Safety Study of Double-Decker Motorcoaches with Rear Luggage Compartment

Final Report

U.S. Department of Transportation
Federal Motor Carrier Safety Administration

December 2017

FOREWORD

This final report documents the tests and inspections performed as part of the project entitled "Safety Study of Double-Decker Motorcoaches with Rear Luggage Compartment" for the Federal Motor Carrier Safety Administration (FMCSA). The goal of the project was to study the effects of a rear luggage compartment on (i) vehicle operations, (ii) fire suppression, (iii) tire loads, and (iv) roadway pavement. This report contains the findings from the study, including experiments and engineering analysis.

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16. Abstract

Section 5510 of Fixing America's Surface Transportation Act, 2015 (FAST Act) required the Secretary of Transportation to conduct a study on the effects of attaching a luggage compartment to the rear of a double-decker motorcoach, with respect to safety of vehicle operations, fire suppression capability, tire loads, and pavement impacts. This report presents the results of that study.

The study was conducted through a combination of analysis and tests with a double-decker motorcoach. The three conditions were a reference loading condition, a regulatory loading condition, and a maximum loading condition. The reference or baseline condition had the load for passengers and luggage but no rear luggage compartment. The regulatory condition had a payload identical to the reference condition, but a rear luggage compartment was attached. In the maximum loading condition the motorcoach, with a rear luggage compartment attached, was loaded to its gross vehicle weight rating (GVWR).

The rear luggage compartment did not affect safe maneuverability over the range of conditions tested. There is an unquantified concern that the compartment could contain heat in a severe engine compartment fire and lead to breaching the rear window. The tires and rims have adequate capacity for their loads. States must enact limits on tire and axle loads that are consistent with Federal Highway Administration (FHWA) regulations. The loads under all conditions may exceed some State limits with respect to the FHWA bridge formula.

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Double-decker, motorcoach, bus, safety, fire risk, emergency egress, tire load, pavement damage, Section 5510, FAST Act

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SI* (MODERN METRIC) CONVERSION FACTORS

Approximate Conversions to SI Units

Symbol	When You Know	Multiply By	To Find	Symbol
		Length		
in.	inches	25.4	millimeters	mm
Ft	feet	0.305	meters	m
Yd	yards	0.914	meters	m
Mi	miles	1.61	kilometers	km
		Area		
in.^{2}	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yards	0.836	square meters	m^2
Ac	Acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		Volume (volumes greater than 1,000L shall be shown in m^3)		
fl oz	fluid ounces	29.57	milliliters	mL
Gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		Mass		
Oz	ounces	28.35	grams	g
Lb	pounds	0.454	kilograms	kg
T	short tons (2,000 lb)	0.907	megagrams (or “metric ton”)	Mg (or “t”)
		Temperature (exact degrees)		
°F	Fahrenheit	5(F-32)/9 or (F-32)/1.8	Celsius	°C
		Illumination		
Fc	foot-candles	10.76	lux	lx
Fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		Force and Pressure or Stress		
Lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

Approximate Conversions from SI Units

Symbol	When You Know	Multiply By	To Find	Symbol
		Length		
Mm	millimeters	0.039	inches	in.
M	meters	3.28	feet	ft
M	meters	1.09	yards	yd
Km	kilometers	0.621	miles	mi
		Area		
mm^2	square millimeters	0.0016	square inches	in.^{2}
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
Ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		Volume		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		Mass		
G	grams	0.035	ounces	oz
Kg	kilograms	2.202	pounds	lb
Mg (or “t”)	megagrams (or “metric ton”)	1.103	short tons (2,000 lb)	T
		Temperature (exact degrees)		
°C	Celsius	1.8c+32	Fahrenheit	°F
		Illumination		
Lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		Force and Pressure or Stress		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

* SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380. (Revised March 2003, Section 508-accessible version September 2009.)

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LIST OF ACRONYMS, ABBREVIATIONS, AND SYMBOLS

Abbreviation	Definition
AASHTO	American Association of State Highway and Transportation Officials
ASME	American Society of Mechanical Engineers
CFR	Code of Federal Regulations
CVSA	Commercial Vehicle Safety Alliance
FAST	Fixing America's Surface Transportation Act, 2015, Public Law 114-94
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
FMVSS	Federal Motor Vehicle Safety Standard
GAWR	gross axle weight rating
GVWR	gross vehicle weight rating
ISO	International Organization for Standardization
MAP-21	Moving Ahead for Progress in the 21st Century Act, Public Law 112-141
NHTSA	National Highway Traffic Safety Administration
PPE	personal protective equipment
SAE	Society of Automotive Engineers International
SAFETEA-LU	Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users
TRC	Transportation Research Center, Inc.
UNECE	United Nations Economic Commission for Europe
USC	U.S. Code
USDOT	U.S. Department of Transportation
VIN	vehicle identification number

EXECUTIVE SUMMARY

This final report transmits the results of a study undertaken by the Secretary of Transportation in response to Section 5510 of the Fixing America's Surface Transportation Act, 2015 (FAST Act). The study examined the operation of a double-decker motorcoach attached at its rear with a luggage compartment. The study covered (i) safety of vehicle operations, (ii) fire suppression capability, (iii) tire loads, and (iv) effects on roadway pavement. State transportation safety and law enforcement officials were consulted, and the study plan was revised according to their comments.

An exemplar motorcoach, a Van Hool TD925, was examined under three loading conditions: a reference condition with ballast to represent a full load of passengers and their normal luggage without a rear luggage compartment; regulatory loading condition with the same amount of ballast and a rear luggage compartment attached; and a maximum loading condition with the vehicle weighted to its gross vehicle weight rating (GVWR).

Where possible, the study applied established standards. Some standards, such as the Federal Motor Vehicle Safety Standards (FMVSSs) provide requirements that must be met. The study considered whether the rear luggage compartment inhibited the ability of the vehicle to meet the standards. The industry standards used in this study are test methods that produce data for characterizing the vehicle's performance. Behavior under the two loading conditions with the rear luggage compartment was compared with that under the reference condition without the compartment. Where no standards were available to assess the fire risk, differences in risk and suppression capability were documented.

Specific topics were examined within each of the four major areas of study. Some of the topics were addressed by driving the motorcoach under one or more of the three loading conditions through a prescribed maneuver on a test track. Other topics were addressed by analysis or calculations. The results of the study are summarized in the tables on the next page.

1. **Safety of vehicle operations:** In this study, the rear luggage compartment did not impair the vehicle's ability to meet any of the FMVSSs tested. Its effects on vehicle handling ability, over the range of conditions tested, were not measurable or were of minimal significance.
2. **Fire risk:** The rear compartment is mounted near the vehicle's engine. The compartment could keep heat from an engine compartment fire near the vehicle, which could accelerate loss of the rear window and allow combustion products in the passenger compartment. The compartment does not block any exit.
3. **Tire loads:** The tires and rims on the motorcoach have adequate capacity for their loads.
4. **Bridge and pavement damage:** States must enact limits on tire and axle loads that are consistent with Federal Highway Administration (FHWA) regulations. The loads under all conditions may exceed some State limits with respect to the FHWA bridge formula. The tire load per width under the maximum loading condition may exceed some State limits.

Table 1. Key findings on operational safety.

Topic	Applicable Standard	Method	Summary Finding
Stopping Distance	FMVSS No. 121, S5.3.1	Test	The luggage compartment did not affect stopping distance.
Turning Radius	SAE J695	Test	Repositioning weight increased turning radius by 7 inches.
High-Speed Cornering	ISO 14792	Test	The compartment had a minimal effect in the test conditions.
Lane Change	ISO 14793, Section 10	Test	The compartment had a minimal effect in the test conditions.
Structural Integrity	(Analysis based on MIL-STD-810G Method 514.7)	Test and Analysis	The lifetime of the attachment hardware is estimated to be adequate.
Lighting	FMVSS No. 108	Inspection	Location and activation requirements were met.
Rear Visibility	FMVSS No. 111, S7	Inspection	The compartment did not interfere with rear visibility.

Table 2. Key findings on fire safety.

Topic	Applicable Standard	Method	Summary Finding
Emergency Egress	FMVSS No. 217	Inspection	The rear luggage compartment blocked no exits.
Chimney Effect	(none)	Inspection	There is an unquantified concern that the compartment might keep heat and smoke near the vehicle.
Unlatching Time	(none)	Inspection	The compartment can be quickly removed by tools carried by a fire suppression crew.
Fuel Source	(none)	Inspection	Compartment contents could become fuel for a fire.

Table 3. Key findings on tire loads.

Topic	Applicable Standard	Method	Summary Finding
Tire Capacity	FMVSS No. 119, S6.5 and S6.6	Inspection	Tires had adequate capacity.
Rim Capacity	FMVSS No. 120, S5.1.2, S5.3	Inspection	Rims had adequate capacity.

Table 4. Key findings on bridge and pavement damage.

Topic	Applicable Standard	Method	Summary Finding
Bridge Formula	State rules based on 23 CFR 658.17 (e)	Calculation	Loads above some State limits.
Maximum Axle Load	State rules based on 23 CFR 658.17 (f)	Calculation	Loads above some State limits.
Tire Load-to-Width Ratio	State rules based on 23 CFR 658.17(f)	Calculation	Some loads are close to some State limits.

1. INTRODUCTION

In accordance with Section 5510 of the Fixing America's Surface Transportation Act, 2015 (FAST Act, Public Law 114-94), the Federal Motor Carrier Safety Administration (FMCSA) conducted the "Safety Study of Double-Decker Motorcoaches with Rear Luggage Compartment." Section 5510 of the FAST Act(1) reads:

> *SEC. 5510. SAFETY STUDY REGARDING DOUBLE-DECKER MOTORCOACHES.*
>
> *(a) STUDY—The Secretary, in consultation with State transportation safety and law enforcement officials, shall conduct a study regarding the safety operations, fire suppression capability, tire loads, and pavement impacts of operating a double-decker motorcoach equipped with a device designed by the motorcoach manufacturer to attach to the rear of the motorcoach for use in transporting passenger baggage.*

1.1 SCOPE OF THE STUDY

The study was performed at the Battelle Memorial Institute in Columbus Ohio (modeling and analysis) and at the Transportation Research Center in East Liberty, Ohio (vehicle inspections and performance testing). The study focused on the rear luggage compartment. A double-decker motorcoach without a rear luggage compartment was the reference for comparison. Government and industry test procedures were used wherever applicable. Stationary inspections of the vehicle with the rear luggage compartment were conducted while the vehicle was parked. High- and low-speed maneuvering tests were conducted on a test track at the Transportation Research Center in East Liberty, Ohio. The tests were conducted with and without the rear luggage compartment.

The requirement of Section 5510 to consult with State transportation safety officials was fulfilled by a webinar with the American Association of State Highway and Transportation Officials (AASHTO) on September 13, 2016. The requirement of Section 5510 to consult with law enforcement officials was fulfilled by a meeting with the Passenger Carrier Committee of the Commercial Vehicle Safety Alliance in Little Rock, Arkansas on September 20, 2016. Adjustments to the research plan were made in response to these consultations. Specific points raised in the consultations are in Appendix A. In addition, a panel of three independent reviewers met to review the study's research plan before the experimental work began, and the panel met again to review the final study report. The reviewers had expertise in heavy vehicle dynamics, heavy vehicle tires, and motorcoach fire safety.

1.2 SUBJECT VEHICLE

The subject vehicle for this study was a Van Hool TD925 double-decker motorcoach with a rear luggage compartment. Photos of the vehicle are provided in Figure 1 and Figure 2. ABC Bus, Inc., the exclusive Van Hool Coach distributor in the United States, leased a vehicle to this study.

The lower deck of the test vehicle has 22 seats for passengers plus a seat for the driver. The upper deck has seats for 59 passengers, for a total of 82 designated seating positions.

The vehicle identification number (VIN) plate on the test vehicle specifies that the gross vehicle weight rating (GVWR) of the vehicle is 62,000 lb. Other information on the VIN plate, including tire size, rim size, and gross axle weight rating (GAWR) of each axle is shown in Table 5. Table 6 provides vehicle dimensions and other information from the manufacturer's specifications.

Figure 1. Photo. The subject vehicle for this study was a 2008 model Van Hool TD925 double-decker motorcoach with a rear luggage compartment.

Figure 2. Photo. The rear luggage compartment extends the length of the motorcoach by about 2 ft, 11 in.

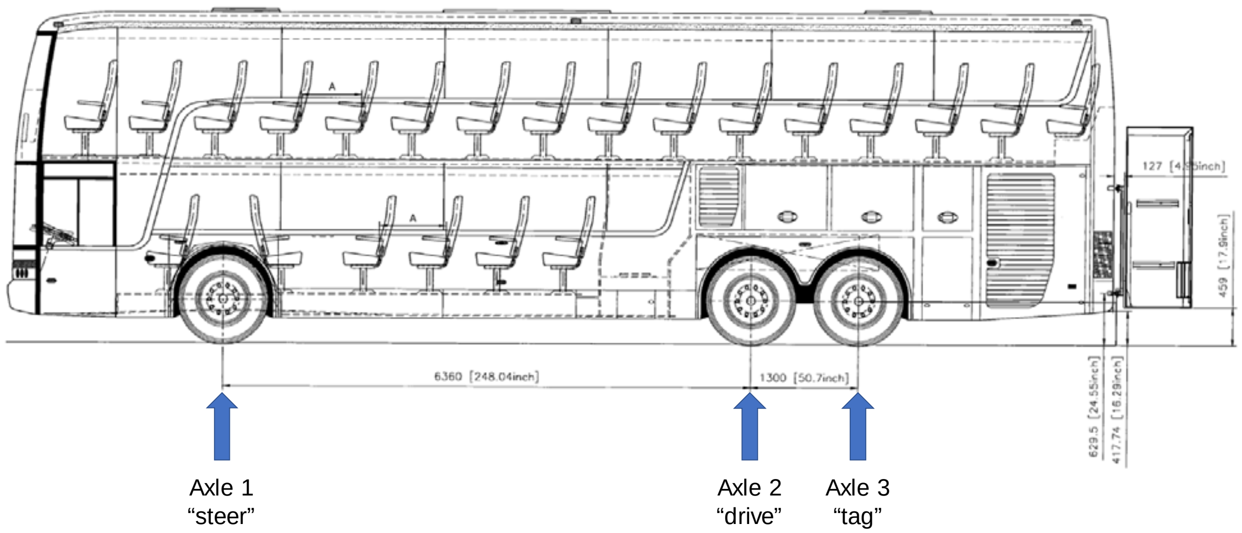
Table 5. GAWR, tire size and inflation, and rim size of the test vehicle (from the VIN plate on the vehicle).

Axle location	GAWR (lb)	Tire size and load range	Rim size
First axle (steer)	18,180	365/70R22.5 – L (single)	10.5 x 22.5
Second axle (drive)	27,575	315/80R22.5 – L (dual)	9.00 x 22.5
Third axle (tag)	18,180	365/70R22.5 – L (single)	10.5 x 22.5

Table 6. Test vehicle specifications (provided by the manufacturer).

Item	Measurement
Length (without rear luggage compartment)	43 ft, 10 in.
Length (with rear luggage compartment)	46 ft, 9 in.
Overall width	102 in.
Overall height	13 ft, 1 in.
Axle spacing	20 ft, 10 in. (first to second) 4 ft, 3 in. (second to third) 25 ft, 1 in. (first to third)
Seating capacity	22 passengers + driver (lower deck) 59 passengers (upper deck) 82 occupants (total)
Headroom	71 in. (lower deck) 67 in. (upper deck)
Fuel tank capacity	166 gallons

A side view drawing of the test vehicle with the rear luggage compartment is shown in Figure 3. The luggage compartment in the vehicle itself is behind the lower seating area, above and behind the rear axles. The tare weight of the rear luggage compartment specified by the manufacturer is 705 lb, and its rated weight capacity is 771 lb, for a total additional weight of 1,476 lb. The specified volume of the rear luggage compartment is 123 cubic ft.



Source: ABC Companies. Used by permission.

Figure 3. Drawing. Side view of the vehicle with the rear luggage compartment.

Figure 4 shows how the rear luggage compartment can swing on hinges on the right side of the compartment after a latch on the left side is disconnected.

Figure 4. Photo. The luggage compartment can swing away from the motorcoach.

2. LOADING CONDITIONS

Three loading conditions were tested. The first was a reference condition without the rear luggage compartment, but with a full complement of passengers and their nominal luggage. The second and third loading conditions had the rear luggage compartment.

2.1 LOADING CONDITIONS

The safety effects of the rear luggage compartment on the operations of the double-decker motorcoach were examined under three loading conditions:

1. *Reference loading condition:* The reference or baseline loading condition refers to the full load of passengers, each with luggage, but without the rear luggage compartment. The weight of the cargo was the average luggage weight multiplied by the number of passengers. Some luggage was in the passenger compartment, and some in the luggage compartments in the vehicle.
2. *Regulatory loading condition:* The regulatory loading condition had the same payload as the reference condition. The difference between this and the reference loading condition was the distribution of the load. In this condition, the rear luggage compartment was attached and filled to its weight capacity by moving luggage from the luggage compartment in the vehicle itself.
3. *Maximum loading condition:* Weight was added to the passenger compartment and the luggage compartments in the vehicle itself to reach the GVWR specified by the manufacturer of 62,000 lb. The rear luggage compartment was loaded to its weight capacity in the regulatory loading condition; accordingly, no new weight was added to the rear luggage compartment for the maximum loading condition.

2.2 PASSENGER WEIGHT

The National Highway Traffic Safety Administration (NHTSA) specifies in 49 CFR 567.4(g)(3) and 567.5(b)(2)(iii) that vehicles other than school buses be rated for not less than 150 lb per designated seating position. Thus, a weight of 150 lb per occupant was used for this study.

2.3 LUGGAGE WEIGHT

There is no regulatory or industry standard for the weight of luggage carried by a motorcoach passenger. Prior studies provide guidance. A study examining the distribution of loads in mid-sized buses considered a number of sources and ultimately took an average weight of 25 lb per occupant stored under the passenger compartment and 5 lb per passenger in the passenger compartment.(2) A similar study that focused on the effect of seating structure and passenger weight on rollover crashworthiness assumed the average density of a luggage to be 6.24 lb/ft^3, resulting in an average total weight of luggage per passenger of 47 lb.(3) Another study on maximum axle weight restrictions for motorcoaches used an average weight of 20 lb per passenger.[(4)] A technical description of the Van Hool TD925 provided by ABC Bus, Inc., allows a luggage weight of 35 lb per person.

This study used the Van Hool amount of 35 lb per person in the first two loading conditions. Of this, 10 lb for each person was allocated to the passenger compartment. The remaining 25 lb of luggage per person was in the luggage compartments, either in the vehicle itself or in the rear luggage compartment, depending on loading condition. In both the regulatory and maximum loading conditions, the rear luggage compartment was loaded to its full rated weight capacity. In the maximum loading condition, additional weight was placed in the passenger and luggage compartments within the vehicle itself.

2.4 ACTUAL LOADS

Passenger weight was simulated by water dummies, torso-shaped polymer tanks that can be strapped to seats to simulate passenger weight (Figure 5). A water dummy weighs about 175 lb when completely full. A standard occupant is 150 lb, and the passenger-compartment luggage allocation is 10 lb, for a total weight per occupant of 160 lb. Each water dummy was left approximately one gallon short of full. This headspace permitted little sloshing to affect the dynamics. Luggage weight was simulated by bags of salt, which were placed in the luggage compartment within the vehicle itself or in the rear luggage compartment. In the maximum loading condition, water dummies were put in the aisle in the upper and lower decks, and salt bags were put on the floor of the passenger compartment. Putting all of the additional weight for the maximum loading condition in the luggage compartment would have put too much weight on the rear axles.

Figure 5. Photo. Water dummies to simulate passenger weight were strapped to the seats in the motorcoach.

Figure 6. Photo. Salt bags in the luggage compartment in the vehicle, which is aft of the lower deck seating.

Figure 7. Photo. Bags of salt were distributed on shelves of the rear luggage compartment.

The vehicle was weighed in five conditions:

1. Empty or “curb” weight without the rear luggage compartment (see Table 7).
2. Empty or “curb” weight with the luggage compartment (see Table 8).
3. Reference or baseline loading condition specified on page 5 (see Table 9).
4. Regulatory loading condition specified on page 5 (see Table 10).
5. Maximum loading condition specified on page 5 (see Table 11).

The empty conditions had no driver, no passengers, no luggage, and no instruments. The loaded conditions were as the vehicle was tested, with human driver, steering machine, water dummies and salt bags, and instruments. The fuel and other fluids were full for all conditions.

The motorcoach was weighed on a set of calibrated vehicle scales. The individual scales were arranged so that the six-axle end loads could be measured separately. The vehicle was weighed twice in every condition. The average of the two weighings is reported in the tables. The greatest difference in axle end loads between repeated weighing was 110 lb.

Table 12 lists the total payload weight in the three loading conditions. The payload weight in the reference loading condition corresponds to 187 lb per occupant. This is close to the target weight of 185, or 150 lb each for the occupants themselves plus 35 lb of luggage per person. The payload per person increased another 6 lb in the regulatory condition. When the motorcoach was loaded to its GVWR, the payload weight per seating position was 253 lb. To achieve that total weight and properly balance the load between the axles, more ballast had to be added to the passenger compartment. In the maximum load condition, a total of 94 water dummies were in the passenger compartment, with some in seats and some on the floor. In practical terms, this means that the average passenger would have weighed more than 150 lb. The longitudinal position of the center of gravity was calculated from the axle loads.

Table 7. Measured loads (lb) of the vehicle at curb weight (no persons or luggage), without the rear luggage compartment.

Axle location	Load on left	Load on right	Total axle load
First axle	5,725	5,315	11,040
Second axle	9,225	8,930	18,155
Third axle	5,815	5,680	11,495
Rear tandem (axles 2+3)	15,040	14,610	29,650
Whole vehicle	20,765	19,925	40,690

Table 8. Measured loads (lb) of the vehicle at curb weight (no persons or luggage), with the rear luggage compartment.

Axle location	Load on left	Load on right	Total axle load	Added by the luggage compartment
First axle	5,400	5,195	10,595	-445
Second axle	9,675	9,205	18,880	725
Third axle	6,065	5,785	11,850	355
Rear tandem (axles 2+3)	15,740	14,990	30,730	1,080
Whole vehicle	21,140	20,185	41,325	635

Table 9. Measured loads (lb) for the reference loading condition (no luggage compartment).

Axle location	Load on left	Load on right	Total axle load	Weight of driver, instruments, passengers, and luggage
First axle	8,795	8,660	17,455	6,415
Second axle	12,225	11,175	23,400	5,245
Third axle	7,965	7,180	15,145	3,650
Rear tandem (axles 2+3)	20,190	18,355	38,545	8,895
Whole vehicle	28,985	27,015	56,000	15,310

Table 10. Measured loads (lb) for the regulatory loading condition (with filled luggage compartment).

Axle location	Load on left	Load on right	Total axle load	Increase over Reference Condition
First axle	8,610	8,360	16,970	-485
Second axle	12,580	11,570	24,150	750
Third axle	8,385	7,615	16,000	855
Rear tandem (axles 2+3)	20,965	19,185	40,150	1,605
Whole vehicle	29,575	27,545	57,120	1,120

Table 11. Measured loads (lb) for the maximum loading condition (with filled luggage compartment, at GVWR).

Axle location	Load on left	Load on right	Total axle load	Increase over Regulatory Condition
First axle	8,995	8,955	17,950	980
Second axle	14,165	12,445	26,610	2,460
Third axle	9,400	8,095	17,495	1,495
Rear tandem (axles 2+3)	23,565	20,540	44,105	3,955
Whole vehicle	32,560	29,495	62,055	4,935

Table 12. Payload weight, including the occupants themselves and their luggage.

Loading Condition	Total Payload Weight (lb)	Payload Weight per Seating Position, Occupant and Luggage (lb)	Longitudinal position of the center of gravity (in. behind the front axle)
Reference (Table 9)	15,310	187	186
Regulatory (Table 10)	15,795	193	190
Maximum (Table 11)	20,730	253	192

3. EFFECT OF THE REAR LUGGAGE COMPARTMENT ON OPERATIONAL SAFETY

The effect of the rear luggage compartment on operational safety was assessed through a series of objective tests. The tests included driving the motorcoach on a test track and inspecting it while it was parked. Evaluations of stopping distance, lighting, and rear visibility were conducted according to NHTSA standards. Industry test methods were used to generate data to compare the behavior of the double-decker motorcoach with and without the rear luggage compartment. The structural integrity of the attachment was assessed by driving the motorcoach over a series of surfaces and evaluating data according to a military standard.

The addition of the weight and the redistribution of the weight with the rear luggage compartment did not significantly affect any of the maneuvering tests in this study. The rear luggage compartment had the lights required by Federal standards, and it did not affect the rearward visibility of the driver.

3.1 STOPPING DISTANCE

Tests of stopping distance of the double-decker motorcoach with rear attachment were patterned after Federal Motor Vehicle Safety Standard (FMVSS) No. 121 S5.3.1.(5) In all three loading conditions, the vehicle stopped in a distance that would have satisfied the standard had this been a formal compliance test.

The standard specifies that, in six attempts, the vehicle—in this case a bus, traveling at 60 mi/h—must stop at least once in not more than a specified distance (in this case, 280 feet). The purpose of the test was to discern the effect of the luggage compartment on the stopping distance of the motorcoach. As such, the vehicle was loaded according to the conditions specified for this study and not according to the standard. This was not a compliance test. The brakes went through the burnishing procedure once, in the reference loading condition before the first set of stops. The pavement, weather, and other applicable conditions were as specified in the NHTSA test procedure for air brake testing.(6)

A series of six stops at 60 mi/h was conducted for each of the three loading conditions. In all loading conditions, the motorcoach was able to stop several times within 280 ft. Results are shown in Table 13.

Table 13. Distance, in ft, that the bus stopped from 60 mi/h, in each of the loading conditions, for all six stops.

Loading Condition	Stop 1	Stop 2	Stop 3	Stop 4	Stop 5	Stop 6
Reference	353	292	260	249	236	247
Regulatory	238	244	240	254	252	255
Maximum	249	238	244	271	262	265

3.2 MANEUVERABILITY: LOW-SPEED TURNING RADIUS

Turning radius at low speeds is a quantitative measure of a vehicle's ability to maneuver in tight situations, such as a yard or urban street. Shifting weight from the main luggage compartment (in the reference condition) to the rear luggage compartment (in the regulatory condition) increased the turning diameter of the motorcoach by 1 ft, 3 in.

Turning radius was measured using the standard, SAE J695, "Turning Ability and Off Tracking—Motor Vehicles."(7) The vehicle was tested in the three loading conditions specified in Section 4, rather than the weight specified in Section 7.3 of the standard.

Three diameters defined by the standard were measured, as shown in Figure 8. All three of the circles have the same center. The diameters are measured with the vehicle executing its sharpest practicable turn. The turning diameter is the diameter of the circle traced by the center of the contact patch on the outside steer tire. This is the innermost dashed semicircle in the figure. The procedure for measuring this diameter is in Section 7.5 of the standard. The turning diameter curb-to-curb is the diameter of the smallest circle within which the vehicle will clear a curb 150 mm (approximately 6 in.) high. It is the middle dashed semicircle in the figure, and the procedure is in Section 7.6 of the standard. The turning diameter wall-to-wall is the diameter of the smallest circle which will enclose the outermost points of projection of the vehicle, which was the side mirror on this motorcoach. This is the largest dashed semicircle in the figure, with the procedure in Section 7.7 of the standard.

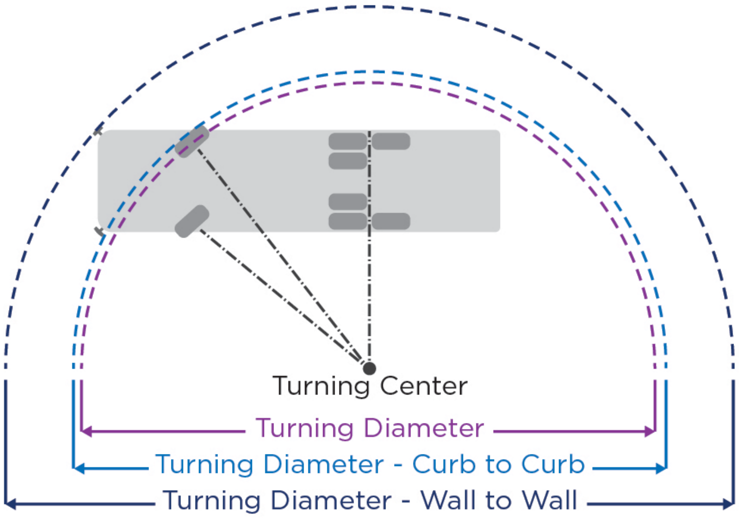


Figure 8. Drawing. The SAE recommended practice defines three turning diameters.

Results from the low-speed turning radius tests are recorded in Table 14. The handwheel could be turned more in one direction than the other, and the diameters for right and left turns were significantly different. The difference in turning diameter between the reference and regulatory loading conditions was insignificant. Although the rear luggage compartment extended the length of the vehicle, the side mirrors were the limiting factor in the wall-to-wall turning diameter.

Table 14. The effect of the rear luggage compartment on turning diameter was small.

Loading condition	Turning Diameter	Turning Diameter, Curb-to-Curb	Turning Diameter, Wall-to-Wall
Reference	Left turn: 80 ft ,10 in. Right turn: 75 ft, 10 in.	Left Turn: 82 ft, 1 in. Right Turn: 77 ft, 1 in.	Left Turn: 88 ft, 10 in. Right Turn: 83 ft, 10 in.
Regulatory	Left turn: 80 ft, 11 in. Right turn: 76 ft, 3 in.	Left Turn:82 ft, 2 in. Right Turn: 77 ft, 6 in.	Left Turn: 88 ft, 11 in. Right Turn: 84 ft, 3 in.
Maximum	Left turn: 82 ft, 0 in. Right turn: 76 ft, 6 in.	Left Turn: 83 ft, 3 in. Right Turn: 77 ft, 9 in.	Left Turn: 90 ft, 0 in. Right Turn: 84 ft, 6 in.

3.3 MANEUVERABILITY: HIGH-SPEED CURVE

Two high-speed tests were conducted to examine the steering dynamics of the double-decker motorcoach. The tests measured whether the rear luggage compartment made the vehicle difficult to handle or susceptible to steering instability. The industry standards for these tests are measurement methods; they do not have pass-fail criteria. Appendix C explains the technical details of the test procedure and presents data from the tests. This section describes a test of steady cornering behavior, which relates to a driver’s ability to control the motorcoach on a freeway ramp. The following section is for a test similar to a lane change at high speed.

The cornering response to a steering command was essentially the same in all three loading conditions. That is, if a driver is in a freeway exit ramp at a speed and curvature similar to one of those in this study, the motorcoach will handle about the same, with or without the rear luggage compartment. As was noted in Table 12, adding the rear luggage compartment and the luggage weight moved the longitudinal center of gravity only 6 in. toward the rear from the reference to the maximum loading condition. This is a small fraction of the overall wheelbase of 25 ft, so the small effect on handling was expected.

A freeway ramp was simulated by the steady-state cornering measurements in the standard, ISO 14792:2011, “Road vehicles—Heavy commercial vehicles and buses—Steady-state circular tests.”(8) At each data point, the vehicle was driven at a constant speed while a steering machine held the handwheel in a constant position for at least 3 seconds. This is the procedure in Section 7.3 of the standard. Turns were made to the right and to the left. The speeds of the test ranged from 20 mi/h to 50 mi/h.

The vehicle never approached a situation of steering instability in any of the three loading conditions. The handling of the vehicle was in an “understeer” condition in all tests (that means that the motorcoach does not have a tendency to overreact to the driver’s steering).

3.4 MANEUVERABILITY: LANE CHANGE

A single lane change on a highway was simulated in accordance with the standard ISO 14793:2011, “Road vehicles—Heavy commercial vehicles and buses—Lateral transient response test methods.”(9) The rear luggage compartment did not significantly affect the ability of the driver to control the vehicle in the conditions tested.

The tests measured how much the vehicle responded to steering inputs and how promptly it responded. Large changes in the measurements would have indicated that the vehicle requires a different level of skill to control during more severe, sudden maneuvers. There were no significant differences among the loading conditions. Appendix D contains the technical details and data.

3.5 INTEGRITY OF THE ATTACHMENT

The rear luggage compartment tested in this study was mounted on the vehicle using fasteners (including pins, a cotter pin, and locking screws). The compartment can swing away from the vehicle when unlatched. The integrity of the attachment was assessed by estimating the number of miles that the attachment could withstand without failure. Sensors called strain gages were mounted near the welds in the attachment. The attachment's behavior was recorded as the motorcoach was driven over a series of bumpy and smooth roads intended to represent a normal service day.

The data were processed via an approach used by the military. The process is described in Appendix E.

The analysis included a series of conservative assumptions. The weld was predicted to last at least 830,000 miles before breaking.

3.6 LIGHTING AND CONSPICUITY

Qualitative assessment of lighting and conspicuity of the double-decker motorcoach with the rear luggage compartment was based on FMVSS No. 108, "Lamps, Reflective Devices, and Associated Equipment."(10) FMVSS No. 108 specifies the color, number, mounting location, and activation of the lighting devices.

The rear luggage compartment tested in this study was fitted with tail lamps, turn signal lamps, stop lamps, and backup lamps that are compliant with the number, mounting location, and activation of rear lighting devices required by FMVSS No. 108. The rear luggage compartment was shorter than the height of the vehicle, so it did not block the visibility of clearance lamps mounted on the far top rear of the vehicle.

According to FMVSS No. 108, S7.8 and S7.9, parking lamps and high-mounted stop lamps are required only for vehicles that are less than 80 in. (2,032 mm) wide. The test vehicle was 102 in. wide, so these lighting devices were not required.

Figure 9. is a photograph from directly behind the vehicle showing all of the rear lamps. Figure 10 indicates the functions of the lamps. All rear lamps required by FMVSS No. 108 were visible, activated as required, and mounted within the correct height:

- S7.1.2 Rear turn signal lamps.
- S7.2 Tail lamps.

- S7.3 Stop lamps.
- S7.5 Clearance lamps.
- S7.5 Identification lamps.
- S7.6 Backup lamps.
- S7.7 License plate lamps.

Figure 9. Photo. The lamps on the vehicle itself and those on the rear luggage compartment were visible from directly behind the vehicle.

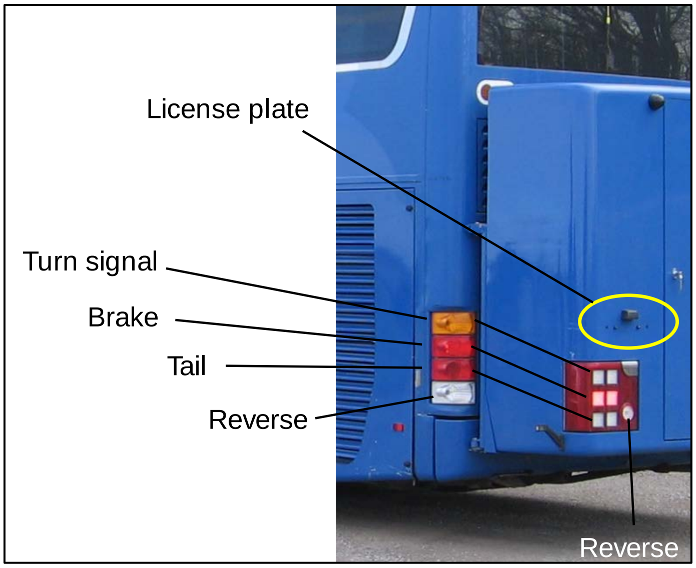


Figure 10. Photo. The lower lamps on the motorcoach itself were duplicated on the rear luggage compartment.

The identification lamps and clearance lamps were on the test vehicle itself and were visible above the rear luggage compartment. When the motorcoach was in reverse gear, the backup lamps came on as required, and the four-way flashing signal lamps came on, as well. The stop lamps came on with the service brake or the parking brake. Rear side marker lamps were on extensions on the side of the rear luggage compartment. They shined in the front, side, and rear directions when the headlamps were on. Lamps themselves were assumed to be compliant; their exact color and vibration tolerability were not assessed.

3.7 REAR VISIBILITY

The rear luggage compartment was not visible from the side mirrors; it did not block the operator's view. The presence of the compartment did not affect the size or shape of the side view mirrors, so compliance with FMVSS No. 111(11) was not affected.

4. EFFECT OF THE REAR LUGGAGE COMPARTMENT ON FIRE SAFETY

The fire safety analysis was conducted through a series of inspections completed by licensed fire investigators. A number of industry and government standards pertain to fire safety of buses, but none specifically apply to rear luggage compartments. The fire safety inspection did not attempt to determine whether the vehicle without the rear luggage compartment meets any requirements or accepted design practices; the study was limited to assessing whether the compartment has an effect on fire safety.

In this study, the engine compartment was located at the rear of the vehicle near the luggage compartment, so the assessment focused on possible engine compartment fires and any new or increased fire risks due to the presence of the rear luggage compartment.

The study was conducted by reference to drawings provided by the vehicle manufacturer and direct inspection of the vehicle.

The rear luggage compartment blocked no emergency exits; it would not impede evacuation of the vehicle. Although the luggage compartment would have to be moved away from the vehicle body for a firefighter to gain full access to the engine compartment, fire suppression crews carry tools that readily can cut through the attachment points.

The most significant concern is that the rear luggage compartment might intensify a fire in the engine compartment. If the skin of the compartment were compromised by heat, the luggage would become involved in the fire. More significantly, the compartment might channel heat upwards toward the rear window. If the window were to fail, heat and smoke would enter the passenger compartment.

Fire exacerbation. Heat and smoke from a fire originating in the engine compartment would be channeled upwards through the gap between the vehicle and the luggage compartment. The presence of the rear luggage compartment could trap heat within this gap and provide more surfaces for flame contact. This chimney effect could possibly increase the heating rate to the passenger compartment and accelerate fire growth. Without this gap created by the rear luggage compartment, heat and smoke more readily flow away from the vehicle and the flames would have only one surface (i.e., the rear of the motorcoach) over which to travel. No experiments or modeling were conducted to quantify this concern.

The rear luggage compartment was located directly below the second-floor rear window, as shown in Figure 9. A fire could compromise this window and enter the passenger compartment on the top level. Accelerating the rate of fire growth could decrease the time that the window and its seal remain intact.

Fuel for the fire. The materials used for the rear luggage compartment and the contents of the compartment may contribute to the fuel for a fire. The storage compartment used in this study was constructed of a combination of aluminum and fiberglass, which are not combustible but lose their integrity when exposed to excessive heat. The interior skin of the luggage compartment appeared to be a fiberglass material or coating, which can help delay the melting of the aluminum skin. The only combustible materials within the empty storage compartment were the particleboard shelves and the plastic materials of the electrical system and attached lights. If a loaded storage compartment was compromised by excessive heat, the contents could be ignited, with the luggage itself being the largest fuel source. The spread of the fire could intensify if the contents were to ignite.

Passenger evacuation. The rear luggage compartment did not block any of the exits. The main and emergency exits were on the sides and roof of the vehicle. The rear window was not an emergency exit. The rear luggage compartment did not affect compliance with any of the exit requirements of FMVSS No. 217; "Bus emergency exits and window retention and release."(12)

Likelihood of a fire. Engine cooling is critical for the safe operation of the turbocharged diesel engine. The 5-in. gap between the rear engine compartment louvers and the luggage compartment did not appear to restrict cooling air flow. Thermocouples mounted at the lower edge of the rear window registered no unusual temperature rise when the motorcoach was driven fully loaded on a hot, sunny day. Louvers on both the right and left side engine compartment doors supported the air flow and were not restricted. Because the rear luggage compartment is exposed to crashes from following vehicles, it should never be used to store any ignitable liquids.

Firefighter access. The tested motorcoach had engine compartment access panels on the left and right sides. There was also a rear access panel, which could not be opened when the rear luggage compartment was in place. Although the left-rear access panel would limit capabilities for firefighter access to the engine components, the right-rear access panel, shown in Figure 11, would provide sufficient access to allow firefighters to extinguish an engine compartment fire. Access to the left and right side engine panels would be more difficult if the motorcoach rolled on its side. One side door would be against the ground, the rear door covered by the luggage compartment, and the other side door accessible only by ladder.

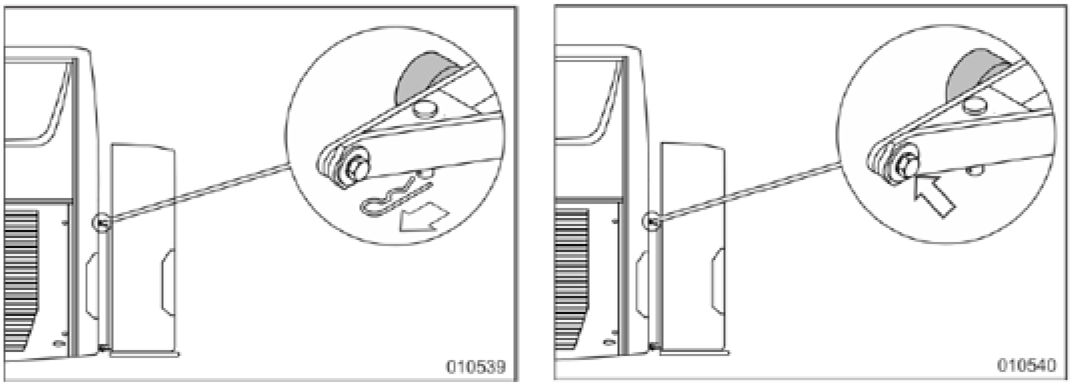
Figure 11. Photo. The engine compartment access door on the right side of the motorcoach would provide adequate capability for a suppression crew to extinguish a fire in the engine compartment.

The rear luggage compartment used in this study can swing away from the vehicle on a pair of hinges. Figure 12 shows the luggage compartment swung away and the main engine compartment door open. During fire suppression or rescue efforts, if the rear storage compartment had to be removed, firefighters would have several options: (1) remove the pins—a Halligan bar could push or pull the four pins; (2) use cutting tools, such as a K12 fire rescue saw or hydraulic cutters to cut sections of the frame; or (3) use hydraulic spreaders to pop the frame off the compartment or motorcoach. When conducting their inspections during this study, inspectors removed the pins using a hammer and chisel (see Figure 13) and swung the rear luggage compartment opened in approximately 30 seconds. They estimated that a K12 fire rescue saw could cut through the hinges in a comparable time.

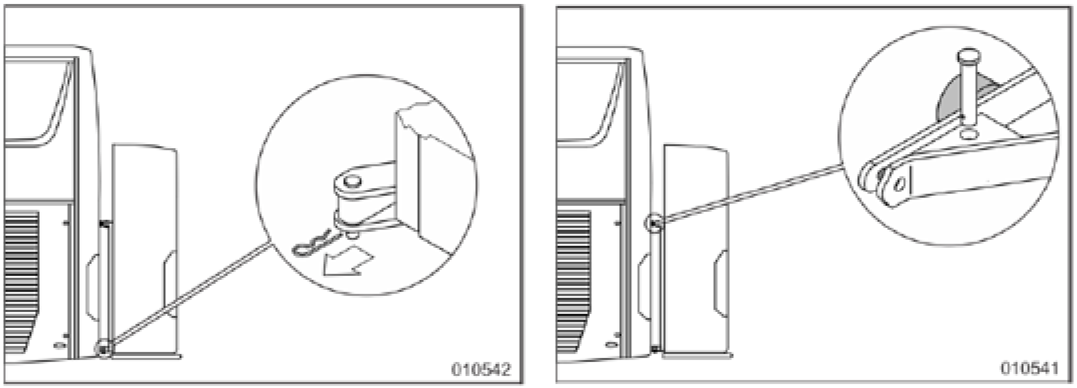
Figure 12. Photo. The engine compartment was accessible after the luggage compartment (visible at the right) was swung out of the way and a door was lifted.

Automatic detection and suppression. The rear luggage compartment would not hinder the automatic detection system and suppression. The system is designed to control a fire within the compartment and not outside the compartment. Controls for the automatic fire detection and suppression system were above the driver’s head.

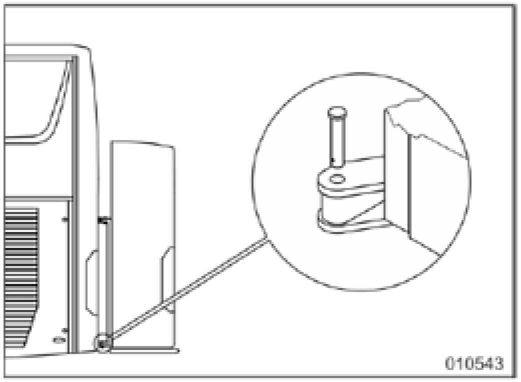
Step 1. Remove the spring cotter from the pin. **Step 2.** Remove the locking screw.



Step 3. Remove the spring cotter from the pin. **Step 4.** Remove the pin.



Step 5. Remove the pin.



The rear luggage compartment can now be turned away from the rear wall of the vehicle.

Source: ABC Companies. Used by permission.

Figure 13. Drawing. Five steps to turn the rear luggage compartment away from the rear wall of the motorcoach.

5. EFFECT OF THE REAR LUGGAGE COMPARTMENT ON TIRE LOADS

This test examined the effect on tire loads due to the additional weight of attaching a luggage compartment to the rear of a double-decker motorcoach. The tires and rims that were on the vehicle when it was delivered for testing had adequate capacity for the loads in the conditions tested. The tires met the requirements of FMVSS No. 119; “New Pneumatic Tires for Vehicles Other Than Passenger Cars”(13) S6.5 and S6.6. The rims met the requirements of S5.1.2 and S5.3 of the same standard.

This chapter and the following chapter both begin with the vertical forces at the interface between the tires and the pavement. This chapter assesses the adequacy of the tires and the rims to handle the loads in accordance with NHTSA regulations for the vehicle. The next chapter compares the loads with Federal Highway Administration (FHWA) regulations and State rules to protect the pavement. The ratings and the weights in both sets of requirements are static loads while the vehicle is stationary.

5.1 TIRE LOADS

The specifications of the tires of the motorcoach are recorded in Table 15 and Table 16. These tables are adapted from Data Sheet 1 on page 25 of the NHTSA test procedure for FMVSS No. 120.(14) The actual tire loads were compared with the tire specifications in Table 17, which is adapted from the Data Sheet 3 on page 29 of the same test procedure.

The highest load measured on a single tire (on the third axle on the left side) was 90 percent of the rated load for the tire. The highest load measured on one of the duals was 86 percent of the tire’s rated load.

Even in the maximum loading condition, all tires and axles were bearing a load that was within their capacity. The axle loads were within 1,000 lb of their capacity, so proper distribution of the load was necessary as the GVWR was approached.

Table 15. Specifications of the tires on the first and third axles.

Tire location (left or right and axle number)	Tires on the right and left sides of the first and third axles
Tire manufacturer	Michelin
Tire brand	Pilote XZA 1
Tire type	R (radial construction)
Tire size designation	365/70R22.5 (VIN plate specifies 315/80/R22.5)
Tire manufacture date	3515 for tires on first axle (35th week of 2015) 3715 for tires on third axle (37th week of 2015)
Tire marked with ‘DOT’? (Yes/No)	Yes
DOT serial number (if marked with ‘DOT’)	DOT B6 JM HHF X 3515 for tires on first axle DOT B6 JM HHF X 3715 for tires on third axle
Max load	4,750 kg (10,500 lb)
Cold tire inflation pressure	860 kPa (125 psi)

Table 16. Specifications of the tires on the second axle.

Tire location (left or right and axle number)	Tires on the right and left (both inside and outside) of the second axle
Tire manufacturer	Michelin
Tire brand	Pilote XZA 1
Tire type	R (radial construction)
Tire size designation	315/80R22.5
Tire manufacture date	3915 (39th week of 2015)
Tire marked with ‘DOT’? (Yes/No)	Yes
DOT serial number (if marked with ‘DOT’)	DOT B6 D7 BEX X 3915
Max load for use as single	4,125 kg (9,090 lbs)
Cold tire inflation pressure for use as single	900 kPa (130 psi)
Max load for use as dual	3,750 kg (8,270 lbs)
Cold tire inflation pressure for use as dual	900 kPa (130 psi)

Table 17. All tires and axles had adequate capacity in all loading conditions.

Item	Tire or vehicle rating* (lb)	Reference loading condition (Table 9) Measured load (lb)	Regulatory loading condition (Table 10) Measured load (lb)	Maximum loading condition (Table 11) Measured load (lb)
Left tire on first axle	10,500	8,795	8,610	8,995
Right tire on first axle	10,500	8,660	8,360	8,955
Front axle	18,180	17,455	16,970	17,950
A left tire† on second axle	8,270	6,112	6,290	7,083
A right tire on second axle	8,270	5,587	5,785	6,222
Second axle	27,575	23,400	24,150	26,610
Left tire on third axle tire	10,500	7,695	8,385	9,400
Right tire on third axle	10,500	7,180	7,615	8,095
Third axle	18,180	15,145	16,000	17,495
Total Vehicle	**62,000**	**56,000**	**57,120**	**62,055**

* Vehicle and axle weight ratings (GVWR and GAWR) were read from the vehicle certification label plate (see Table 5). Vehicle tire load ratings were read from the tires (see Table 15 and Table 16).

† Dual tires were assumed to share the load equally between the two tires.

5.2 RIM LOADS

The specifications of the rims of the motorcoach are provided in Table 18 and Table 19 (both of these tables are adapted from Data Sheet 1 on page 26 of NHTSA Test Procedure 120). The capacity of the rims on the first and third axles were identical to the capacities of the tires on those axles, and the capacities of the rims on the second axle were greater than the capacities of the tires on that axle. As was shown in Table 17, the capacities of the tires were not exceeded in any of the loading conditions. The rims had an aggregate capacity greater than the GAWR of the axle where they were mounted. The capacities of the rims were adequate to meet S5.2 of FMVSS No. 120.(15)

Table 18. Specifications of the rims on the first and third axles.

Rim location (left or right and axle number)	Rims on the right and left sides of the first and third axles
Rim manufacturer	Alcoa
Rim size designation	22.5x10.5
Source of rim's published designations	T (Tire and Rim Association)
Rim manufacture date	All rims were manufactured in June 2013, but the rim on the right side of the third axle was manufactured in July 2013.
Rim marked with 'DOT'? (Yes/No)	Yes
DOT serial number (if marked with 'DOT')	803501DB
Rim load ratings	(kg) 4,760 (lb) 10,500

Table 19. Specifications of the rims on the second axle.

Rim location (left or right and axle number)	Rims on the right and left (both inside and outside) of the second axle
Rim manufacturer	Alcoa
Rim size designation	22.5x9.00
Source of rim's published designations	T (Tire and Rim Association)
Rim manufacture date	March 2011, February 2013, April 2009, and March 2012 for the left-inside, left-outside, right-inside, and right-outside of the second axle, respectively.
Rim marked with 'DOT'? (Yes/No)	Yes
DOT serial number (if marked with 'DOT')	896513DB
Rim load ratings	(kg) 4,125 (lb) 9,090

6. EFFECT OF THE REAR LUGGAGE COMPARTMENT ON BRIDGE AND PAVEMENT DAMAGE

Federal size and weight regulations for commercial motor vehicles are specified in 23 CFR 658.(16) States enact and enforce laws that are consistent with these regulations, but they are not necessarily identical to these regulations. The length of the motorcoach with the luggage compartment attached exceeds some States' overall length limits, and the tire and axle loads may exceed some State limits.

Regulations considered were FHWA Bridge Formula weight limits, maximum axle and tandem weights, and tire load-to-width ratios. The previous three sections addressed safety of the vehicle with the rear luggage compartment attached; this chapter addresses the effect of the vehicle (with rear luggage compartment attached) on bridges and pavement.

6.1 SIZE LIMITS

States impose limits on the maximum length, width, and height of commercial motor vehicles. The dimensions in this analysis were taken from specifications provided by the motorcoach manufacturer and were confirmed by direct measurements.

a) **Length**: 23 CFR 658.13(d) specifies that "*no State shall impose a limit of less than 45 feet on the length of any bus on the [National Network]*." The length of the test vehicle without the rear luggage compartment was 43 ft 10 in., and 46 ft 9 in. with the compartment. Therefore, the vehicle would not exceed the length requirement of any State when driven without the rear luggage compartment. However, it could exceed the length requirements of certain States if driven with the rear luggage compartment. For example, the maximum allowable length of all bus-type passenger vehicles (except transit buses and articulated buses) in the States of New York and Ohio is 45 ft.(17,18)

b) **Width**: 23 CFR 658.15(a) specifies that "*no State shall impose a width limitation of more or less than 102 inches.*" The width of the test vehicle was 102 in., and the rear luggage compartment was narrower than the width of the vehicle. Therefore, the rear luggage compartment did not exceed width requirements.

c) **Height**: No Federal limit is imposed on the maximum height of a commercial motor vehicle; however, most States impose a maximum height between 13 ft 6 in. and 14 ft 6 in. The height of the test vehicle was 13 ft 1 in. and the rear luggage compartment was shorter than the height of the vehicle. Therefore, the rear luggage compartment did not exceed height requirements.

6.2 BRIDGE FORMULA WEIGHT LIMITS

FHWA regulation 23 CFR 658.17(e) specifies the weight that can be carried on a group of axles with a certain spacing by the Bridge Formula.(19) A vehicle passes the Bridge Formula if two or more consecutive axles are loaded not more than the amount calculated by Figure 14.

$$W = 500\left(\frac{L * N}{N - 1} + 12 * N + 36\right)$$

Figure 14. Equation. The Bridge Formula.

where:

W is the overall gross weight on any group of two or more consecutive axles to the nearest 500 pounds.

L is the distance in feet between the outer axles of any group of two or more consecutive axles.

N is the number of axles in the group under consideration.

The double-decker motorcoach used in this study had three axles and the distance between the outer axles was 25 ft (see Table 6). The maximum permitted gross weight of the vehicle, based on the Bridge Formula, was approximately 54,500 lb, as shown in Figure 15.

$$W = 500\left(\frac{25 * 3}{3-1} + 12 * 3 + 36\right) = 54{,}750,\ \ \textit{rounds to}\ 54{,}500\ \text{lb.}$$

Figure 15. Equation. The Bridge Formula applied to the three-axle motorcoach with an overall wheelbase of 25 ft.

Comparing the gross vehicle weight allowed by FHWA’s Bridge Formula (54,500 lb) to the total vehicle loads in the reference, regulatory, and maximum loading conditions (56,000 lb, 57,045 lb, and 62,000 lb, respectively), the double-decker motorcoach may exceed States’ limits of the Bridge Formula in all loading conditions.

6.3 MAXIMUM AXLE AND TANDEM LOADS

Section 1522 of Moving Ahead for Progress in the 21st Century Act (MAP-21, Public Law 112-141) makes permanent an exemption in 23 CFR 658.17(k) concerning over-the-road buses. The term “over-the-road bus” means a bus characterized by an elevated passenger deck located over a baggage compartment (42 U.S.C. 12181). The exemption raised the maximum load limit of a single axle for “over-the-road” and public transit buses operating on the Interstate System from 20,000 to 24,000 lb. Covered States as defined in 23 U.S.C. 1522 must set their maximum single-axle weight limits at no less than 24,000 lb. for over-the-road buses operating on the Interstate System. Non-Covered States may also allow maximum single-axle weight limits above 20,000 lb at their discretion.

First, note that this exemption and other MAP-21 amendments [Sec. 1522, 126 Stat. 405, 579] have not been codified into 23 CFR 658.17(k), but the statute prevails over the regulation. Second, note that this exemption does not prohibit a State from enforcing its own State laws regarding maximum single-axle weight limits on non-Interstate System roads within its jurisdiction. Third, note that neither this exemption nor any Federal regulation impairs a State’s ability to weigh over-the-road buses. Fourth, note that the exemption applies to only maximum single-axle weight limits— not the maximum gross, tandem, or other weight limits on the Interstate System.

The axle loads transmitted by the double-decker motorcoach in the three loading conditions are shown in Table 9, Table 10, and Table 11. The loads on the first and third axles were less than the 20,000 lb limit allowable in Non-Covered States in all of the three loading conditions. However, the load on the second axle exceeded the 20,000 lb limit allowable in Non-Covered States in all three loading conditions, and it exceeded the 24,000 lb limit in the regulatory and maximum loading conditions.

23 CFR 658.17 states that the maximum weight on any tandem-axle configuration is 34,000 lb. However, Non-Covered States (as described above) may allow a maximum tandem-axle limit above 34,000 lb for an over-the-road bus. Per the CFR, tandem axle weight is defined as "*… the total weight transmitted to the road by two or more consecutive axles whose centers may be included between parallel transverse vertical planes spaced more than 40 inches and not more than 96 inches apart…*" The second and third axles are separated by 50.7 in.; they are tandem axles. The loads by the tandem-axle pair were 38,545 lb, 40,150 lb, and 44,105 lb in the reference, regulatory, and maximum loading conditions, respectively.

Depending on how the double-decker motorcoach is classified and where States have set their limits, the second axle and the rear tandem may carry more than the maximum allowed weights.

6.4 MAXIMUM TIRE LOADS

FHWA specifies a minimum ratio of tire load to tire width that a State may regulate. The requirement in 23 CFR 658.17(f) reads in part, "*States may not limit tire loads to less than 500 pounds per inch of tire or tread width, except that such limits may not be applied to tires on the steering axle.*" While the Federal regulations do not dictate a maximum tire load per inch of tire width, the States may impose a maximum tire load per inch of tire width. For example, the maximum load-to-width ratio allowed by the States of Ohio and Washington are 650 and 600 lb per in., respectively.(20,21)

The analysis of tire loads is provided in Table 20. Axle loads in the three conditions are taken from Table 9, Table 10, and Table 11. The specifications of the tires on the third axle are provided in Table 15. The specifications for the tires on the second axle are provided in Table 16. The loads were close to or above the Federal minimum of 500 lb per in. Tire loads on the third axle were above the value in both the regulatory and maximum loading conditions. Tire loads on both rear axles were above the value in the maximum loading condition. In most cases, the excess was small enough that it may have been within enforcement tolerances or it could have been eliminated by repositioning the load.

Table 20. Evaluation of tire load per width.

Tire	Tire width (mm)	Tire width (in.)	Reference loading condition (Table 9) Measured load (lb)	Reference loading condition (Table 9) Load (lb/in.)	Regulatory loading condition (Table 10) Measured load (lb)	Regulatory loading condition (Table 10) Load (lb/in.)	Maximum loading condition (Table 11) Measured load (lb)	Maximum loading condition (Table 11) Load (lb/in.)
A left tire† on the second axle	315	12.4	6,112	493	6,290	507	7,083	571
A right tire on the second axle	315	12.4	5,587	451	5785	466	6,222	502
Left tire on the third axle tire	365	14.4	7,965	554	8,385	584	9,400	654
Right tire on the third axle	365	14.4	7,180	500	7,615	530	8,095	563

† Dual tires were assumed to share the load equally between the two tires.

7. CONCLUSIONS

This study examined the effect of a luggage compartment attached to the rear of a double-decker motorcoach, Van Hool model TD925. The study examined (i) safety of vehicle operations, (ii) fire suppression capability, (iii) tire loads, and (iv) roadway pavement, as mandated by Congress. The study was conducted by inspecting a specimen vehicle and by driving the vehicle through prescribed maneuvers on a test track. The study referred to Government or industry standards wherever possible. The motorcoach was operated through the maneuvers under a reference load condition, a regulatory load condition, and its maximum load condition. The reference condition for most comparisons had the same vehicle without the luggage compartment attached; the other two conditions had the same vehicle (with additional weight under the maximum loading condition) with the luggage compartment attached to the rear.

Most aspects of this study were not significantly affected by the addition of a rear luggage compartment. With the exception of the extended length of the vehicle, characteristics of the motorcoach that were satisfactory without the rear luggage compartment were also satisfactory with the rear luggage compartment. Loads on pavement that were a concern with the luggage compartment were also a concern for a loaded vehicle without the compartment.

7.1 PROPERTIES NOT CHANGED BY THE REAR LUGGAGE COMPARTMENT

The safety of vehicle operations of the motorcoach was not significantly affected by the attachment of the luggage compartment to the rear of the vehicle. Stopping distance from 60 mi/h was not impaired. High-speed handling in steady conditions (as on a freeway exit ramp) and dynamic conditions (as in a lane change) were also essentially identical with and without the compartment. The luggage compartment used in this study had lights that met the location and activation requirements specified in FMVSS No. 108. The compartment did not impair required lighting or rearward visibility. The attachment is expected to maintain its structural integrity through the normal service life of the vehicle.

The tires and rims that were delivered with the vehicle for testing had adequate capacity for the various test loads.

7.2 PROPERTIES CHANGED BY THE REAR LUGGAGE COMPARTMENT

According to the manufacturer’s specifications, the length of the test vehicle without the rear luggage compartment is 43 ft 10 in. The compartment adds 2 ft 11 in., so the length of the vehicle with the rear luggage compartment is 46 ft 9 in. 23 CFR 658.13(d) specifies that “*no State shall impose a limit of less than 45 feet on the length of any bus on the [National Network]*.” Some States allow only the minimum of 45 ft, and the motorcoach with the rear luggage compartment exceeds this length.

If a severe engine fire were to develop, the rear luggage compartment could keep heat near the body of the motorcoach and channel it toward the rear window. If the heat compromised the rear window, smoke and flame would enter the passenger compartment. The aluminum and fiberglass wall of the luggage compartment would resist a small fire. A severe fire could melt the walls, and the contents would begin to burn. Firefighters could access the engine compartment through a side door, or they could remove the luggage compartment in about 30 seconds using tools normally carried by suppression crews. The luggage compartment did not block any emergency exits.

7.3 CONCERNS WITH OR WITHOUT THE COMPARTMENT

The Bridge Formula allows a maximum vehicle weight of 54,500 lb for a three-axle vehicle where the first and third axle are 25 ft apart. When an occupant load of 150 lb per person (as specified in Federal regulations) and a luggage load of 35 lb per person are carried, the total weight of the motorcoach without the rear luggage compartment is 56,000 lb. The vehicle did not meet the bridge formula, even without the rear luggage compartment. Individual and tandem axle loads may exceed the maximum loads allowed in some States.

APPENDIX A: CONSULTATIONS WITH STATE OFFICIALS

The study was conducted in consultation with State transportation safety and law enforcement officials. Preliminary plans for the analysis and experiments were presented to State officials. This appendix lists the important points raised by the officials (in *italics*) and the response to them.

The consultation with State safety officials was held during a webinar with the American Association of State Highway and Transportation Officials (AASHTO) Standing Committee on Highway Safety on September 13, 2016. Two questions were raised:

1. *One participant observed that the load distribution on the two rear axles of the motorcoach might depend on the adjustment of the air suspension on those axles.*

   According to the manufacturer, the driver needs to take no action to ensure that the two rear axles share the load properly. The vehicle was weighed twice in all three loading conditions as a measure of variations in how the axles share the load. Differences between weighings were minor.

2. *Another participant wrote after the webinar with comments on the distribution of load between the rear axles, a State's regulations on the Bridge Formula, and the effects on stability of placing mass behind the rear axle.*

   The question about axle loads was handled by measuring actual axle loads with the test vehicle. The State allows an alternative version of the Bridge Formula for some vehicles. The discussion of size and weight regulations in Section 6 notes in several places that States' regulations are not all identical to the FHWA limits. The third observation was that placing weight behind the rear axle would diminish handling stability, especially on slippery surfaces. Handling stability was assessed by the two high-speed maneuvers. The scope of this study was limited to dry surfaces.

The consultation with State law enforcement officials was held during a meeting of the Passenger Carrier Committee of the Commercial Vehicle Safety Alliance (CVSA) in Little Rock, Arkansas, on September 20, 2016.

1. *An inspector observed that the regulatory average of 150 lb per passenger is lower than the actual average of some groups of passengers. The inspector asserted that substantially heavier passengers can overload axles*.

   The study followed the regulation. The three specified loading conditions were all within the rated capacity. Chapter 2 of the report observes that, when the motorcoach was loaded to its GVWR, the payload weight per seating position was 253 lb.

2. *Another commenter suggested that a driver could distribute the passengers so that the load is distributed among the axles*.

Identical water dummies were installed in every seat in the reference and regulatory loading conditions. Additional ballast was distributed as necessary to reach the GVWR without exceeding any axle weight ratings.

3. *One asked whether luggage in the rear compartment might shift during a severe maneuver.*

   Tumbling suitcases would not present the same dynamic load as sloshing liquid. Although load shift in the rear luggage compartment is a possibility, the amount of mass would not significantly affect the vehicle's dynamics. There were no experiments with a shifting load.

4. *A participant questioned the subjective assessment of firefighter access to the rear of the motorcoach.*

   The time to release the hitches on the rear luggage compartment was measured. The study team searched for fire safety standards to apply and found none. One of the purposes of the independent review panel was to provide additional perspectives where subjectivity was necessary.

Following the AASHTO webinar, Greyhound sent a letter to FMCSA raising several issues:

1. *In the webinar, there is a comment from a member of the study team to the effect that length is not an issue in this study. In fact, it should be a primary issue, at least with regard to "safety operations." Will this longer and heavier bus perform safely in all driving conditions, including dense urban traffic and high wind and heavy precipitation conditions? Will the longer and heavier bus stop and maneuver safely in all such conditions? And will the driver have the same level of control and visibility that he/she would have in a normal motorcoach? These are the fundamental questions that need to be asked and answered after appropriate testing and analysis.*

   The FHWA size regulations are included in Section 6. Most of the effects of length that are named in the paragraph were included in the study. Dense urban traffic was addressed through the turning radius measurements. Standard tests assessed stopping distance and the driver's ability to steer the vehicle. Rear visibility was included in the study.

   Adverse weather was not considered. The stopping distance and maneuverability tests were conducted on dry pavement and calm wind according to the requirements of the respective standards.

2. *A related safety operations issue has to do with the functionality of the rear bumper. Since the rear bumper would be largely covered by the backpack, is its required functionality impeded? How would the impact of a light duty vehicle striking the rear of the bus change if part or all of the smaller vehicle hits the backpack? This should be added to the safety operations list.*

The fire safety assessment in Section 4 notes that ignitable liquids should not be stored in the rear luggage compartment. Crashworthiness was not otherwise part of the study.

3. *The three weight configurations described in the webinar – no backpack, some baggage moved to the backpack but no change in overall weight, and backpack loaded to GVWR – do not include the most important configuration. That is, the backpack fully loaded to capacity with baggage or freight and the main cabin fully loaded with passengers and baggage. That weight may be higher or lower than the manufacturer's stated GVWR, but that fully loaded weight is what counts when measuring the increased weight's impact on safety operations, tire loads, and pavement damage.*

   The vehicle and its components were loaded close to, but not beyond, their rated capacity in the maximum loading condition.

4. *Two of the key fire suppression questions should be — does the blockage of the rear engine compartment by the backpack reduce the overall engine compartment ventilation and thus enhance the chances of engine overheating? And to what extent would the backpack impede the driver or fire professional from getting to and controlling a thermal event?*

   The first question is not addressed at all in the webinar presentation. The second question is addressed by a fire professional "walking around" and making an assessment. There should at least be testing of how long it takes and how difficult it is to access the engine compartment with a backpack locked in place in front of the access panel. Also, it should be borne in mind that the first person to attempt to access the engine compartment is likely to be a driver, not a trained fire professional.

   Thermocouples on the rear exterior of the vehicle showed no greater rise in temperature with the rear luggage compartment than without. The time to unhitch the rear luggage compartment was measured.

5. *With regard to tire loads, those conducting the study should be aware of the two FMCSA bulletins* [the distributed bulletin was a form of a Motorcoach Safety Advisory Bulletin.(22)] *expressing concern about overloading and inadequate tire pressure on double-deck motorcoaches without a backpack. Obviously, this is a major safety concern and one that is exacerbated by the extra load of the backpack. The study needs to address this issue in depth.*

   Tire ratings were addressed in Section 5. The tires were properly inflated for all tests.

6. *Also on tire loads, there was a comment from FMCSA to the effect that the study only dealt with "tire load," not overall weight. FMCSA is mandated to study the impact of the backpack on "tire loads," not "tire load." This is clearly intended to include overall tire loads, not just the load on one individual tire. Thus, the impact of a fully loaded bus and backpack on single and tandem axle weight and overall vehicle weight should be studied and recorded.*

Sections 5 and 6 examined loads on individual tires, loads on axles, and loads on groups of axles. The quantities are governed by manufacturer’s specifications and by regulations.

APPENDIX B: VEHICLE SPECIFICATIONS

This appendix provides further specifications of the test vehicle.

PERSUANT TO 49CFR567, FMVSS 120 5.3.1 AND CMVSS 120 (14)
VAN HOOL PROVIDES THIS ADDITIONAL TIRE AND RIM INFORMATION
MODEL **TD925**

	TIRE SIZE - LOAD RANGE	RIM SIZE	COLD INFLATION PRESSURE
Front	365/70 R22.5 - L	10.50 x 22.5	125 Psi (single)
Rear	365/70 R22.5 - L	10.50 x 22.5	125 Psi (single)

ALL OTHER GAWR, TIRE SIZE AND INFLATION PRESSURES REMAIN THE SAME AS ON ORIGINAL CERTIFICATION LABEL

Mfd by VAN HOOL N.V. Lier 2500 BELGIUM
Month / Year of construction: 04/08
GVWR: 62.000 Lbs

	GAWR	TIRE SIZE LOAD RANGE	RIM SIZE	COLD INFLATION PRESSURE
Front	18.180 Lbs	315/80R22.5 - L	9,00 x 22,5	130 Psi (Single)
First intermediate	27.575 Lbs	315/80R22.5 - L	9,00 x 22,5	130 Psi (Dual)
Rear	18.180 Lbs	315/80R22.5 - L	9,00 x 22,5	130 Psi (Single)

This vehicle conforms to all applicable U.S. Federal Motor Vehicle Safety Standards in effect on the date of manufacture shown above.

GVWR and GAWR are based on ORIGINAL equipment. Any change may affect vehicle capacities. See Owner's Manual for other tire and capacity information.

Vehicle identification number : -YE2DG11B292042325-
Classification : BUS

PRODUCTION NUMBER N° 42325

Figure 16. Photo. The VIN was on the plate inside the door.

Figure 17. Photo. The motorcoach had doors at the front and rear. It had two stairs, one by each door.

According to measurements made on the vehicle, the rear luggage compartment sat approximately 18 in. above the ground; the motorcoach body sat approximately 11 in. above the ground. The interior of the luggage compartment was accessed through a door measuring approximately 77.75 in. high and 39.5 in. wide. The interior of the rear luggage compartment contained three shelves made of particle board. Each particle board shelf measured approximately 88 in. long, 21 in. deep, and 5/8 in. thick. Two light fixtures were included in the interior of the rear luggage compartment.

APPENDIX C: HIGH-SPEED CORNERING TEST

A freeway ramp was simulated by the steady-state cornering measurements in the standard, ISO 14792:2011, "Road vehicles—Heavy commercial vehicles and buses—Steady-state circular tests." At each data point, the vehicle was driven at a constant speed while a steering machine (Figure 18) held the handwheel in a constant position for at least 3 seconds. Turns were made to both the right and the left. The vehicle was instrumented with sensors to measure the motion of the vehicle. The quantities that were measured included:

- Velocity in the forward, lateral, and vertical directions.
- Acceleration in the forward, lateral, and vertical directions.
- Roll, pitch, and yaw angles.
- Roll, pitch, and yaw angular velocity.
- Roll, pitch, and yaw angular acceleration.

Roll, pitch, and yaw are the three rotation angles. Yaw is the angle that the vehicle is turned with respect to the direction of a reference path. Yaw velocity is the speed that the vehicle is turning, in degrees per second.

These motion variables were used to derive handling diagrams that can be used to assess vehicle stability. This derivation was done in accordance with ISO 14792:2011. This procedure is given in Section 7.3 of the standard.

Figure 18. Photo. The steering machine provided repeatable inputs for the high-speed maneuvers.

The two high-speed tests were deliberately limited to stay well within the vehicle’s roll stability limits. The rollover threshold of the loaded vehicle was conservatively estimated before the tests to be 0.4 G.* The vehicle did not have outriggers to prevent it from rolling over during the test, so the initial highest planned centripetal acceleration was 0.3 G, or 75 percent of the threshold. The driver judged that the vehicle’s roll angle was as much as was prudent when the lateral acceleration was held steady at only 0.2 G, so this test was limited to that level. The behavior of a vehicle can change as it nears its threshold of stability, and that behavior was not covered in this study.

The data from steady-state circular maneuvers can be used to analyze the boundaries between understeer and oversteer conditions and to explore the handling stability limit. Nearly all vehicles, especially at low speeds, are in the understeer condition. That is, the curvature traveled by the vehicle is slightly less than would be predicted by a purely geometric analysis of the angle of the steer tires and the length of the wheelbase. This is an inherently stable condition because the driver must definitely move the handwheel to achieve a path curvature. At higher speeds, some vehicles can change to an oversteer condition. Oversteer means that the vehicle turns slightly more than what would be expected from the steering angle. A skilled driver can control an oversteer vehicle, but an overreaction in a vehicle with a strong oversteer characteristic can be a bad combination. When weight is moved to the rear of a vehicle, the vehicle generally becomes less strongly understeer or more oversteer. As an oversteer vehicle increases its speed, it can reach a speed where the slightest steering input produces an unbounded turning response. At this speed, called the critical speed, the vehicle cannot be controlled and is unstable. This test was intended to explore the effect of the rear luggage compartment on the boundary between understeer and oversteer conditions.

The handling diagrams(23) for the three loading conditions are plotted in Figure 19, Figure 20, Figure 21, and Figure 22. The symbols used in the graphs are provided in Table 21. The black lines on the right-hand sides of these diagrams represent the purely kinematic relationship between the centripetal acceleration and the curvature of the vehicle trajectory (nondimensionalized as a ratio to the equivalent wheelbase). The colored lines on the left-hand side were calculated from the test data. As on the right-hand side, the vertical axis is the centripetal acceleration of the vehicle. The horizontal axis to the left is the difference between the handwheel angle and the curvature of the vehicle trajectory.

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* The uppercase G is used to denote gravitational units (approximately 9.8 m/s^2 or 386 $in./s^2$) to distinguish it from lower case g, grams.

Table 21. The symbols used in the handling diagrams.

Symbol	Description	Unit
δ_H	Handwheel Angle (the angle that the driver or steering machine turns the steering wheel)	degrees
i_s	Steering Ratio (the ratio of the angle that the front tires turn to the angle the handwheel turns)	(none)
l_e	Equivalent Wheelbase (calculated according to ISO 14792:2011; approximately the distance from the front axle to the center of the tandem)	feet
R	Radius of the Vehicle Path	feet

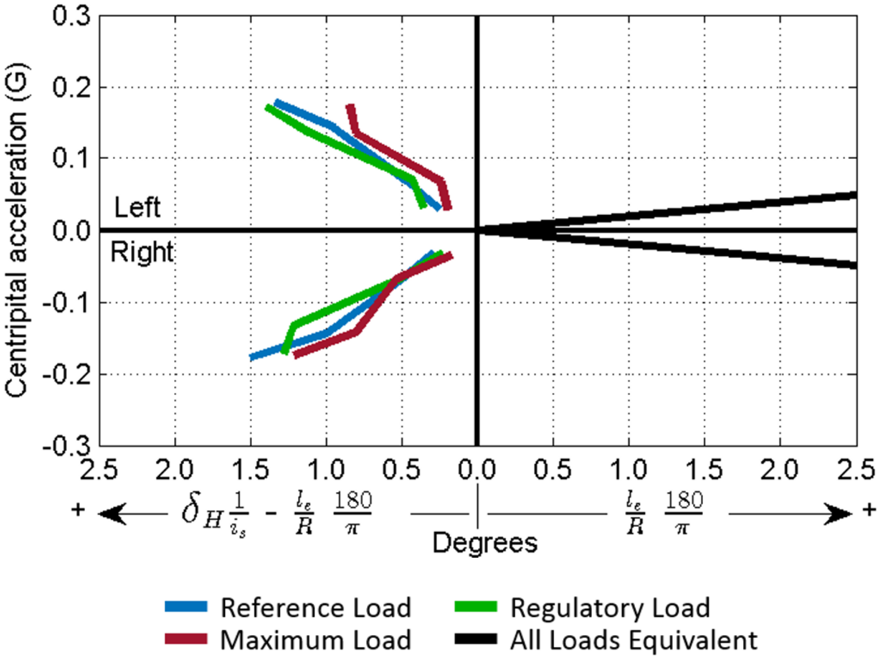

Figure 19. Graph. Handling diagram for the motorcoach at 20 mi/h.

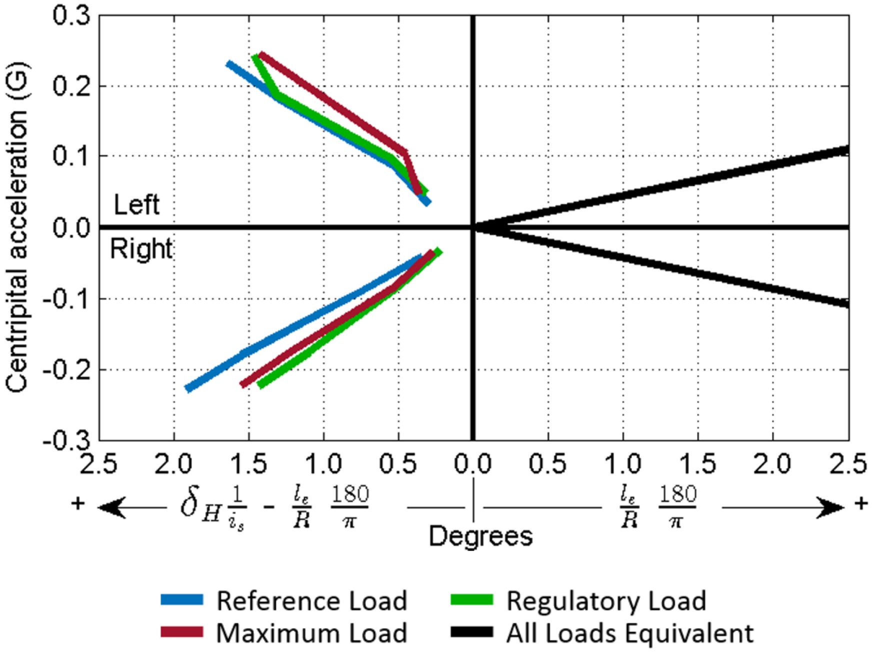

Figure 20. Graph. Handling diagram for the motorcoach at 30 mi/h.

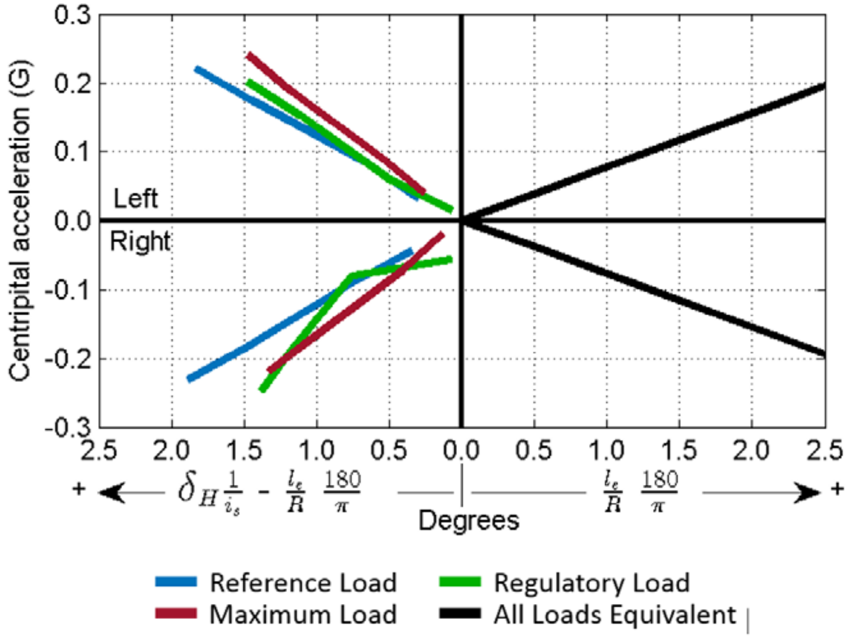

Figure 21. Graph. Handling diagram for the motorcoach at 40 mi/h.

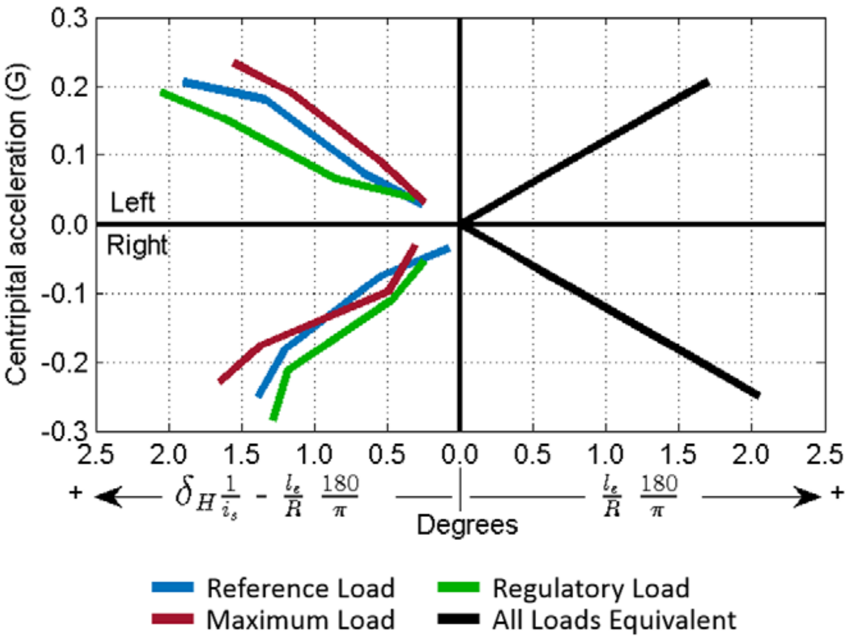

Figure 22. Graph. Handling diagram for the motorcoach at 50 mi/h.

The understeer gradient is related to the slope of the lines plotted on the left-hand sides. In this case, the data falls on essentially straight lines. That means that the motorcoach is in an understeer condition and that the understeer gradient does not change with increasing speed or curvature. This indicates that the vehicle is stable in steering over the range of conditions tested. Had the data plots curved toward the vertical axis, that would have indicated a decrease in the amount of understeer. In some of the plots, the line for the maximum loading condition (the red line) is slightly closer to the vertical axis than the other two lines. This means that the understeer margin in the maximum loading condition was slightly less than in the other conditions. A lower understeer margin is expected when the center of gravity moves toward the rear of a vehicle. However, the measured effect is slight and in some cases no greater than the repeatability of the measurement.

The addition of the rear luggage compartment and the redistribution of the loads did not significantly affect the handling of the motorcoach in the high-speed steady-cornering tests. Table 22 provides the understeer coefficients in the conditions that were tested.

Table 22. The understeer gradient in the three loading conditions (degrees per G).

Loading condition	20 mi/h	30 mi/h	40 mi/h	50 mi/h
Reference	Left turn: 7.4 Right turn: 8.0	Left turn: 6.9 Right turn: 8.6	Left turn: 8.0 Right turn: 8.0	Left turn: 8.6 Right turn: 6.3
Regulatory	Left turn: 8.0 Right turn: 8.6	Left turn: 6.3 Right turn: 6.3	Left turn: 7.4 Right Turn: 6.9	Left turn: 10.9 Right turn: 5.2
Maximum	Left turn: 5.7 Right turn: 6.9	Left turn: 5.7 Right turn: 6.9	Left turn: 6.3 Right turn: 6.3	Left turn: 6.3 Right turn: 8.0

Note: Positive values indicate an understeer condition, which is preferable for normal driving. If the values were negative, that would be oversteer, which can be more difficult to steer.

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APPENDIX D: HIGH-SPEED TRANSIENT STEER

A single lane change on a highway was simulated in accordance with the standard ISO 14793:2011, "Road vehicles—Heavy commercial vehicles and buses—Lateral transient response test methods." The one-period sine wave open-loop input in Section 10 of this standard approximates a single lane change. Because of the load transfer from one side of the vehicle to the other during the beginning of the sinusoid, the vehicle response in the second half is not a mirror image of the first half, so the path of the vehicle after the maneuver is not parallel to the original path.

ISO 14793:2011 specifies two frequencies: 0.2 Hz (corresponding to a slower lane change over a period of five seconds) and 0.5 Hz (corresponding to a quicker lane change that takes place over only two seconds). The test was conducted at 50 and 55 mi/h.

The steering input was from the steering machine. All maneuvers were in pairs, with one to the left followed by an identical maneuver to the right. Each pair at the lower frequency (0.2 Hz) was followed by the pair at the higher frequency (0.5 Hz). Then the two pairs at the next higher acceleration amplitude were run. After the highest peak lateral acceleration was completed, the process began again at the lowest acceleration. The standard calls for each combination of speed, steering rate, steering amplitude, and direction to be repeated three times so variability can be observed.

The vehicle was instrumented as it was for the high-speed cornering. Data were recorded continuously during these maneuvers. As specified in ISO 14793:2011, peaks of yaw velocity and lateral acceleration were plotted.

The lateral acceleration gain is a measure of how much the vehicle responds to a transient steering input. A large change in this parameter at higher acceleration levels would have indicated that the vehicle requires a different level of skill to control during more severe, sudden maneuvers. There were no significant differences between the loading conditions.

Plots of the results from these tests show how little the loading condition's effect is. Figure 23 is the variation of peak lateral acceleration in the maneuver as a function of the handwheel angle. Maneuvers that are initially to the left are on the right side of the figure, and maneuvers initially to the right are on the left side. A larger peak handwheel angle produces a larger peak acceleration, and the relation is linear over the range of the tests. The effect is stronger for the slower 0.2-Hz maneuvers represented by the circles. The three loading conditions are represented by darker shades of the two colors. They are difficult to distinguish in the figure, which means that the loading condition does not have an appreciable effect. Figure 24 is a similar graph of the dependence of the peak yaw velocity (turning rate) on handwheel angle. Figure 25 plots the time lag in seconds (s) from the moment the handwheel input reached its peak and the moment when the vehicle's lateral acceleration reached its peak. Figure 26 plots the time lag from the moment of the peak handwheel input and the peak of the vehicle's yaw velocity. Again, the effect of the loading condition is difficult to discern.

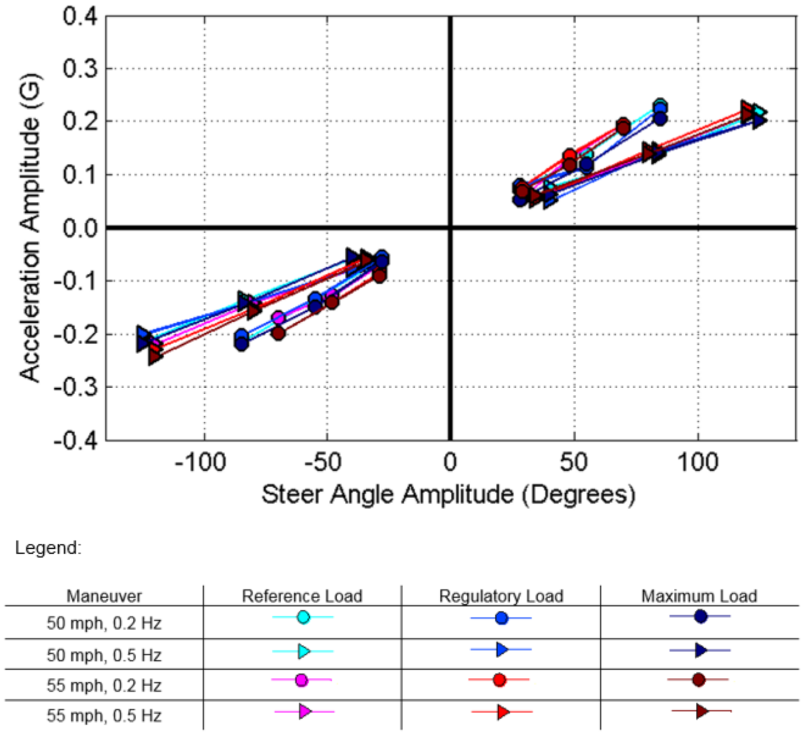

Figure 23. Graph. The lateral acceleration produced in a sinusoidal steer did not change with the loading condition.

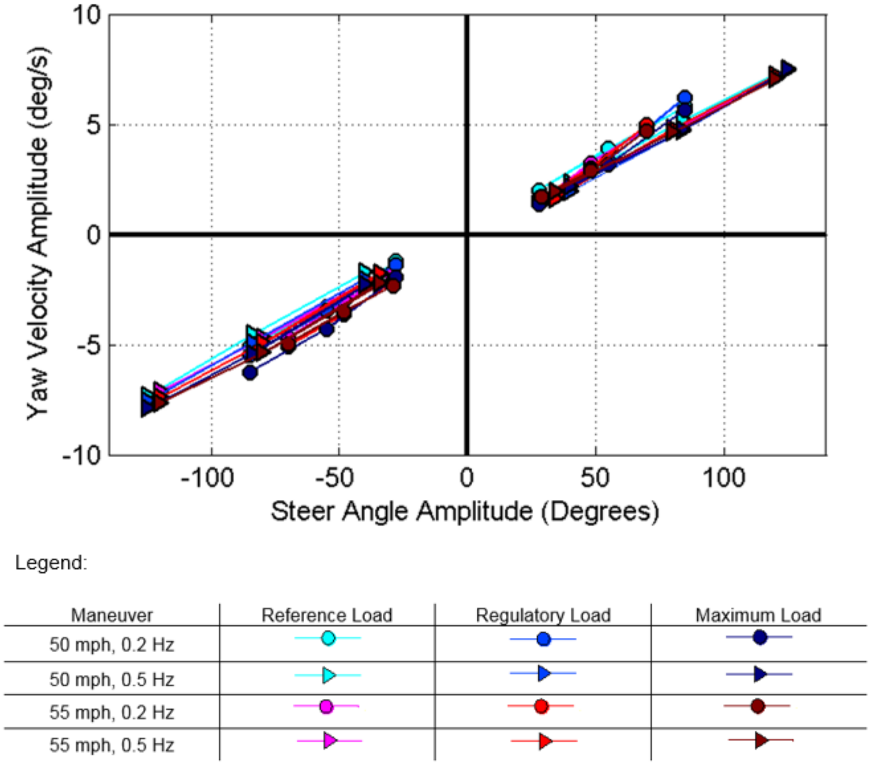

Figure 24. Graph. The yaw velocity produced in a sinusoidal steer did not change with the loading condition.

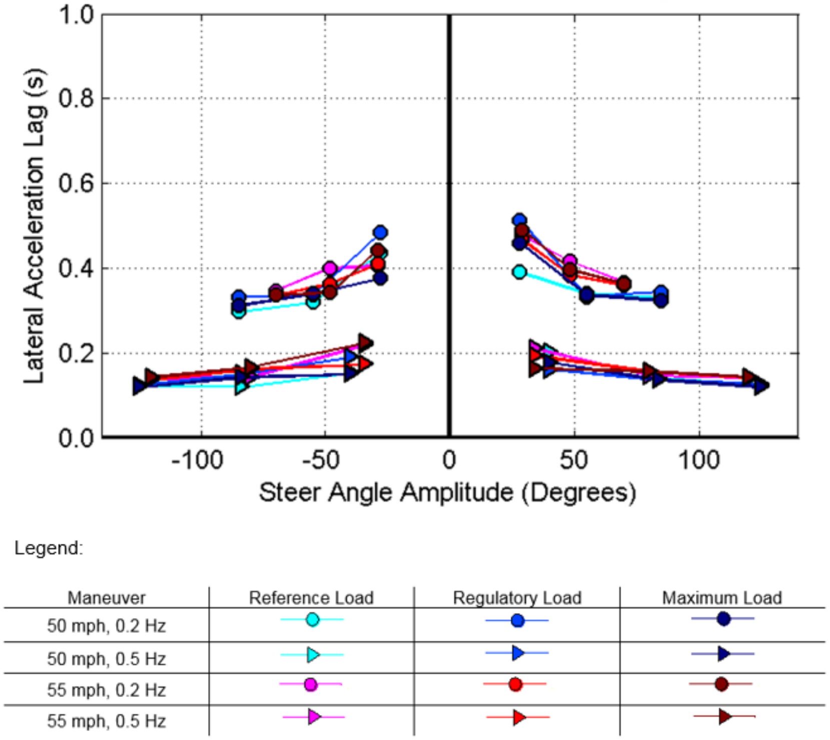

Figure 25. Graph. The time lag between handwheel input and vehicle lateral acceleration response did not change with the loading condition.

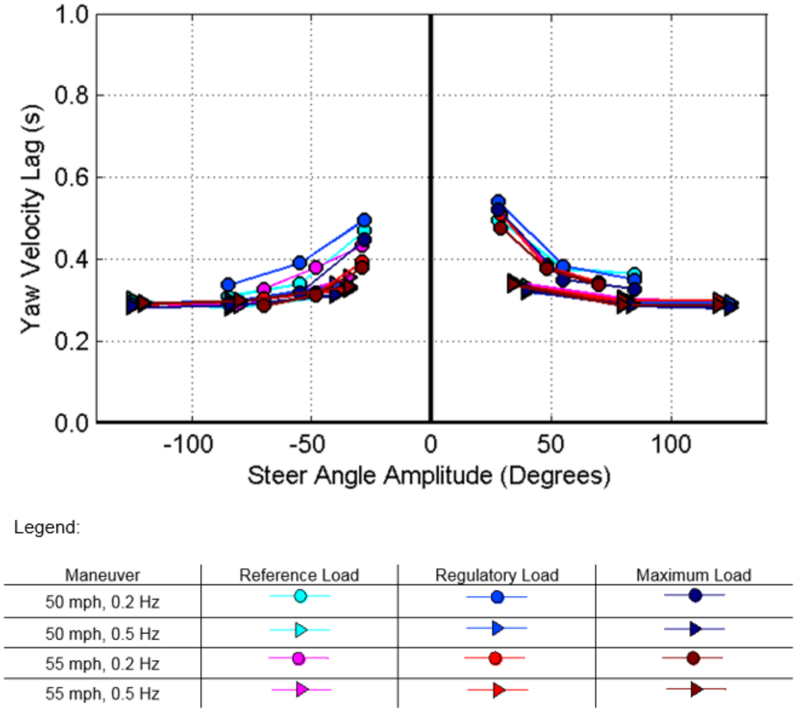

Figure 26. Graph. The time lag between handwheel input and vehicle yaw velocity response did not change with the loading condition.

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APPENDIX E: INTEGRITY OF THE ATTACHMENT

This appendix presents the approach for analyzing the structural integrity of the attachment, which is reported on page 14 of the main text.

The framework for the approach to estimating the service life is in MIL-STD-810G (with CHANGE-1) Method 514.7 Annex F,(24) which calls for describing the various conditions the part will encounter in its lifetime. The strains were measured as the motorcoach in the regulatory loading condition was driven over courses selected to represent the range of service conditions. A simple finite-element model of a hinge was used to estimate stresses in the critical welds. Finally, failure criteria accepted by the American Society of Mechanical Engineers (ASME) were applied.(25,26)

The hinges that support the rear luggage compartment have been judged to be the most critical member of the attachment, so the analysis focused on the upper hinge, as indicated in Figure 27.

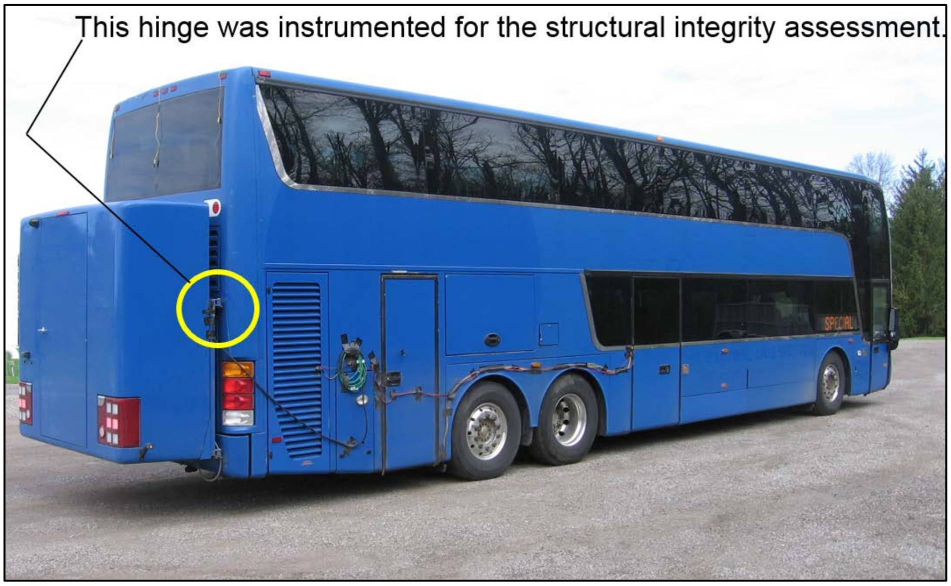

Figure 27. Photo. Strain gages were mounted on the upper hinge that supports the weight of the compartment.

The assumed service conditions in 1 million miles of the life of a motorcoach is provided in Table 23. This defines the typical life of a motorcoach and the number of miles traveled on various types of terrain and at various speeds. The distribution of speed (i.e., the number of miles driven in various speed ranges for each surface type) was estimated using the Beta distribution method described in MIL-STD-810G. The distribution of speed is provided in Table 24.

Table 23. The service life of the motorcoach is broken down by road surfaces.

Surface Type	Miles	Maximum Speed (mi/h)	Average Speed (mi/h)
Paved Road	950,000	70	55
Secondary Road	49,000	40	25
Bumpy Road	1,000	15	10

Table 24. The service life of the motorcoach is further broken down by speed.

Speed (mi/h)	Miles on Paved Road	Miles on Secondary Road	Miles on Bumpy Road
1	< 1	< 1	1
5	< 1	< 1	108
10	< 1	463	545
20	59	7,243	346
30	2,457	23,065	0
40	28,950	18,228	0
50	156,260	0	0
60	424,154	0	0
70	338,121	0	0

The motorcoach in the regulatory loading condition was driven at speeds up to 70 mi/h on different surfaces to collect data for the conditions shown in Table 24. For the paved road, representing a well-maintained highway, the motorcoach was driven on a high-speed oval track. The secondary road was a surface of chipped pavement with minor bumps on the entrance and exit. The bumpy road, representing the occasional curb strike or pothole, was simulated by three bumpy segments, as shown in Figure 28. The speed for the paved and secondary roads started at 5 mi/h, and the speed for the bumpy road started at 1 mi/h. From 10 mi/h, the speed increased in increments of 10 mi/h until reaching the maximum speed for the surface. The motorcoach was driven for at least 60 seconds in every test condition.

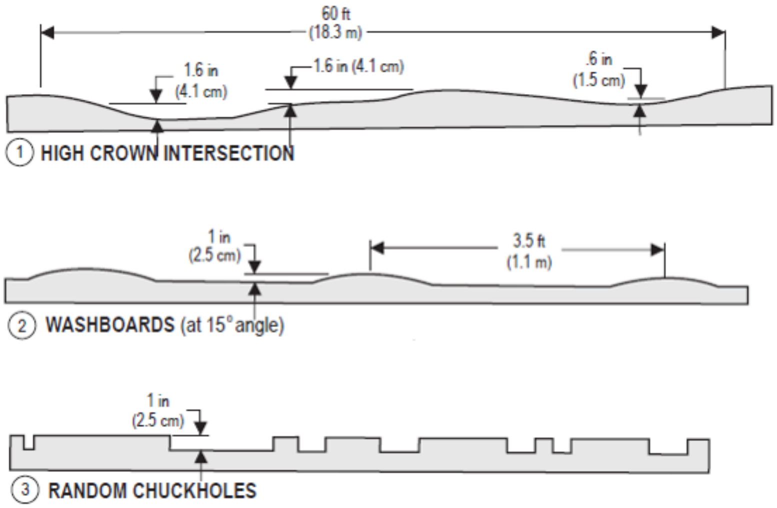

Figure 28. Drawing. The bumpy road was simulated by a series of three surfaces.

A finite-element model described the luggage compartment and its joints. Rigid boundary conditions were placed at the locations where the joint structure attaches to structural members of the vehicle. The simulated compartment was filled with a compliant mass to represent the luggage. This model was used to determine potential failure locations in the compartment joints.

A close-up of the hinge that was instrumented is shown in Figure 29. The rear of the motorcoach is in the left of the picture and the forward surface of the luggage compartment is to the right. Figure 30 is a finite-element model of the hinge, from approximately the same vantage point.

Figure 29. Photo. This hinge was instrumented for the structural integrity assessment.

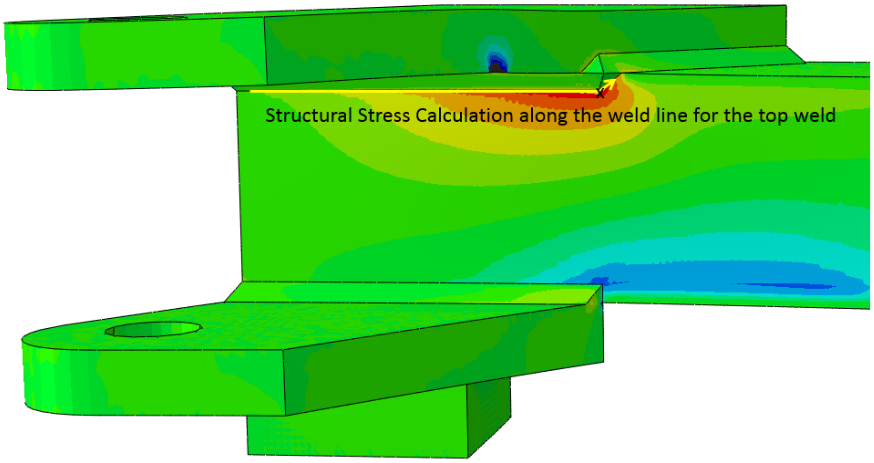

Figure 30. Drawing. The finite-element model of the hinge shows a red area by the weld indicating the location of peak stress.

Strain gages were mounted on the hinge. The locations and orientations of the gages were selected to measure the strain at potential failure locations determined with the finite element model. Adjacent gages were mounted at right angles to measure multi-axial strain. A close-up of some of the gages is shown in Figure 31. Strain data were recorded as the motorcoach was driven at various speeds over several roads representing those defined in Table 23.

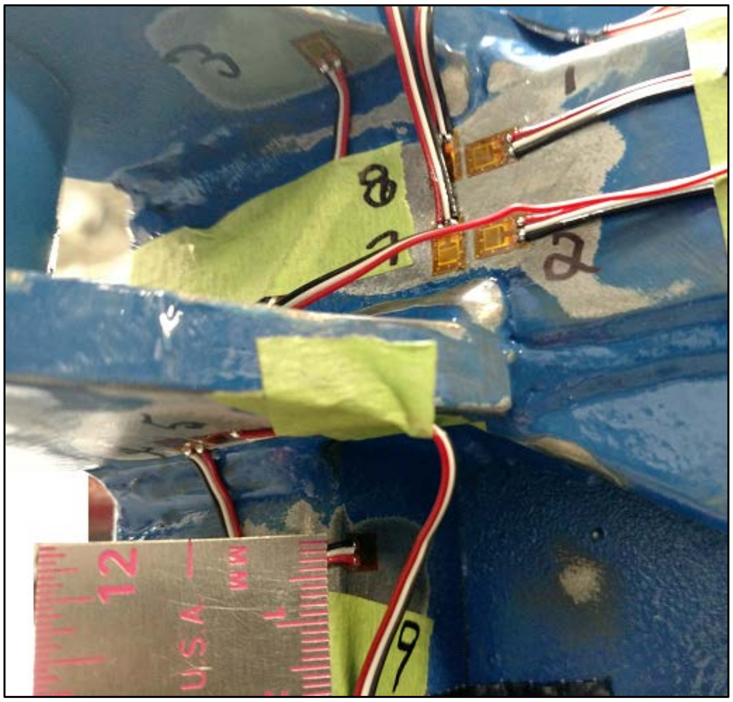

Figure 31. Photo. A total of nine uniaxial strain gages were mounted near welds on the hinge.

The strains measured near the upper weld were analyzed with the finite-element model to determine the peak structural stress along the weld line. A multi-axial cycle counter was used to convert this data to effective stress ranges and cycles.(27) The effective stress range and the number of cycles were calculated over several seconds of travel at each speed and surface type in Table 24. These results were extrapolated to estimate the average loading cycle experienced by the hinge in the assumed 1 million miles in the table.

The number of cycles (N) and stress (S) range data were used with a standard S-N curve to determine the fatigue life of the attachment in miles. The master S-N curve that was used is appropriate for any steel weld. The service life of the weld is 2.6 million miles if the mean value of the S-N curve is applied. A more conservative approach is to take a number of cycles that is two standard deviations below the mean of the S-N curve. This establishes a lower bound on the service life of 830,000 miles to failure.

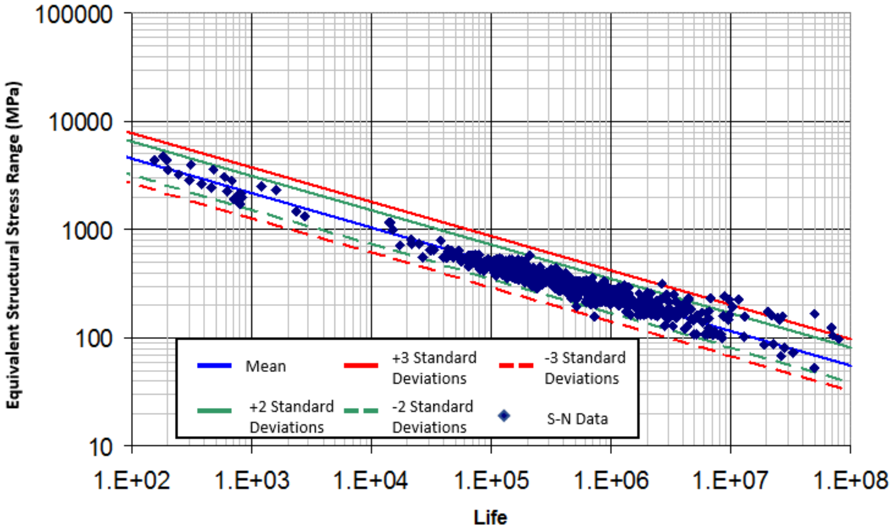

Figure 32. Graph. Master S-N curve for steel welds—ASME Div 2, API 579/ASME FFS-1 (2007).

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