U.S. Passenger Rolling Stock Car Count

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Appendix B.
Section Modulus Calculations

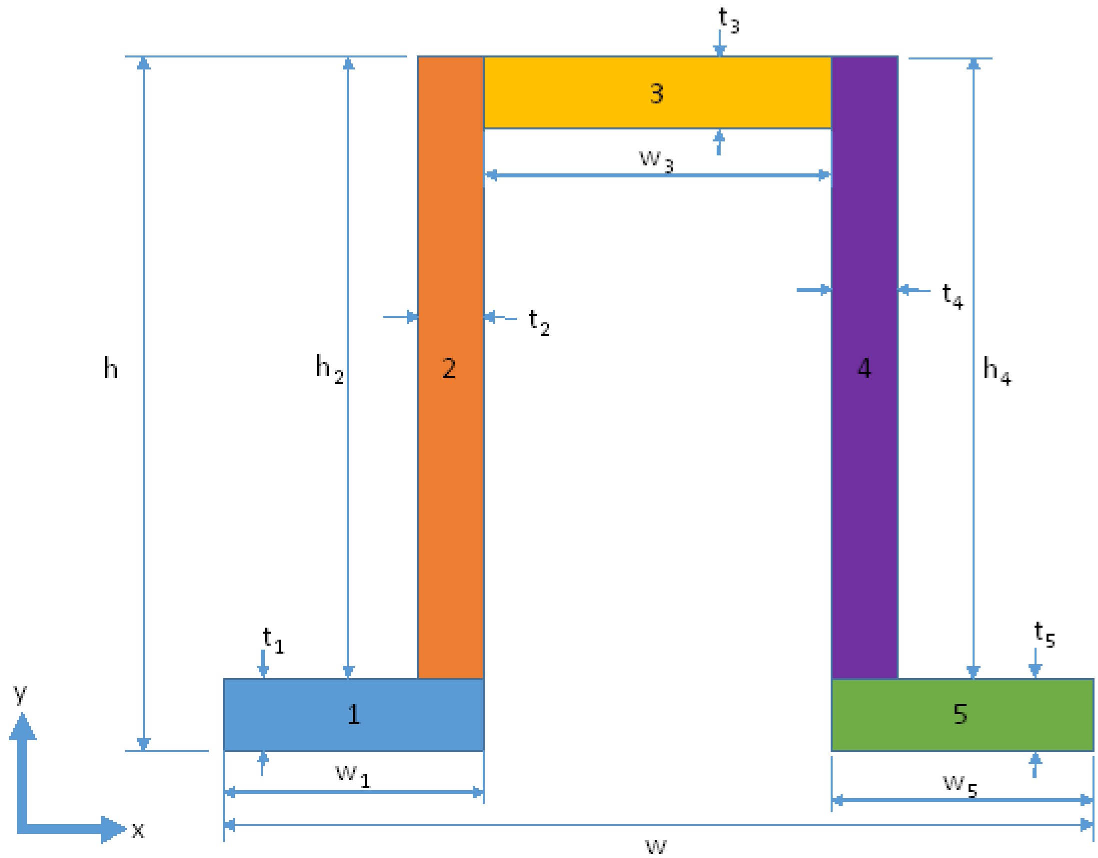

Figure B1. Generalized Sidewall Post Cross-section

User-defined Section Dimensions

w_1=1.75in

w_3=1.75in

w_5=1.75in

$w=w_1+w_3+w_5$=5.25in

$t_5=t_4=t_3=t_2=t_1$=0.125in

h=2.75in

$h_2=h-t_1$=2.625in

$h_4=h-t_5$=2.625in

User-defined Material Parameters

$E=3x10^7$ psi

$\sigma_{yieldactual}$=100,000 psi [Note: values of 60,000 and 80,000 psi were also used]

User-defined Carbody Parameters

n_{posts}=15 [number of side posts]

$Distance_{endpanelcenters}$=81 feet [End panel center distance defined in CFR]

$H_{sidepost}$=65in [height of side post]

$\Delta_{posttopost}=Distance_{endpanelcenters}/n_{posts}$=64.8 in [Average distance between post centers]

Calculate Cross-sectional Area of One Post

$A_1=w_1 \cdot t_1 = 0.21875$ in^2
$A_2=t_2 \cdot h_2 = 0.328125$ in^2
$A_3=w_3 \cdot t_3 = 0.21875$ in^2
$A_4=t_4 \cdot h_4 = 0.328125$ in^2
$A_5=w_5 \cdot t_5 = 0.21875$ in^2
$A_{total}=A1+A2+A3+A4+A5=1.31$ in^2

Calculate Centroid Location and Area Moments of Inertia for Bending About Centroid

Reference: Example A1 of Mechanics of Materials, Fifth Edition, R.C. Hibbeler

$Centroid_x=[A_1 \cdot (w_1/2)+A_2 \cdot (w_1-t_2/2)+A3 \cdot (w_1+w_3/2)+A_4 \cdot (w_1+w_3+t_4/2)+A_5 \cdot (w_1+w_3+w_5/2)]/A_{total}$

$Centroid_x$=2.625 in

$Centroid_y=[A_1 \cdot (t_1/2)+A_2 \cdot (t_1+h_2/2)+A3 \cdot (h-t_3/2)+A_4 \cdot (t5+h_4/2)+A_5 \cdot (t_5/2)]/A_{total}$

$Centroid_y$=1.1875 in

Moment of Inertia of Each Segment about an X-axis through its Local Centroid

$I_{1xaxis}=1/12 \cdot w_1 \cdot t_1^3 = 2.85 \cdot 10^{-4}$ in^4

$I_{2xaxis}=1/12 \cdot t_2 \cdot h_2^3 = 0.188416$ in^4

$I_{3xaxis}=1/12 \cdot w_3 \cdot t_3^3 = 2.85 \cdot 10^{-4}$ in^4

$I_{4xaxis}=1/12 \cdot t_4 \cdot h_4^3 = 0.188416$ in^4

$I_{5xaxis}=1/12 \cdot w_5 \cdot t_5^3 = 2.85 \cdot 10^{-4}$ in^4

Moment of Inertia of Each Segment about an Y-axis through its Local Centroid

$I_{1yaxis}=1/12 \cdot t_1 \cdot w_1^3 = 5.58 \cdot 10^{-2}$ in^4

$I_{2yaxis}=1/12 \cdot h_2 \cdot t_2^3 = 4.27 \cdot 10^{-4}$ in^4

$I_{3yaxis}=1/12 \cdot t_3 \cdot w_3^3 = 5.58 \cdot 10^{-2}$ in^4

$I_{4yaxis}=1/12 \cdot h_4 \cdot t_4^3 = 4.27 \cdot 10^{-4}$ in^4

$I_{5yaxis}=1/12 \cdot t_5 \cdot w_5^3 = 5.58 \cdot 10^{-2}$ in^4

Distance in X-direction from Local Centroid of Each Segment to Global Centroid

d_{1x}= (w_1/2)-$Centroid_x$ = -1.75 in

d_{2x}= (w_1-t_2/2)-$Centroid_x$ = -0.9375 in

d_{3x}= (w_1+w_3/2)-$Centroid_x$ = 0 in

d_{4x}= (w_1+w_3+t_4/2)-$Centroid_x$ = 0.9375 in

d_{5x}= (w_1+w_3+w_5/2)-$Centroid_x$ = 1.75 in

Distance in Y-direction from Local Centroid of Each Segment to Global Centroid

d_{1y}= t_1/2-$Centroid_y$ = -1.125 in

d_{2y}= (t_1+h_2)-$Centroid_y$ = 0.25 in

d_{3y}= (h-t_3/2)-$Centroid_y$ = 0.25 in

d_{4y}= (t_5+h_4/2)-$Centroid_y$ = 0.25 in

d_{5y}= t_5/2-$Centroid_y$ = -1.125 in

Bending about X-axis from Load in Y-direction

$I_{xaxis} = (I_{1xaxis}+A_1 \cdot d_{1y}^2)+(I_{2xaxis}+A_2 \cdot d_{2y}^2)+(I_{3xaxis}+A_3 \cdot d_{3y}^2)+(I_{4xaxis}+A_4 \cdot d_{4y}^2)+(I_{5xaxis}+A_5 \cdot d_{5y}^2)$

I_{xaxis} = 1.4646in^4

[If section is asymmetric there will be two difference distances from global centroid to extreme fiber:]

c_{ydir1} = $Centroid_y$

c_{ydir2} = h-$Centroid_y$

Z_{xaxis1}=I_{xaxis}/c_{ydir1} = 1.23 in^3

Z_{xaxis2}=I_{xaxis}/c_{ydir2} = 0.94 in^3

[The smaller of Z_{xaxis1} or Z_{xaxis2} should be used in meeting minimum section modulus requirements]

Bending about Y-axis from Load in X-direction

$I_{yaxis} = (I_{1yaxis}+A_1 \cdot d_{1x}^2)+(I_{2yaxis}+A_2 \cdot d_{2x}^2)+(I_{3yaxis}+A_3 \cdot d_{3x}^2)+(I_{4yaxis}+A_4 \cdot d_{4x}^2)+(I_{5yaxis}+A_5 \cdot d_{5x}^2)$

I_{yaxis} = 2.084961 in^4

c_{xdir1} = $Centroid_x$

c_{xdir2} = w - $Centroid_x$

Z_{yaxis1}=I_{yaxis}/c_{xdir1} = 0.794271 in^3

Z_{yaxis2}=I_{yaxis}/c_{xdir2} = 0.794271 in^3

[The smaller of Z_{yaxis1} or Z_{yaxis2} should be used in meeting minimum section modulus requirements]

Total Section Modulus per Car Side

$Z_{xaxistotal}$=$n_{posts} \cdot min(Z_{xaxis1},Z_{xaxis2})$ = $\underline{14.06\ in^3}$

$Z_{yaxistotal}$=$n_{posts} \cdot min(Z_{yaxis1},Z_{yaxis2})$ = $\underline{11.91\ in^3}$

Abbreviations and Acronyms

ACRONYM	EXPLANATION
AAR	Association of American Railroads
APTA	American Public Transportation Association
ATD	Anthropomorphic Test Device
CFR	Code of Federal Regulations
CG	Center of Gravity
DOT	Department of Transportation
FMVSS	Federal Motor Vehicle Safety Standards
FRA	Federal Railroad Administration
IIHS	Insurance Institute for Highway Safety
MDB	Moving Deformable Barrier
ms	milliseconds
NHTSA	National Highway Traffic Safety Administration
NPRM	Notice of Proposed Rulemaking
NTSB	National Transportation Safety Board
PATH	Port Authority Trans-Hudson
PESS	Passenger Equipment Safety Standards
TSB	Transportation Safety Board of Canada
UTS	Ultimate Tensile Strength
Volpe	Volpe National Transportation Systems Center