Development of Car/Trailer Handling and Braking Standards. Vol. I: Executive Summary
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DEVELOPMENT OF CAR/TRAILER HANDLING AND BRAKING STANDARDS

Volume I: Executive Summary

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16. Abstract

This report summarizes the development of handling and braking performance requirements for passenger cars towing trailers. These requirements are based on the results of over 2000 combination-vehicle tests with eight trailers and three rear wheel drive tow cars (in 95 different configurations), over 500 tests with three trailers and two front wheel drive tow cars (in 38 different configurations), plus the results of previous trailer towing research. The proposed standards include recommendations for straight line braking performance, trailer swing stability, tow car steady turn stability, and combined brake in turn stability and performance. For straight line braking, the recommended performance criterion is 0.4 g deceleration of the combination-vehicle. A tow car weight based on trailer brake capability requirement is presented to insure that the combination-vehicle will meet this deceleration requirement. For trailer swing stability the safety-related performance measure is damping ratio, or the equivalent cycles to one-half amplitude. A minimum damping ratio of 0.15 (or 3/4 cycles to one-half amplitude) has been recommended. Test procedures and analysis are presented which can be used to determine damping ratio for each trailer. In this case a minimum hitch load criterion based on tow car weight is suggested to insure performance compliance. For tow car stability a tentative performance criterion of maintaining a positive tow car understeer gradient up to and including 0.3 g cornering has been recommended. This requirement sets a limit on the

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ABSTRACT (concluded)

maximum allowable hitch load for a given tow car weight and is a function of the load leveling torque applied by a weight equalizing (Class III) hitch. Due to the compatibility of these latter two handling requirements, they have been integrated into a single hitch load versus tow car weight graph unique to each trailer. Use of this graph by a user or manufacturer will define the proper hitch load range for a given tow car size and/or help specify the minimum weight tow car for a given trailer.

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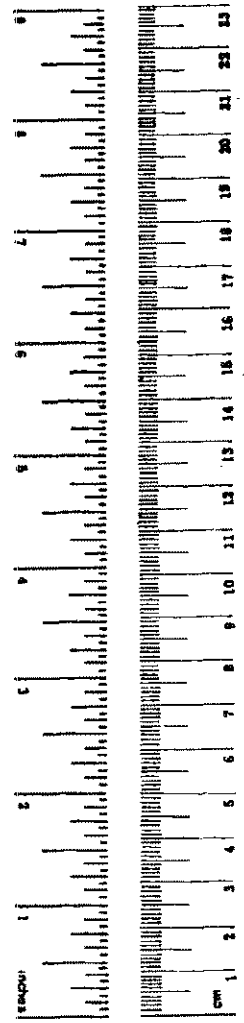
METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

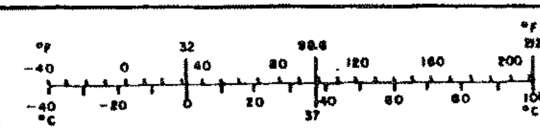
Symbol	When You Know	Multiply by	To Find	Symbol
	LENGTH			
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
	AREA			
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
	MASS (weight)			
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
	VOLUME			
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
	TEMPERATURE (exact)			
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
	LENGTH			
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
	AREA			
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
	MASS (weight)			
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
	VOLUME			
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
	TEMPERATURE (exact)			
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



FOREWORD

This document comprises Volume I of a four-volume technical report documenting the development of car/trailer handling and braking standards. This volume contains a condensed executive summary of the program and key results. Volume II presents the main technical discussion and summary test results of Phase I testing with three rear wheel drive tow cars. Volume III contains appendices providing raw data and other supportive material for the Phase I tests. Volume IV contains additional Phase II test results for two front wheel drive cars and three trailers used for validation of the proposed safety boundaries.

The research program was accomplished by Systems Technology, Inc., Hawthorne, California, for the Office of Passenger Vehicle Research of the National Highway Traffic Safety Administration, under Contract DOT-HS-7-01720. The Contract Technical Manager was Dr. J. Kanianthra, and the STI Project Engineer was Mr. R. H. Klein, The STI Technical Director was Mr. I. L. Ashkenas.

Significant contributions made by STI staff members include Mr. H. T. Szostak for test direction and data analysis, Mr. L. A. Ingersoll for vehicle instrumentation and maintenance, Mr. S. Whitfield for test driving, and Mr. G. L. Teper and Ms. S. A. Riedel for development of automated data reduction techniques.

Special acknowledgment is given for the fine cooperation and assistance extended to this program by the following organizations: SAE On-Highway Recreational Vehicle Committee, Recreational Vehicle Industry Association, U-Haul, Fleetwood Enterprises, Prowler Industries, Coachman Industries, Shasta Trailers, Holiday Rambler, Atwood Mobil Products, Dexter Axle Co., Cal-Camp, and Eaz-Lift.

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SECTION I

INTRODUCTION

This report summarizes the development of braking and handling performance criteria and compliance formats that can be used to develop the foundation for passenger car/trailer safety standards. The need for this work stems from the reported (i.e., Ref. 1) higher accident rate for vehicles pulling trailers than for passenger cars alone. Critical parameters in car/trailer combinations (as opposed to passenger cars alone) are frequently determined by the driving public, via "rules of thumb," often with little regard to the few recommended practices available. As a result, accidents involving car/trailer vehicles can be caused by loss of control during straight-ahead and sub-limit (normal) driving, as well as during accident avoidance and limit-of-performance conditions. Accordingly, a need exists for a basic, uniform, performance-related handling criterion to improve product safety. The criterion must be directly relevant to dominant physical parameters and not legislate minor design details which might stifle competition. The related tests and measures must be simple and easily performed so as to not work a hardship on the smaller manufacturer. Finally, the criteria, tests, and measures must take into account the fact that the trailer manufacturer has no direct control over what the customer will do with the other two companion elements — the tow vehicle and hitch device — which have a profound interactive influence on the combined-vehicle handling and safety.

In this regard, this program is a direct extension to prior work addressing the underlying problem of devising handling and braking tests and key performance parameters for automobile/trailer combinations. This prior work was accomplished by STI (Refs. 2 and 3) and by the University of Michigan, Highway Safety Research Institute (HSRI) (Ref. 4). As an extension, this program takes full account of the analytical methods, test procedures, performance measures, and test apparatus used in accomplishing the preceding research. The major thrust of this effort, however, was to define the performance criteria, recommend compliance test procedures, and produce the foundation for a trailer handling/braking safety standard.

The approach taken to accomplish the above task was threefold. First, preliminary analyses were performed to suggest the rule format and trends to be expected. These are documented in Volume II. Second, a full-scale test program was performed in which over 130 different hookup configurations were tested using nine trailers and five tow cars, as summarized in the next section and detailed in Volumes II and IV. Based on test results the third step included selection of the applicable performance criteria and recommendations for a rule format.

Primarily, only four key test maneuvers were used; these included straight line braking, step steer, pulse steer, and brake in turn, which are also described in the next section. Individual sections of Vols. II and IV are organized according to these four key test procedures; that is, each section represents one test maneuver and stands alone in its treatment of analytical foundations, full-scale test results, development of tentative standards format, selection of performance criteria, and, finally, recommendations for a rule format and compliance test procedure.

The final section of this report summarizes the results and recommendations presented in each of the individual sections of Vols. II and IV.

SECTION II

PERFORMANCE REQUIREMENTS

A. STRAIGHT LINE BRAKE PERFORMANCE

A significant problem in trailering safety is increased stopping distance due to increased total vehicle mass without proportional increase in braking effectiveness. At the present time there are no federal braking performance standards for recreational or utility trailers designed for towing by passenger cars or light trucks. There are, however, stopping distance standards for the tow vehicles, i.e., FMVSS 105-75 (Ref. 5). In addition, even if there were a trailer brake standard, the many variables present in tow car/trailer hookups have sufficient influence such as to alter the expected "combination-vehicle" stopping distances. In other words, the total may not necessarily be equal to the sum of the parts. With this problem in mind, a basic objective of this program was to conduct sufficient tests to identify appropriate braking requirement levels for combination-vehicles and trailers alone to form the basis of a federal standard.

B. TRAILER DAMPING PERFORMANCE

Trailer stability represents the second performance parameter for which a vehicle handling standard is required. This trailer mode is the pendulous swing oscillation of a trailer commonly seen on the highway. If trailer mass and inertia are small with respect to the tow vehicle, this motion is more of a nuisance than a handling problem and, in fact, cannot become unstable if the hitch point does not move. However, as the trailer approaches or exceeds the tow vehicle in mass and inertia, the forces and moments applied by the oscillating trailer to the hitch point (and hence to the automobile) become large enough to cause loss of control, trailer separation, and/or combination-vehicle rollover.

Due to the frequency and damping separation between the tow car and trailer modes, the trailer mode oscillation can be accurately modeled by a simple second-order system response. By analogy, the resulting performance measure used to assess trailer stability is the <u>reduction</u> in swing amplitude with successive oscillations. In vehicle dynamics terminology such oscillatory stability is measured by cycles to one-half amplitude, or (an equivalent) damping ratio, ζ. When $\zeta = 0$ the oscillation is sustained (undamped), and at $\zeta = 0.5$ the oscillation ceases within 1 cycle. At $\zeta = 1.0$ there is no oscillation. If damping ratio becomes negative, the oscillation amplitude increases with time, and hence is unstable — a very undesirable condition. The most significant changes pertinent to trailer swing occur at low or negative damping ratios, i.e., from negative to 0.3, where the oscillations are perceptible to the driver and where safety implications arise.

C. TOW CAR STEADY-STATE TURN STABILITY

It has been shown in previous car/trailer handling studies (Refs. 2 and 3) that a sensitive, repeatable, and easily determined handling parameter for quantifying combined-vehicle directional steady-state control and dynamic stability is the understeer/oversteer gradient, or stability factor, K. When K is positive the vehicle exhibits the normal understeer characteristic present in most vehicles. When K is zero the vehicle is said to be neutral steering and the turn radius for a given steer angle is independent of speed. When K is negative the vehicle exhibits oversteer, which results in a tendency to jaccknife. The importance of this parameter has been well recognized, and in the Ref. 6 study the first known attempt to establish a trailer towing performance safety standard based on this parameter was made. In this program we have suggested an approach for using K to isolate requirements imposed on the tow vehicle by the trailer, compared full-scale results to tentative stability boundaries, and suggested recommendations for stability criteria and test procedures.

D. COMBINED BRAKING AND CORNERING

The fourth combination-vehicle performance requirement was aimed at uncovering tow car and/or trailer stability problems during a brake-in-turn maneuver. Ideally, if the automobile and trailer meet the individual and combined vehicle requirements described previously, then there should be little or no response degradation during the combined maneuver. If a response degradation does occur, then the preceding requirements should be altered or new requirements developed.

A combined-vehicle performance parameter was developed in Ref. 2 to relate initial tow vehicle directional rate of change (stability factor change) and deceleration level. Time duration of any adverse response was also a weighting factor. For example, Ref. 2 data suggested that yaw rate change per unit speed change greater than $|0.3|$ (deg/sec)/mph sustained for 1 sec or longer would result in a car/trailer jackknife. It was felt that it would be almost impossible for the average driver, within one second, to recognize the onset of a jackknife condition and initiate corrective action.

SECTION III

TEST PROGRAM

This section summarizes the test vehicles, combination-vehicle configurations, and test procedures germane to the full-scale test portion presented in Vols. II and IV. Additional vehicle specifications, instrumentation details, complete run logs, and raw data are in Vols. II and IV and the Vol. III appendices.

A. TOW VEHICLE SELECTION

Based on contract requirements, three rear wheel drive tow cars representing an intermediate, compact, and subcompact were selected for Phase I testing. To provide a range of design differences each was to be represented by a different major automobile manufacturer, i.e., GM, Ford, and Chrysler. All were to be 1976 model year or newer, so that they would comply with the passenger car braking standard FMVSS 105-75. For Phase II, two subcompact front wheel drive cars were recommended. These were to validate or revise the requirements developed in Phase I. The final selection of tow vehicles is described in Table 1.

B. TRAILER SELECTION

Characteristics considered in selecting the test trailers were type, weight, class, number and position of axles, and brake type. Combining all these factors led to the selection of eight trailers for Phase I. These are described in Table 2 and include four travel trailers (two Class 2 single axle, one Class 3 tandem axle, and one Class 4); one Class 2 single-axle boat trailer with surge brakes; two Class 1 camper and utility trailers with single axles and no brakes; and one Class 4 horse trailer with brakes on only one axle. For the second, or validation, phase of testing the two small trailers plus an additional 16 ft travel trailer were tested.

TABLE 1. TEST TOW CARS

DRIVE AXLE	TYPE (GVWR)	CURB WEIGHT / TEST WEIGHT[a] (lb)	WHEELBASE (in.)	TIRES
Rear Wheel Drive (Phase I)	Intermediate (5513)	4140/4700	116	GR70-15 TPC 1007
	Compact (4775)	3400.4100	112.5	D78-14
	Subcompact (3863)	2175/3400	96	BR-78-13X
Front Wheel Drive (Phase II)	Subcompact (3571)	2722/3200	105	P185/80R-13 TPC 1029
	Subcompact (3165)	2250/2675	99	P155/80R-13

[a]Includes driver, instrumentation, hitch receptable, hitch head, hitch angle sensor, load leveling bar,s and one-half fuel.

TABLE 2. TEST TRAILERS

TYPE	OVERALL LENGTH (ft)	TEST WEIGHT / GVWR	AXLES	BRAKES	TIRES (PRESSURE)
Utility	12[a]	1500/2500	1	None	6:70 × 15 LT LRC (45 psi)
Camper	15[a]	1600/2090		None or surge	5:30 × 12 LRC (80 psi)
	16[b]	2400, 3000/3000	1	Electric, 2	7:00 × 14 LRC (36 psi)
Small Travel	18	3000, 3880/3888	1	Electric, 2	8:55 × 15 LRC ST (50 psi)
	19	4000/ Unknown	1	Electric, 2	7:00 × 15 LT LRC (45 psi)
Medium Travel	22	4000/5000	2	Electric, 4	7:75 × 15 ST LRB (35 psi)
Large Travel	27	6000/6800	2	Electric, 4	7:00 × 15 LT LRC (45 psi)
Boat	20	3000/3100	1	Surge, 2	H78-14 LRB (32 psi)
Horse	11	4000, 5800/5960	2	Electric, 2	7:75-15 LRB (32 psi)

[a]Tested in Phases I and II.
[b]Tested in Phase II only.

C. TEST PROCEDURES AND CONDITIONS

Four basic test maneuvers were used. These included straight line braking tests, handling tests (step steer and pulse steer), and a combined handling and braking test (brake in turn). Each is described below.

1. Straight Line Braking

The approach taken in this program was to investigate rational combination-vehicle stopping distance requirements based on trailer-alone deceleration capabilities. This is similar to the approach of HSRI in Ref. 4. Many combination-vehicles and hookup variables were then tested to develop practical limits for the requirements.

Braking tests were tailored after FMVSS 105-75 (Ref. 5), HSRI (Ref. 4), and SAE Recommended Practice J134 (Ref. 7) for the tow car alone, trailer alone, and combination-vehicle, respectively. They were shortened, however, to include only the preburnish effectiveness, burnish, and second effectiveness tests.

Several points are worth noting with regard to the test procedures. First, a test speed of 40 mph was selected. This was done to tie in with the previous HSRI and STI work that used 40 mph as the test speed. Second, the trailer-alone and combination-vehicle (CV) procedure allowed trailer lockup. This was consistent with SAE J134 and that recommended by HSRI. Third, the CV tests were aimed at maximum performance. This was defined as "incipient" tow car wheel lockup; hence the fixed pressure brake actuator mechanism was set to provide at least three stops just below lockup and at least three stops at partial lockup.

Appendices for Vols. II and IV give the exact sequences and raw data results for each vehicle.

2. Handling

The step and pulse steer test procedures specified in Ref. 2 were used. These are described below.

a. Step Steer Test

A constant amplitude step steer was applied and held for a minimum of 90 deg path change at constant speed. The steer angle input was adjusted to provide a 0.3 g turn at 30 mph for the combination-vehicle. This was usually between 60 and 90 deg steering wheel. The test was rerun at speeds between 10 and 50 mph in 5 mph increments to derive understeer gradient. When a combination-vehicle had a jackknife potential (i.e., high hitch load), additional 2.5 mph test speed increments were used in order to obtain data points in the transition range to jackknife. Both left- and right-hand turns were performed; however, due to data variability the right-hand turns were discontinued later in the test program.

An alternative test procedure tailored after SAE XJ266, "Passenger Car Steady State Directional Control Response Test Procedure," was also used. This test procedure required driving the vehicle around a 200 ft constant radius circle at increasing speed. Data were taken with the steering wheel position and throttle position fixed at a steady-state condition. The vehicle was then accelerated to the next speed at which data were taken. In general, this corresponded to 0.05 g lateral acceleration increments. Steer angle was plotted versus lateral acceleration to determine understeer gradient.

b. Pulse Steer Test

The vehicle was driven in a straight line at 55 mph and a fixed amplitude rapid pulse was applied to the steering wheel to excite the tow vehicle and trailer dynamic modes. Four replications were performed to provide a measure of the variance in damping ratio.

3. Combined Handling and Braking Test (Brake in Turn)

Constant brake level stops were initiated from 40 mph during a steady-state turn on a 355 ft radius circle. This provided 0.3 g lateral acceleration. Brake pedal pressure levels were increased on succeeding runs up to lockup of one tire on one axle of the tow car. In all cases the steering was held fixed during the deceleration interval. The test was also performed with full and with partial trailer brakes.

4. Additional Tests

Several other peripheral tests were performed to check analysis or data consistency. These included a trailer-alone damping test (external force applied at axle); tests to determine effects of speed, inertia, and lateral acceleration on trailer damping; and coast-down versions of step steer and constant radius circle tests to determine power effects. These are described in detail in Appendix B of Vol. III.

5. Test Conditions

All tow vehicles and trailers were new or put in "as new" condition with OEM brakes, tires, and adjustable air shocks. Each tow vehicle except the smallest front wheel drive car was also equipped with a Class III frame mounted hitch and Kelsey-Hayes electric brake controller.

Tire inflation pressure of all vehicle tires was maintained at the manufacturers' recommended cold inflation pressure for the test loading condition. The vehicle was then driven at 40 mph for 15 mi to establish the "hot" inflation pressure. This inflation pressure was then maintained for all tests conducted under the given loading condition. In addition to maintaining inflation pressures, all new tires were "broken in" prior to effectiveness testing. For the tow vehicles, the burnish procedure was adequate for this purpose. For the trailers, several turns (both left and right) around the 200 ft radius circle were performed.

Trailer electric brakes were set up using an external resistor mounted in the tow car. Since no quantitative procedure was provided by the manufacturer for selecting the resistor value it was set up such as to provide a minimum of 10 volts at the trailer brakes with full controller application.

D. TEST CONFIGURATION SUMMARY

1. Phase I

In addition to the 24 potential combination-vehicles (3 cars × 8 trailers), several other variables were considered in order to develop meaningful handling and braking performance standards. These were the trailer weight, hitch load, load leveling torque, air shocks, and trailer brake authority. In general, each combination-vehicle was tested through a range of hitch loads. At the heavier hitch loads a minimum of two values of load leveling were then used. These corresponded to the current recommended practice of "+25 percent" (i.e., 25 percent of the hitch load being transferred to the tow vehicle front axle) and that recommended by STI in Ref. 3 of "only that necessary to relevel the combination-vehicle <u>after</u> air shocks have been used to their fullest."

The resulting matrix of test configuations is given in Table 3a. This table shows 92 different configurations tested in seven different maneuvers. The matrix is not full factorial, however, since the trailer damping test (pulse steer), for example, is only relevant with light hitch loads, and tow car stability and braking tests (step steer, straight line brake, and brake in turn) are only significant with heavy hitch loads. This selection process resulted in 250 total configuration/maneuvers requiring a total of over 2000 actual test runs. The complete run log summary is contained in Appendix C of Vol. III.

2. Phase II

In Phase II the two tow cars and 3 trailers were tested in 34 different combination-vehicle configurations. These are listed in Table 3b. Basically, no load leveling can be used with these vehicles, since a Class III hitch cannot (or will not) be installed. However, a specially built Class III hitch was installed on one front wheel drive car in order to demonstrate towing with the rear wheel <u>off</u> the ground. Again only the potentially worst case conditions were evaluated. This resulted in almost 250 individual test runs, which are listed in Vol. IV.

TABLE 3a. FULL-SCALE TEST SUMMARY FOR PHASE I

TRAILER	TEST CONFIGURATION: WEIGHT	HITCH LOAD	LOAD LEVELING	AIR SHOCKS	TEST PROCEDURES: SST			CRT			PS			SLB			BIT			BTA			OTHER		
					I	C	S	I	C	S	I	C	S	I	C	S	I	C	S	I	C	S	I	C	S
Utility	1500	0	N →	N →							x	x	x				x								
		2.5		Y									x												
		5		N Y Y							x	x	x				x								x
		7.5		Y									x												
		10		N Y Y	x		x	x		x	x	x	x	x	x	x	x		x						
		20	↓	Y	x			x			x			x			x						x		
Camper	1600	0	N →	N →							x	x	x												
		5		Y →	x						x	x	x	x			x								
		10			x			x			x	x	x	x		x	x		x						
		15			x			x			x			x			x								
		20	↓	↓	x			x			x			x			x								
18 ft Travel	3000	13	25	N	x			x			x			x			x			x					
			N	Y	x			x			x			x			x								
	3420	5	N	Y			x			x			x												
		7.5	N	Y			x						x												
	3880	5	N 20 31	N →							x	x	x										x		
		7.5	21										x												
		10	25 35 34		x			x			x	x	x	x		x	x								
		15	23 23	↓		x						x	x		x			x			x			x	
		20	-25	Y	x			x			x			x			x								
		20	25	N	x			x			x			x			x								
19 ft Travel	[illegible]000	5	N 0 N	Y N Y							x	x	x												
		10	N 10 0	Y N Y							x	x	x												
		15	25	N	x			x			x			x			x			x					
		15	-32	Y	x									x			x								
22 ft Travel	4000	0	N	N							x														
		5	N →	Y →		x			x		x	x	x												
		7.5	N →	Y →		x			x			x	x												
		10	N	Y	x			x			x			x			x								
		10	0 -29 0	N Y Y	x	x		x	x		x	x	x	x		x	x			x					
		10	25	N	x			x			x			x			x								
		12.5	-6	Y		x			x			x													
		15	-7	Y		x			x			x			x										
		15	17	N		x			x			x			x			x			x			x	
		17.5	4	Y		x			x			x													
		20	25	N	x			x			x			x			x								
27 ft Travel	6000	5	N 13	Y N							x	x											x		
		10	-15	Y	x																				
		10	25 15	N N	x	x		x			x	x		x			x			x					
		15	-20	Y	x																				
		15	0	Y				x						x			x								
		15	25	N	x			x			x			x			x								
Boat	2275	25	28	N		x			x															x	
	3000	0	N →	N →			x			x	x	x	x												
		3	N	Y									x												
		5	N →	Y →			x			x	x	x	x												
		5	0	N			x			x			x												
		7.5	0	N									x												
		10	N N 32	Y Y N	x		x	x		x	x	x	x	x		x	x		x	x					
		15	N -14	Y Y	x						x			x	x										
		15	25 35 21	N N N	x		x	x		x	x	x	x	x	x										
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		15	possible		x						x														
	h000	5	with									x	x												
		10	this			x						x	x		x			x			x				
	2000	10	trailer	↓							x														

Notes:

Hitch Load – percent of trailer weight

Load Leveling – percent of hitch load transferred to front axle

Air Shocks – Yes if used to level CV; No if not used

SST – step steer test (steering set for 0.3 g at 30 mph)

CRT – constant radius turn (400 ft diameter circle at 0.3 g at 30 mph)

PS – pulse steer (steer pulse at 55 mph)

SLB – straight line brake (maximum deceleration from 40 mph)

BIT – brake in turn (maximum deceleration from 40 mph at 0.3 g cornering)

BTA – trailer-alone brake capability test

Other – miscellaneous tests (calibrations, damping, inertia, braking, etc.)

I – intermediate; C – compact; S – subcompact

TABLE 3b. FULL-SCALE TEST SUMMARY FOR PHASE II

TRAILER	TEST CONFIGURATION						TEST PROCEDURES											
	WEIGHT	HITCH LOAD	AIR SHOCKS		BRAKES		CRT		PS		SLB		BIT		BTA		OTHER	
							S2	S3	S2	S3	S2	S3	S2	S3	S2	S3	S2	S3
Utility	1000	0		N	N					×								
		10	Y	N	N				×	×	×	×						
	1500	0	N	N	N			×	×	×	×	×						
		5	Y	N	N		×	×	×	×	×							
		10	Y	N	N		×	×	×	×	×	×						
		15	Y	N	N		×	×	×	×	×	×	×	×				
		20	Y	N	N		×	×										
	2600	5		N						×								
		10	Y	N	N				×	×	×	×						
Camper	1600	0	N	N	—				×	×								
		5	Y	N	—				×	×								
		10	Y	N	Y	Y	×	×	×	×	×	×			×			×
		10	Y		N						×		×					
		15	Y	N	Y	Y			×	×								
Travel	2400	5	Y	N	—				×	×								
		10	Y	N	0%	N					×			×				×
		10	Y	N	50%						×							
		10	Y	N	100%	Y	×	×			×	×	×	×	×			×
		15	Y	N	—				×	×								
	3000	10		N		Y										×		

Note:

S2 – Subcompact No. 2 (FWD)
S3 – Subcompact No. 3 (FWD)

SECTION IV

SUMMARY AND RECOMMENDATIONS

This program has provided the fourth step in the process of developing motor vehicle safety standards covering the handling and braking performance of passenger cars pulling trailers. Previous work has established meaningful test procedures, performance measures, and in one case a proposed rule format. This current step has proposed and evaluated a justifiable set of performance criteria and tested over 125 different combination-vehicle configurations against them. This section summarizes these criteria, suggests means for insuring compliance, recommends manufacturers' test procedures, and offers user guidelines.

A. HANDLING AND BRAKING PERFORMANCE CRITERIA

The following performance criteria are suggested for passenger car/trailer combinations:

- All combination-vehicles should be capable of stopping within 134 ft from 40 mph, i.e., average deceleration of 0.4 g.

- All trailers of a combination should exhibit a minimum trailer swing damping ratio of 0.15 (i.e., 3/4 cycles to one-half amplitude) at 55 mph.

- All tow cars of a combination should exhibit a positive understeer gradient up to and including 0.3 g cornering.

- All combination-vehicles should demonstrate maximum or 0.4 g deceleration (whichever comes first) during 0.3 g cornering, without incurring transient oversteer for longer than 1 sec duration.

All these requirements can be met by proper selection of a trailer for a given tow car size (i.e., weight) and proper setting of the hitch load.

B. MEANS FOR INSURING COMPLIANCE

Using the above criteria it was possible to derive tow car and trailer characteristics that would insure the combination-vehicle meets requirements.

1. Combination-Vehicle Deceleration

To insure 0.4 g combination-vehicle deceleration it is possible to specify a minimum tow car size (i.e., weight) for each trailer weight. This selection must also consider the trailer brake capability.

The primary problem that will occur in meeting the straight line brake requirements is specifying the tow car weight necessary for unbraked trailers. This occurs because some states allow unbraked trailers up to 3000 lb. For example, it was recommended in Phase I, for rear wheel drive tow cars, that the tow car be a minimum of 2.1 times the trailer weight. In Phase II we determined that for front wheel drive cars this multiplier could be reduced to 1.5. This value definitely represents a lower bound since it requires optimum front and rear brake balance. If we hope to meet (or exceed) a 0.4 g deceleration requirement with all tow vehicles, then the 2.1 value represents a more conservative recommendation. However, even assuming the more optimistic value of 1.5, the 3000 lb unbraked trailer would have to be towed by at least a compact size vehicle (GVWR $\geq$ 4500 lb). If such a restriction is not possible, then the overall stopping distance requirement will have to be relaxed. This would, however, be inconsistent with the stopping capability of braked trailer combinations.

For braked trailers the recommended tow car to weight ratio selected above can be reduced by a factor of 3.5 times the "trailer-alone" braking capability (in g units), i.e.,

$$\frac{W_c}{W_t} \geq 1.5 - 3.5\, a_{x_{ta}}$$

Contemporary trailer manufacturers are providing 0.43 g capability, and best results from both phases showed 5 out of 7 trailers (with brakes) exceeded this value. Only when the trailer weight exceeded 1500 lb per each 2 × 10 in. brake did a trailer not meet 0.43 g. Assuming this trailer brake design criterion, there would be no restriction on minimum tow car weight.

In terms of test compliance, stopping distance should be the primary performance measure. This measure accounts for brake actuation time delays. Average deceleration can then be computed from stopping distance.

2. Trailer Stability

Trailer stability can be insured by specifying a minimum hitch load boundary (as a function of tow car and trailer weight) for each trailer model. A different model would be defined as a change in weight, effective torque length, tires, and/or moment of inertia. Methods have been presented in Vol. II and Ref. 9, and by the Recreational Vehicle Manufacturers Association, to analytically derive this boundary. However, some full-scale CV tests are necessary, especially for large trailers that require load leveling in order to properly coalesce the analytical and empirical results.

3. Tow Car Stability

Sufficient tow car stability can be insured by specifying a fixed maximum hitch load boundary as a function of tow car to trailer weight ratio for various values of load leveling. This relationship is illustrated in Fig. 1. Three values of load leveling have been shown: none (using air shocks only); minimum (based on using air shocks to their fullest and then adding leveling torque as necessary to relevel the CV); and maximum (based on no air shocks and leveling torque such as to transfer 25 percent of the hitch load to the front axle).

Combining the trailer and tow car stability boundaries results in an integrated handling compliance plot for each trailer. Figures 2a through 2i show examples of this format for the nine trailers tested in this program. Note that the minimum tow car size is equal to greater than the trailer weight — a good rule of thumb. Also, the front wheel drive tow cars allow a lighter hitch load than an equal weight rear wheel drive car; in either case, the optimum hitch load for the minimum weight tow

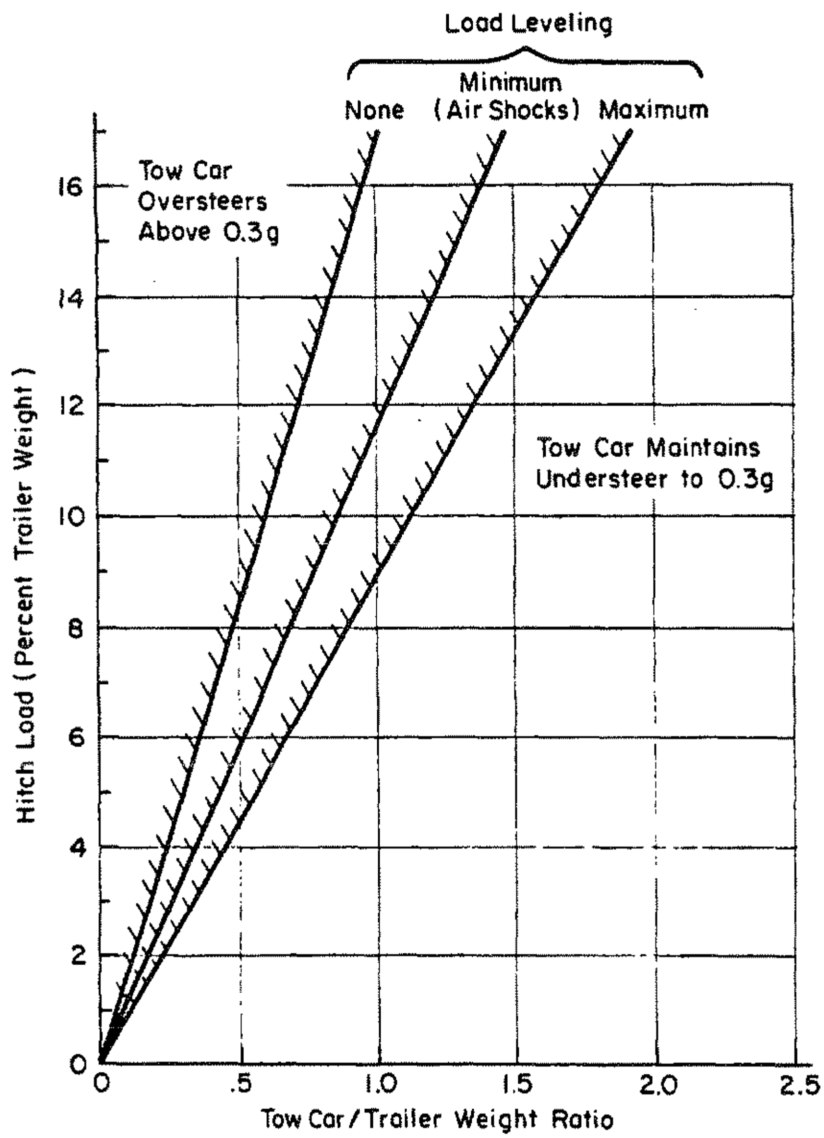


Figure 1. Proposed Maximum Allowable Hitch Load Boundary to Provide Understeering Tow Car up to 0.3 g Cornering

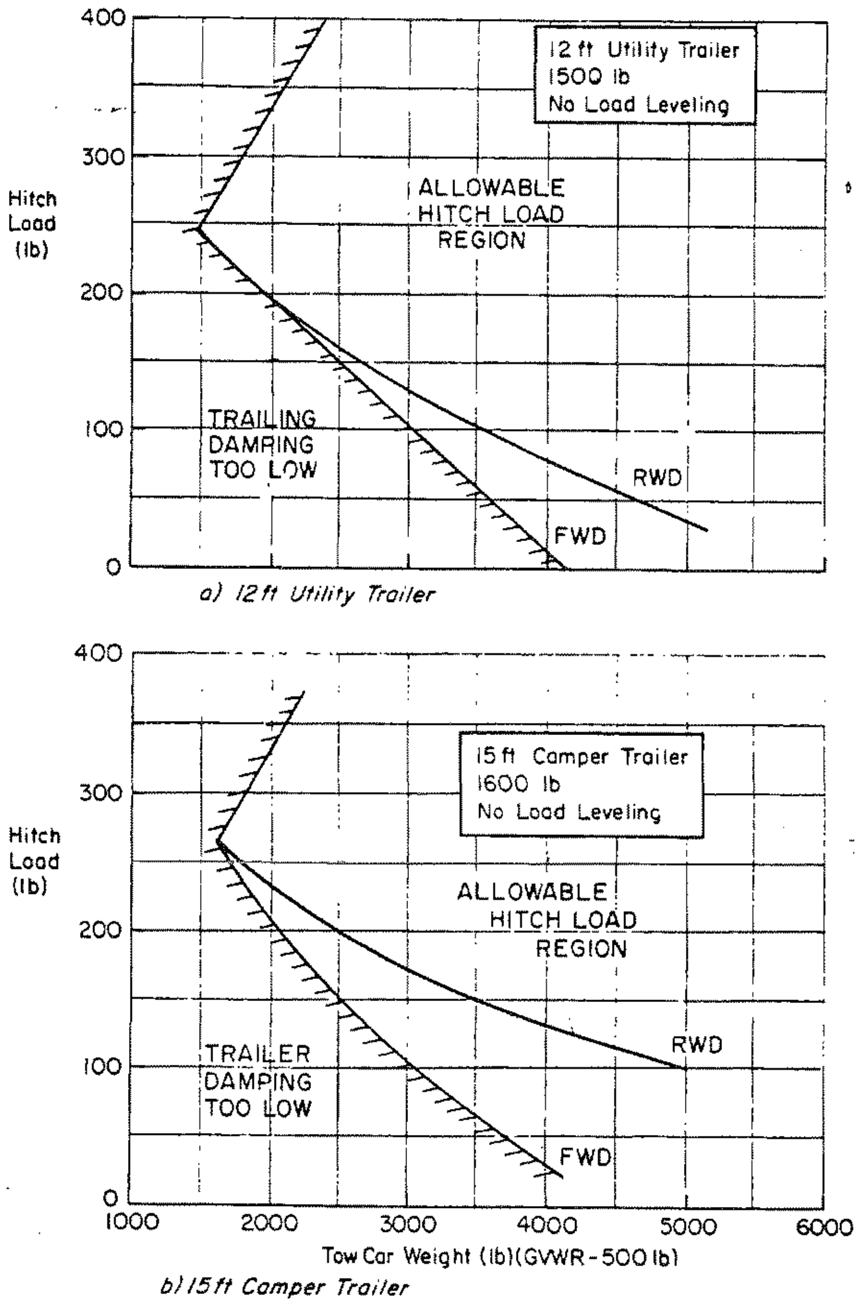
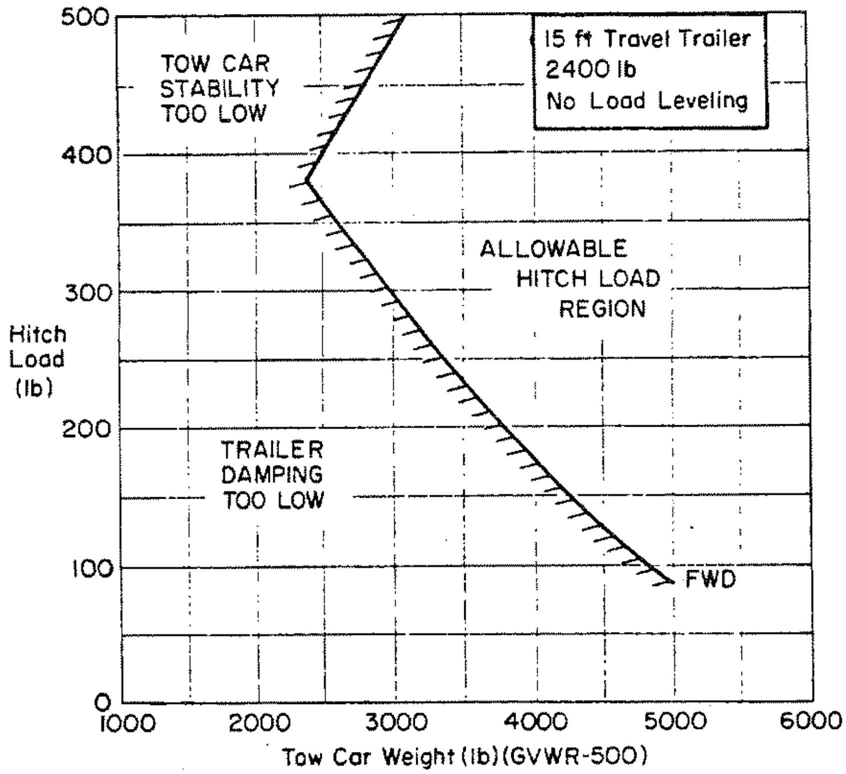
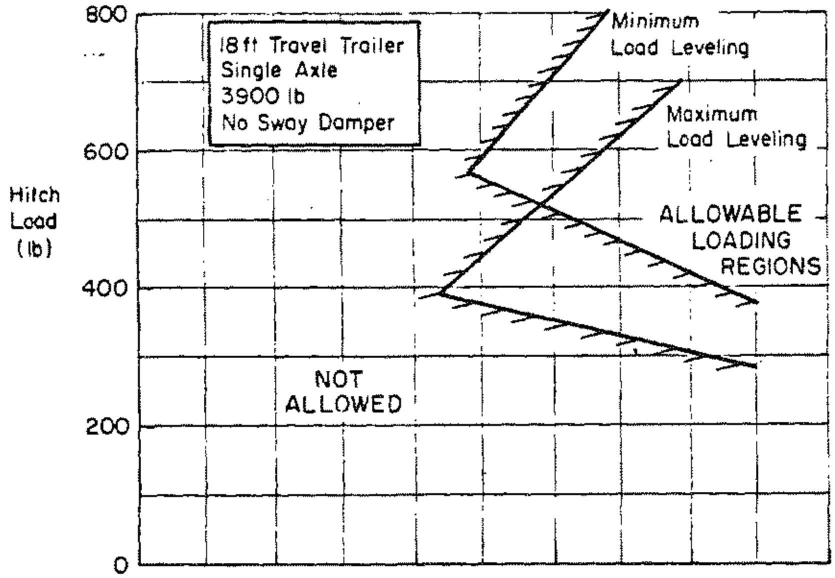


Figure 2. Recommended Integrated Trailer Handling Standard Examples

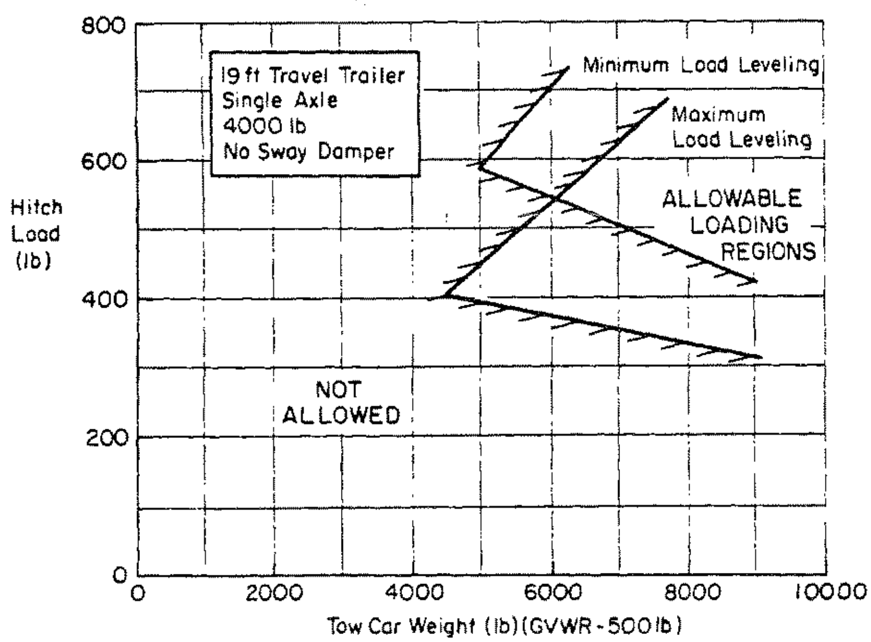


c) 16 ft Travel Trailer

Figure 2. (Continued)

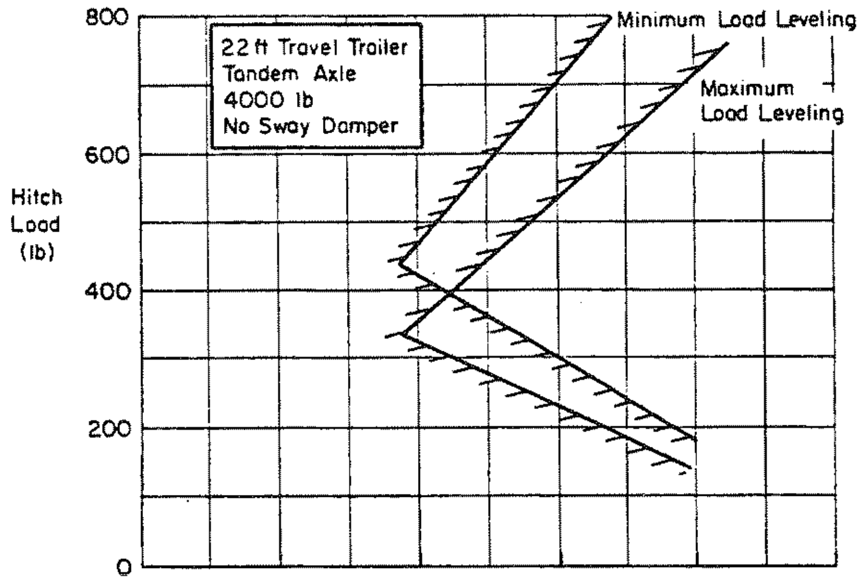


d) 18 ft Travel Trailer

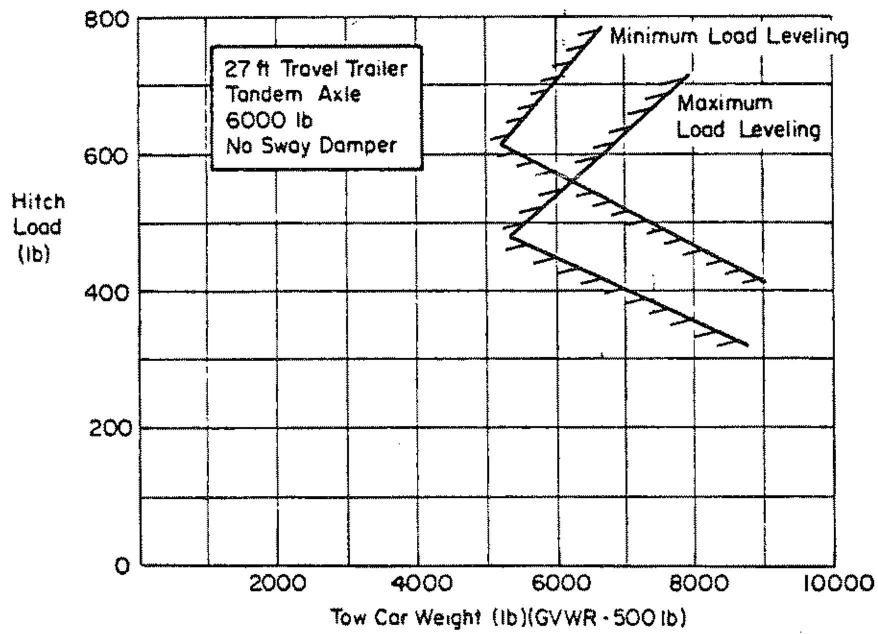


e) 15 ft Travel Trailer

Figure 2. (Continued)



f) 22 ft Travel Trailer



g) 27 ft Travel Trailer

Figure 2. (Continued)

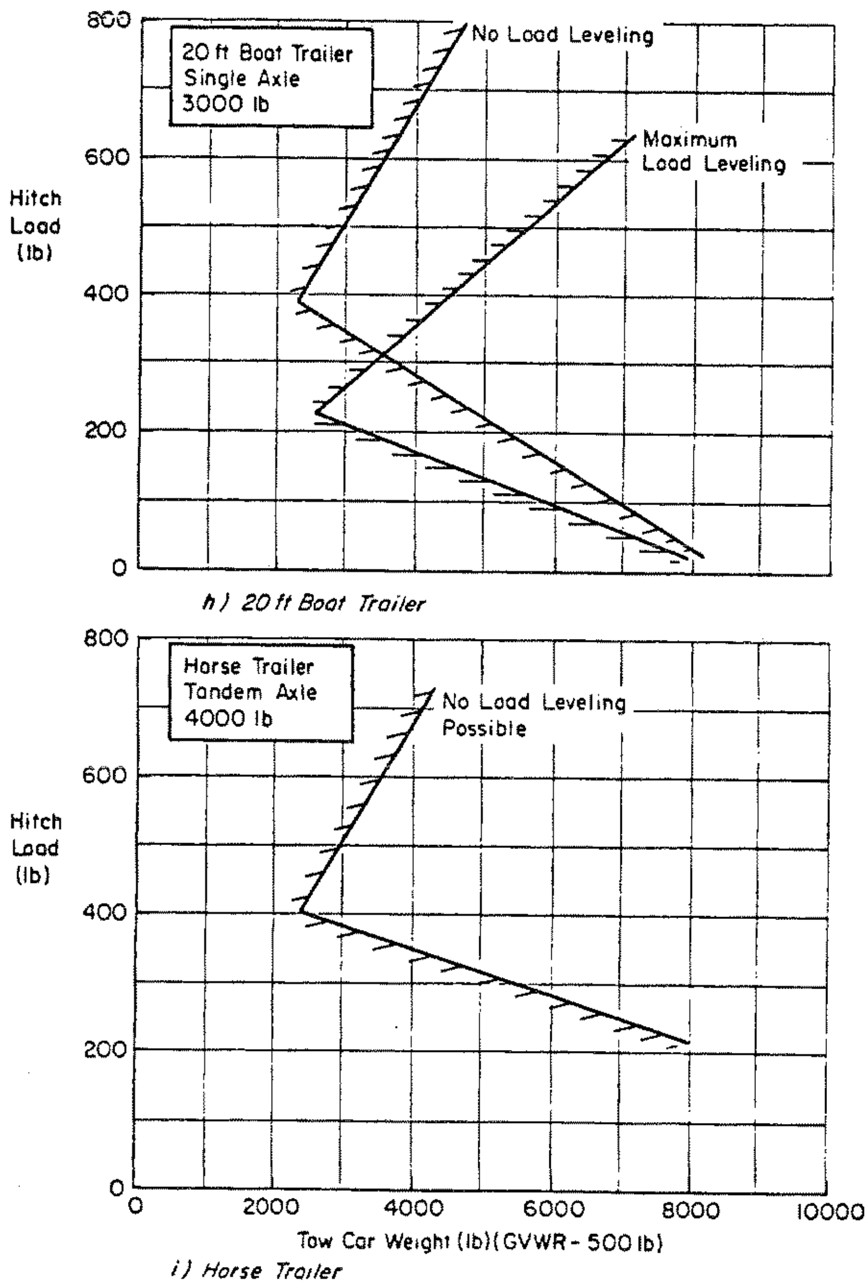


Figure 2. (Concluded)

car is about 10-15 percent. This figure is another common rule of thumb. Increasing the tow vehicle weight rating quickly opens up the allowable hitch load region. This consistency implies a proper selection of the performance criteria.

Although the trailer examples presented in Fig. 2 give a good overall picture of the tow car/trailer tradeoffs, application by a user probably always will start with a specific tow car. In this case, the upper hitch load limit may be dictated by the tow car manufacturer due to limitations of power, cooling, structure, etc. Generally, the manufacturer's limit will occur prior to reaching the stability limit. For example, many subcompacts recommend hitch loads no more than 100 lb; whereas Fig. 1 would allow up to 400 lb. In short, manufacturers' maximum hitch load recommendations should always take precedence.

3. Handling and Braking

No additional handling requirements appear necessary in order to meet the brake in turn performance requirements. However, unbraked trailers weighing more than 67 percent of the tow car cannot decelerate at a 0.4 g average. Since tow car lockup determines the transient tow car stability change, it is recommended that if the CV cannot decelerate at 0.4 g the test be conducted at the maximum deceleration with lockup of one wheel on one axle permitted.

C. DESIGN TEST PROCEDURES FOR TRAILERS ALONE

Two procedures should be utilized by trailer manufacturers to determine trailer-alone brake capability and trailer-alone damping ratio.

1. Braking

Straight line braking procedures for the trailer-alone have been detailed in Table 4, which follows the format of SAE Recommended Practice J134a and the Canadian Standards Association proposed Standard D313. Key points of the procedure include:

TABLE 4. TRAILER-ALONE BRAKE PERFORMANCE TEST PROCEDURE

TEST NUMBER	TEST TYPE	NUMBER OF STOPS	TEST SPEED[a] (mph)	DECELERATION[b]	INITIAL BRAKE TEMPERATURE	COOLING	REMARKS
1	Instrumentation Check	10	40 → 30	8 V to brakes	—	—	—
2	Preburnish Effectiveness	6[c] at maximum performance	$40\sqrt{W_t/W_{cv}}$	2, 4, 6, 8, 10, 12 V to trailer brakes	200-250°F	—	Plot average deceleration vs. applied voltage level. Determine maximum trailer-alone deceleration capability. a_{xta}
3	Burnish	200	$40 \rightarrow \sqrt{1600 - 1200\frac{W_t}{W_{cv}}}$	$12(W_t/W_{cv})$	200-250 or 1 mi between snubs	—	—
4	Second Effectiveness		Same as No. 2				$a_x \geq 0.435$ g at 12 V
5	Fade Baseline	≤8 3	30 30	$12(W_t/W_{cv})$ Voltage necessary	200-250 〃	—	Determine voltage necessary.[b] Measure SD; average.
6	Fade Snubs	10	$40 \rightarrow \sqrt{1600 - 1200\frac{W_t}{W_{cv}}}$		200-250 before <u>first</u> stop	1.5 mi at 30 mph, then start deceleration	
7	Recovery	5	30	Baseline voltage		1.5 mi between	SD for last stop +30%, −40% average baseline
8	Reburnish		Same as No. 3 except 35 snubs				
9	Third Effectiveness		Same as No. 2				$a_x \geq .435$ g at 12 V

Condition of Test: Use trailer brakes only. Plot stopping distance vs. speed for effectiveness tests. Compute deceleration from $a_{xta} = (u^2/2SD)$.

[a] W_t = static axle weight; W_{cv} = combination-vehicle weight.

[b] For surge brake trailers, voltage increments replaced by trailer brake pressure increments, increasing to lockup.

[c] Only one stop necessary at lower voltage levels; at maximum, attempt to have three below and three above wheel lockup.

- Lockup of one wheel on one axle is allowed.
- Brake stops are made from a test speed of $40\sqrt{W_t/W_{cv}}$ (mph) to account for the unbraked mass of the tow car.
- Average deceleration at the static axle weight, W_t, is calculated from stopping distance at 40 mph, SD_{40}. This must be ratioed to the gross axle weight rating, GAWR, if lockup cannot be obtained with full trailer brakes, i.e.,

$$a_{x_{ta}}\ (g's) = \frac{53.7}{SD_{40}} \times \frac{W_t}{W_{GAWR}}$$

- Brake voltages are increased in increments up to maximum, at which point six incipient lockup runs are made.

For surge brake trailers a special apparatus is necessary to apply the brake pressure input. In this case incremental pressure changes replace the incremental voltage changes used for electric braked trailers. Also, the "surge brake gain," G, i.e., the amount of brake force generated per pound of horizontal hitch force, must be determined. Once this is known the "effective" trailer-alone brake capability for this type of trailer can be determined using the following equation:

$$a_{x_{ta}} = \frac{a_{x_{cv}}\left(\frac{G}{1 + G}\right)}{1 - \frac{\%HL}{100}}$$

where $a_{x_{cv}}$ represents the combination-vehicle deceleration requirement.

2. Trailer Swing

The analytical/empirical expression derived in Volume II requires measurement of the trailer-alone moment of inertia as a function of hitch load. This is readily accomplished with a roller bearing turntable (such as used for wheel alignments), two coil springs, and a stopwatch. The trailer wheels are held off the ground with a block positioned on the roller bearing support turntable. A counterweight is added to the rear of the trailer to balance the hitch load such that the trailer floats freely on the turntable with no offset forces. The trailer is oscillated (by hand), and elapsed time measurements are taken to determine the frequency of oscillation. Knowing this (plus the coil spring rate and wheelbase), the moment of inertia can be calculated using equations given in Volume II or Ref. 9.

D. SUPPORTIVE RESULTS

Significant results reported in Vols. II and IV of the report are summarized below.

1. Braking

- Several combination-vehicle configurations tested in Phase II were unable to exceed 0.5 g deceleration even though the tow cars exceeded the requirements of FMVSS 105-75 and the trailers were not loaded to full GVWR. These results very closely matched the analytical predictions using a generalized static braking model including load transfer, load leveling, and tow car brake proportioning.

- Provided that unbraked trailers are used by tow cars weighing at least 1.5 times their weight, all combination vehicle configurations tested in the program except the horse trailer at full GVWR would theoretically be able to pass a 0.4 g deceleration requirement.

- Trailer-alone deceleration levels for seven braked trailers ranged from 0.35 g to 0.6 g when adjusted to GAWR. The current deceleration design goal for trailer electric brake systems appears to be 0.435 g.

- All five tow cars exceeded the stopping distance requirements of FMVSS 105-75 from 40 mph during second effectiveness tests. Average deceleration for incipient lockup was 0.71 g for the three rear wheel drives and 0.64 g for the two front wheel drive vehicles.

- Tow vehicles with rear brake lockup tendency will provide higher braking forces when trailer towing than tow cars with front lockup tendency.

- Suspension design of the horse trailer caused an undesirable increase in hitch load with increasing deceleration. Since this trailer does not allow for load leveling, braking tests could not be performed at full GVWR without scraping the hitch on the ground.

- Average actuation time delay of the surge brake system was 0.3 sec. No significant differences due to load leveling could be determined. Previously, as indicated in Refs. 2 and 4, load leveling rendered the surge mechanism inoperative. Consequently, it appears that a surge mechanism can be manufactured which is compatible with Class III hitches.

- Combination-vehicle stopping distances appeared slightly improved with load leveling; however, the results were not totally consistent.

- Pedal forces in combination-vehicle braking tests were less than the 120 lb recommendation of SAE J135.

- Maximum performance combination-vehicle stopping distances with tow car lockup were not significantly different from those with no tow car lockup.

2. Trailer Swing

- For the same hitch load, heavier tow cars provide higher combination-vehicle damping.

- Front wheel drive tow cars appear to have better combination-vehicle damping than equivalent weight rear wheel drive tow cars. In the analytical expression this results in a lower tow car sensitivity constant.

- There is a strong decrease in damping with increasing speed. This trend is biased up (to higher damping) with higher hitch loads (or higher tow car weight) and biased down (to lower damping) with lighter hitch loads.

- Longer trailer wheelbases (i.e., longer hitch to axle distances) are desirable in order to maintain high damping ratios at low hitch loads. In terms of sensitivity, increasing tongue length on an 18 ft travel trailer merely one foot increases damping 0.08 units.

- For trailers with minimum load leveling the trailer damping of the combination-vehicle can be estimated by an analytical/empirical relationship.

- Load leveling improves trailer damping. This effect is due, primarily, to the tow car roll steer geometry and hence is difficult to predict. However, empirical results showed an average increase in trailer damping of 0.06 units per 1000 ft-lb of applied load leveling torque. This is higher than previously found in Ref. 3.

- A friction sway damper can significantly improve trailer damping. At 55 mph this type of damper was able to increase damping on a large travel trailer by 0.19 units. The electric brake type of damper acted primarily as a speed control device by limiting speed to that for zero damping.

- Increased trailer moment of inertia (separated load) reduces trailer damping in a predictable manner.

- High cornering levels significantly reduce trailer damping. For example, damping ratio of the medium travel trailer was reduced 0.29 units when the lateral acceleration was increased to 0.4 g. This effect was attributable to the loss of cornering stiffness of the trailer tires at high slip angles, which in turn produces a loss of damping according to the trailer-alone damping equation.

- Steering free play can have a significant effect on reducing the trailer damping. For example, allowing steering to be free reduced trailer damping as much as 0.4 units at 55 mph as compared to that measured with steering held fixed. This effect has strong implications for tow cars with excessive steering free play and/or for drivers who allow the steering wheel force feedback to move the wheel. This, in turn, amplifies the trailer swing oscillation. Holding the wheel fixed is the safest procedure.

- A trailer-alone damping test procedure was successfully used with one test trailer to check analytically derived predictions. Results were sufficiently close as to not warrant formalization (or recommendation) of a separate trailer-alone damping test procedure.

3. Tow Car Stability

- For the intermediate tow car a hitch load of 800 lb produced a neutral steer response at low cornering (less than 0.3 g). If viewed as a mass distribution this implies that <u>any</u> loading resulting in a 37/63 front to rear weight distribution would likely result in oversteer at or above 0.3 g cornering.

- The compact and subcompact tow cars became neutral steering at approximately 600 and 400 lb hitch loads, respectively. These levels convert to 39/61 and 41/59 front/rear weight distributions, respectively.

- Front wheel drive tow cars are less sensitive to hitch load since they start out with a heavy front weight bias, e.g., 62/49. Consequently, the same hitch load applied to a FWD car does not produce as much of a rear mass distribution as would be obtained with a RWD vehicle.

- Load leveling 25 percent of the hitch load to the tow car front axle reduced understeer about 1.1 deg/g from that required to relevel the combination-vehicle with air shocks and minimum or no load leveling.

- Right-hand turn results showed understeer gradients 0.7 deg/g less than those for left-hand turns. This is attributable to rear axle torque effects during the turn at constant speed.

- Due to the general nonlinear variation in understeer gradient with lateral acceleration, a constant radius circle test procedure is recommended as a combination-vehicle test procedure. This procedure provides a closer determination of the lateral acceleration at which the tow vehicle becomes neutral steering and provides a continuous readout of trailer articulation angle change with speed. This is necessary for trailer stability factor calculations. An optimum radius of 200 ft is recommended.

4. **Brake in Turn**

- All rear wheel drive combination-vehicle configurations could decelerate (from 40 mph) at or above 0.4 g during a 0.3 g turn without loss of control.

- All front wheel drive configurations could decelerate at maximum capability, with tow car lockup, during a 0.3 g turn without loss of control, or transient oversteer longer than 1 sec duration. Based on this, and the above, no additional recommendations can be added to the suggested braking and handling standards previously presented.

E. USER GUIDELINES

Based on the full-scale results of this and previous NHTSA-sponsored trailer braking and handling programs several general recommendations for the user can be offered. These might be used to supplement public information documents such as Ref. 8.

- There is definitely an optimum hitch load for each tow car and trailer combination. Hitch loads too high, even with load leveling, will cause the tow vehicle to "dig in" during sudden turning maneuvers and sharpen the turn even further. The trailer will then tend to push the rear of the tow car into a jackknife position. Hitch loads too light lead to trailer swing. Heavier tow cars reduce the effect of both problems. In general, the tow car gross vehicle weight rating should exceed the trailer gross vehicle weight rating.

- Use of load leveling should be supplemented by the use of air shocks and heavy duty suspension. In addition, the manufactuer's maximum hitch load rating should not be exceeded with or without these devices.

- Tire inflation pressure should be set for the maximum rated tire load. If recommended or allowable, it is desirable from a handling standpoint to set the front tires at a lower inflation pressure than the rear.

- If trailer swing occurs, the steering wheel should be held fixed and the combination-vehicle allowed to decelerate by itself, or by applying trailer brakes. Sway dampers are also useful in reducing trailer swing.

- Sharp cornering should be avoided at highway speeds. The increased lateral acceleration induced by these maneuvers reduces trailer damping, tow car stability, and braking capability.

- Tire and brake capacity of the trailer should be carefully checked. Tire capacity is stamped on the tire by the manufacturer. Adequate brake capacity may be judged by multiplying the number of braked wheels by 1500 lb. For 10 in. brakes this value should exceed the trailer GVWR.

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