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EFFECT OF CARGO SHIFTING ON VEHICLE HANDLING

March 1978

Final Report

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Prepared for

FEDERAL HIGHWAY ADMINISTRATION

Offices of Research & Development

Washington, D. C. 20590

FOREWORD

This report covers a test program which had the objective of determining if and to what degree shifting cargos affect the handling of heavy vehicles. In the first phase of the contract several trucking companies were surveyed to determine the procedures used by the industry when transporting shifting cargos. The findings helped in planning the test program, in which two types of cargo were used, water in tank trailers, and hanging beef halves in refrigerated vans. Handling performance was evaluated relative to a non-shifting cargo vehicle. The same tractor was used to tow the different semitrailers, under varying load conditions.

Tests were conducted in braking, cornering, and combined maneuvers. Acceleration measurement and driver reaction were used to compare the handling performance. It was concluded that some handling deterioration occurred in almost every case of shifting cargo.

Charles F. Scheffey
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Director, Office of Research
Federal Highway Administration

NOTICE

TECHNICAL REPORT STANDARD TITLE PAGE

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16. Abstract

The objective of the program was to determine in full-scale testing how dynamic cargo shifting affects the stability of articulated trucks and establish the severity of the problem for two cases: (1) sloshing of liquid cargo and (2) swinging of hanging meat.

Two tasks (A and B) were accomplished. Task A, Planning and Preparation, was devoted to obtaining information on hanging meat and liquid cargo loading procedures; identifying representative test vehicles on the basis of industry usage, accident exposure, and mileage accumulation; and developing the test plans, procedures, and instrumentation.

Task B, Conduct of Tests, was devoted to preparing the vehicles and instrumentation; mounting the instrumentation and performing necessary calibrations; driver selection, training, and system orientation; conducting the tests; and data acquisition and analysis.

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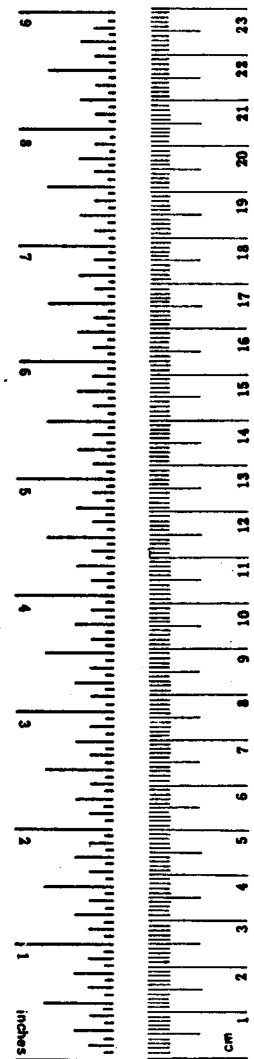
METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

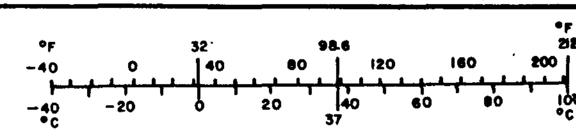
Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	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



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1.0 INTRODUCTION

Cargo shifting is a problem inherent in practically all types of cargo truck handling operations. The effectiveness of measures taken to prevent or reduce the problem depends a great deal on the experience and training of personnel who accomplish the loading and, to a greater degree, on the ability and judgment of the vehicle operators who accept the loads and then accomplish transfer between given points. Those operators who are unable to counter the effects of internal load movement in transit often experience accidents with disastrous effects on their lives and the lives of others on or near the roadways being traveled. Failure to handle the pre-accident emergency can be induced by any one or all of many human, vehicle, and environmental factors involved - though the operator is usually faulted in most major cargo truck accidents.

To consider cargo shifting, two types of loads can be defined. Static loads are those which can be stabilized by being placed in containers such as van body trucks or trailers (examples: crates, cartons, drums, cans, mail sacks, etc.), or the load can be secured to a truck or trailer bed with suitable restraints or tie-downs (examples: pipe, animal feed, logs, building materials, etc.). Loads of this type do experience some shifting, but not to the extent that dynamic loads do.

Dynamic loads comprise products or commodities which have an internal rearrangement capability regardless of containerization or tie-down methodology, and such rearrangement has a constant and varying effect on operator and vehicle performance because of critical center of gravity changes. Liquid commodities and free-standing or free-hanging products are dynamic loads which pose the greatest threat to operator control in emergency and even routine road conditions. Some examples of dynamic loads are: liquid petroleum products, liquefied gases, livestock, and hanging livestock carcasses (whole, halves, or quarters).

Operator remedial response to dynamic cargo shifting can be enhanced by various means. These include balanced loading, strapping (together) of hanging loads, or internal baffles in liquid cargo tanks. These methods still leave severe handling problems in loads of less-than-full capacity.

Recognizing that cargo shifting can cause operator problems, and that these problems can become more severe with recently increased truck loads and requirements for shorter stopping distances,* the Bureau of Motor Carrier Safety of the Federal Highway Administration, U.S. Department of Transportation, authorized the program reported herein to investigate the effect of cargo shifting on vehicle handling. Specifically, two cases of dynamic loads were investigated, liquid cargo and hanging meat, through full-scale testing as authorized under Contract DOT-FH-11-9195.

*Federal Motor Vehicle Safety Standard 121, Air Brake Systems.

The contract objective was to determine in full-scale testing how dynamic cargo shifting affects the stability of articulated trucks and to establish the severity of the problem for:

1. Sloshing of liquid cargo.

2. Swinging of hanging meat.

To accomplish the objective, the program was organized in two tasks:

A - Planning and Preparation, with five subtasks.

B - Conduct of Tests, with four subtasks.

Concurrent with the test program, a study entitled "Computer Simulation of the Cargo Shifting Effect on Vehicle Handling" was conducted by Johns Hopkins University Applied Physics Laboratory (JHU/APL). Data from the test program were furnished to JHU/APL for the simulation effort.

The results of the test program are presented in the following manner.

Section 2.0 explains the requirements of Task A and details the planning and preparations necessary to:

- Select eight representative trucking companies engaged in liquid and meat hauling operations which will provide vehicle, accident, and operator training information on their fleets.

- Obtain information from the eight companies which will facilitate selection of test vehicles (tractors and trailers).

- Select and justify the test vehicles.

- Develop the test program.

- Select necessary instrumentation (electronic and photographic).

Section 3.0 provides details on conducting the tests, including:

- Vehicle and instrumentation preparations.

- Instrumenting the vehicles.

- Driver selection and operational check-outs.

- Test operations.

Section 4.0 presents the test results by test vehicle type and a comparative discussion of vehicle performance.

Section 5.0 presents conclusions derived from results of Tasks A and B activity.

Section 6.0 presents recommendations for work which will reduce the dangers associated with continued use of existing vehicles.

2.0 TASK A - PLANNING AND PREPARATION

Effort under Task A was devoted to obtaining information on hanging meat and liquid cargo loading procedures; identifying representative test vehicles on the basis of industry usage, accident exposure, and mileage accumulation; and developing the test plans, procedures, and instrumentation.

2.1 TASK A-1 - INDUSTRY INVOLVEMENT

Requirement: Obtain a listing of large trucking companies engaged in liquid and meat hauling operations. Select up to eight companies which are able and willing to supply the information specified in Task A-2. The companies shall be selected from different regions in the continental United States and shall represent a fraction of the total United States liquid and meat hauling operations.

The listing of large trucking companies who engage in liquid and meat hauling operations was developed through the cooperation of trucking representation associations in Washington, D.C., and regional and state associations.

To satisfy the geographic representation requirement, large trucking companies headquartered in the following locations who transport meat in refrigerated vans were identified and contacted:

Omaha, Nebraska	Lakeland, Florida
Forest Park, Georgia	Waterloo, Iowa
Dallas, Texas	Green Bay, Wisconsin
Auburndale, Florida	

For liquid cargo tanker operations, carriers from the following locations were identified and contacted:

Los Angeles, California	Tampa, Florida
Glendale, Arizona	Dallas, Texas

These carriers handle a variety of liquid cargoes, e.g., petroleum products, milk, and other food and agricultural products.

2.2 TASK A-2 - INDUSTRY EXPERIENCE

Requirement: Meet with a representative from each of the selected eight companies and obtain the following information:

1. Total number of tractors

2. Total number of trailers

3. Number of tank trailers

4. Number of meat vans

5. For tank trailers and meat vans obtain:
   a. Make and model
   b. Dimensions and weight
   c. Yearly mileage in full, empty, and partially loaded conditions
   d. Accident involvement over several years of operation
   e. Detailed information on accidents
   f. Assessment of handling problems common to all units and specific to some makes and models

6. Handling and safety problems with other cargo types

7. Company policy on driver training:
   a. Does company conduct training?
   b. Does company require training?
   c. Does training cover handling and safety problems characteristic of various cargo types?
   d. Are all drivers qualified to operate tractor-trailers with any type of cargo?

8. Does the company operate units which meet FMVSS No. 121 and, if so, what is the experience so far?

All of the carriers contacted were most cooperative and willing to share their experiences and company record matter with the contractor. This is evidenced by the comprehensive information presented in Appendix A, a summary of the extensive effort made to obtain industry information on which to base test vehicle selection and gain firsthand knowledge of carrier operations.

2.3 TASK A-3 - SELECTION OF TEST VEHICLES

Requirement: Based on the information obtained in Task A-2, select a tractor and three trailers (tank without baffles, tank with baffles, meat hauling van). Prepare a detailed report on the information obtained and give rationale for the proposed selection of tractor and trailers. All three trailers should be of similar size and weight and be compatible with the tractor. The suspension and brake systems shall be representative of the majority of similar vehicles on the road. In order to reduce the cost of the program, select a reasonable substitute to replace the swinging meat.

(In selecting the test vehicles, due consideration was given to the availability of vehicle data for the simulation conducted by the Johns Hopkins University [JHU/APL].)

Table 1 summarizes the results of the carrier survey. The size of the companies contacted, based on tractor and trailer ownership, varied considerably. The majority of the companies also have a positive approach to training, either conducting or requiring training which covers handling and safety problems characteristic of various cargo types.

The information obtained relative to operation of FMVSS 121 units also shows a favorable overall response. Of note, however, is the fact that, while the survey may be considered geographically representative, it did not include companies operating in either the northeast or northwest parts of the continental U.S.A.

With regard to selection of the tractor to be used for testing, efforts were made to obtain the same model tractor that was used for a simulation program by the Highway Safety Research Institute for the Motor Vehicle Manufacturers Association (thus permitting use of available parameters). This was not successful; however, a tractor with similar characteristics (i.e., cab over engine, dual-drive axles, and four-leaf spring suspension) was chosen and used throughout this test program.

Trailer selection centered on two types, vans and cargo tankers. The vans were to be the baseline vehicle and the hanging meat transport, both about 40 feet long. Cargo tanker selection evolved to a compartmented trailer with baffles, typical of MC-306 construction for low-density products (petroleum), with capacity around 9,000 gallons. The other type of cargo tanker was to be for high-density products (acids) with capacity between 4,000 and 4,800 gallons, typical of MC-312 construction; this configuration was both with and without baffles.

Table 1. Survey summary.

Hauler Location	Tractor	Meat Van	Tanker	Other	Typ. Empty Wt. (Klb)	Total Year Mileage (million miles) Full	Partly Full	Empty	Training Policy Con-duct	Re-quire	Cover Safety	Qualify All Prod.	FMVSS 121 Brake System % of Units Trailer	Tractor	Experience	Accident in One Year Acci-dents Per Year Total	Accidents Per Year Involving Liquid or Hanging Meat Cargo Total	Per Million Miles
Midwest	50	87	0	0	15.8	3.60	0.02	0.05	Y	Y	Y	Y	25	10	Excellent on trailers	8	1	0.27
South	1040	1345	0	0	16.0	84.70	33.60	16.10	Y	N(2)	Y	Y	-10-(3)		Favorable	685	39	0.29
South-west	450	635	0	0	17.0	31.70	22.20	9.50	Y	Y	Y	Y	25	45	Normal	635	127	2.00
Midwest	301	31	82	349	NA	NA	NA	NA	Y	Y	Y	Y	-10-(3)		No major problems	NA	NA	NA
South	205	228	11	12	14.8	13.70	0.0	2.30	Y	Y	Y	Y	-3-(3)		No problem	NA	2	0.13
Pacific	88	0	88	0	7.6	5.10	0.0	5.10	M	M	L	Y	-2-(3)		Totally un-acceptable	NA	1	0.10
South-west	NA	NA	397	NA	NA	8.00	0.0	8.00	Y	Y	Y	Y	0	0	-	NA	Sev-eral	0.13
South	200	0	300	0	20.0	8.00	7.00 (1)	15.00	N	N(2)	-	Y	5	0	Good	NA	2	0.07
South-west	5	0	6	0	20.0	0.01	0.04	0.01	Y	Y	Y	Y	0	0	-	0	0	0.00

NA = not answered; Y = yes; N = no; M = minimal; L = limited.
(1) Due to weight limit.
(2) Hire only experienced drivers.
(3) Estimated percent of total units.

2.3.1 Tractor Specification

The following vehicle was used for all tests:

Tractor - Unloaded

1966 White Freightliner - cab-over-engine type tractor with dual rear axle; Model WF T 8164T, Serial Number AP19658.

Bobtail weight:	14,790 lb
Empty weight by wheel:	
Right front	3,670 lb
Left front	3,670 lb
Right front driver	2,065 lb
Left front driver	2,065 lb
Right rear driver	1,660 lb
Left rear driver	1,660 lb
Wheelbase length:	167 in.
Track width:	
Front	74.52 in.
Inside duals	60 in.
Outside duals	86 in.
Frame width:	33 in.
Number of axles:	3
Number of tires per axle:	2 front, 4 rear
Type of tires:	
Right and left front	10.00x20 Goodyear "Super Hi-Miler"
All drivers	10.00x20 Goodyear "Custom Cross Rib Hi-Miler"
Tire rolling radius:	
Front	19.5 in.
Rear drivers	20.5 in.

Fifth wheel location:

164 in. aft of front axle; 29 in. forward of rear drive axle; and 3 in. forward of center of dual driver assembly.

2.3.2 Baseline Van Specification

The following trailer was used as the baseline vehicle:

Trailer With Non-Shifting Ballast/Freightliner Tractor

Strick - 40-foot, van type, 2-axle, semitrailer; Model 0.0S35SBFV1, Serial Number B22524

Empty weight of trailer: 11,260 lb

Tractor/trailer weight by wheel (lb):

	Empty	20,000-lb Load	40,000-lb Load
Tractor:			
Right front	3,695	3,960	4,000
Left front	3,695	3,960	4,000
Right front driver	2,870	5,245	8,125
Left front driver	2,870	5,245	8,125
Right rear driver	2,005	4,670	6,565
Left rear driver	2,005	4,670	6,565
Trailer:			
Right front	2,340	4,645	6,815
Left front	2,340	4,645	6,815
Right rear	2,115	4,700	7,575
Left rear	2,115	4,700	7,575
Total Vehicle Weight:	26,050	46,440	66,160

Wheelbase length (tractor 5th wheel to center of dual rear axles): 341.64 in.

Track width:
- Inside duals 57 in.
- Outside duals 84 in.

Frame width: 96 in.

Number of axles: 2

Number of tires per axle: 4

Fifth wheel location:

135.24 in. aft of center of dual rear axle assembly; 27 in. to left of longitudinal centerline of vehicle.

Type of tires:

All eight trailer tires - 10.00x20 Goodyear "Custom Hi-Miler"

Inside dimensions of trailer cargo area:

Length	472 in.
Width	92.5 in.
Height	101 in.

2.3.3 Refrigerated Van Specification

The following van trailer was used:

Meat Trailer/Freightliner Tractor

1977 American - 45-foot, refrigerator van type, 2-axle semi-trailer, with ceiling meat hanging rails; Serial Number 30261.

Empty weight of trailer: 17,580 lb

Tractor/trailer weight by wheel (lb)

	Empty	Full Load
Tractor:		
Right front	3,925	4,065
Left front	3,925	4,065
Right front driver	4,155	9,725
Left front driver	4,155	9,725
Right rear driver	2,930	7,130
Left rear driver	2,930	7,130
Trailer:		
Right front	2,365	5,735
Left front	2,365	5,735
Right rear	2,810	8,190
Left rear	2,810	8,190
Total Vehicle Weight:	32,370	69,690

Wheelbase length (tractor 5th wheel to center of dual rear axles):	435.5 in.
Track width:	
Inside duals	59 in.
Outside duals	85 in.
Frame width:	96 in.
Number of axles:	2
Number of tires per axle:	4

Type of tires:

All eight trailer tires - 10.00x20 Goodyear "Custom Hi-Miler"

Inside dimensions of trailer cargo area:

Length	530 in.
Width	89 in.
Height	100 in.

Cargo hung from seven 1.75-in. diameter rails attached to ceiling 12 in. on center and 97.5 in. above floor. Rails began 42 in. from front bulkhead, ran 480 in. aft, and were supported every 24 in. along their length. The supports at every 24 in. prevented the meat hooks from moving fore and aft more than 24 inches.

Total weight of meat cargo:	37,320 lb
Number of quarters of beef:	
Fore	110
Hind	110
Average weight of quarters:	
Fore	177.7 lb
Hind	161.6 lb
Hook length from rail to quarter:	24 in.

Number and description of swing loads (3 types):

110 single hindquarter loads:

Average weight:	161.6 lb
Estimated C.G. height above trailer floor:	45 in.
Average length:	52 in.
Average diameter:	15 in.

10 double forequarter loads:

Average weight:	355.4 lb
Estimated C.G. height above floor:	51 in.
Average length:	70 in.
Average diameter:	12 in.

30 triple forequarter loads:

Average weight:	533.1 lb
Estimated C.G. height above floor:	40 in.
Average length:	70 in.
Average diameter:	
Top	12 in.
Bottom	24 in.

Average swing load pendulum lengths from ceiling rail to bottom of load:

Single hindquarter:	70 in.
Double forequarter:	80 in.
Triple forequarter:	80 in.

Figure 1 shows the refrigerated van, and Figure 2 shows a typical load of hanging meat.

2.3.4 Low-Density Cargo Tanker Specification

The following cargo tanker was used:

Gasoline Tank Trailer/Freightliner Tractor

1971 Pennco - 34-foot, 5-compartment, elliptical-tank type 8,000-gallon capacity, 2-axle semitrailer; Type MC-306, Serial Number 2-11734-3.

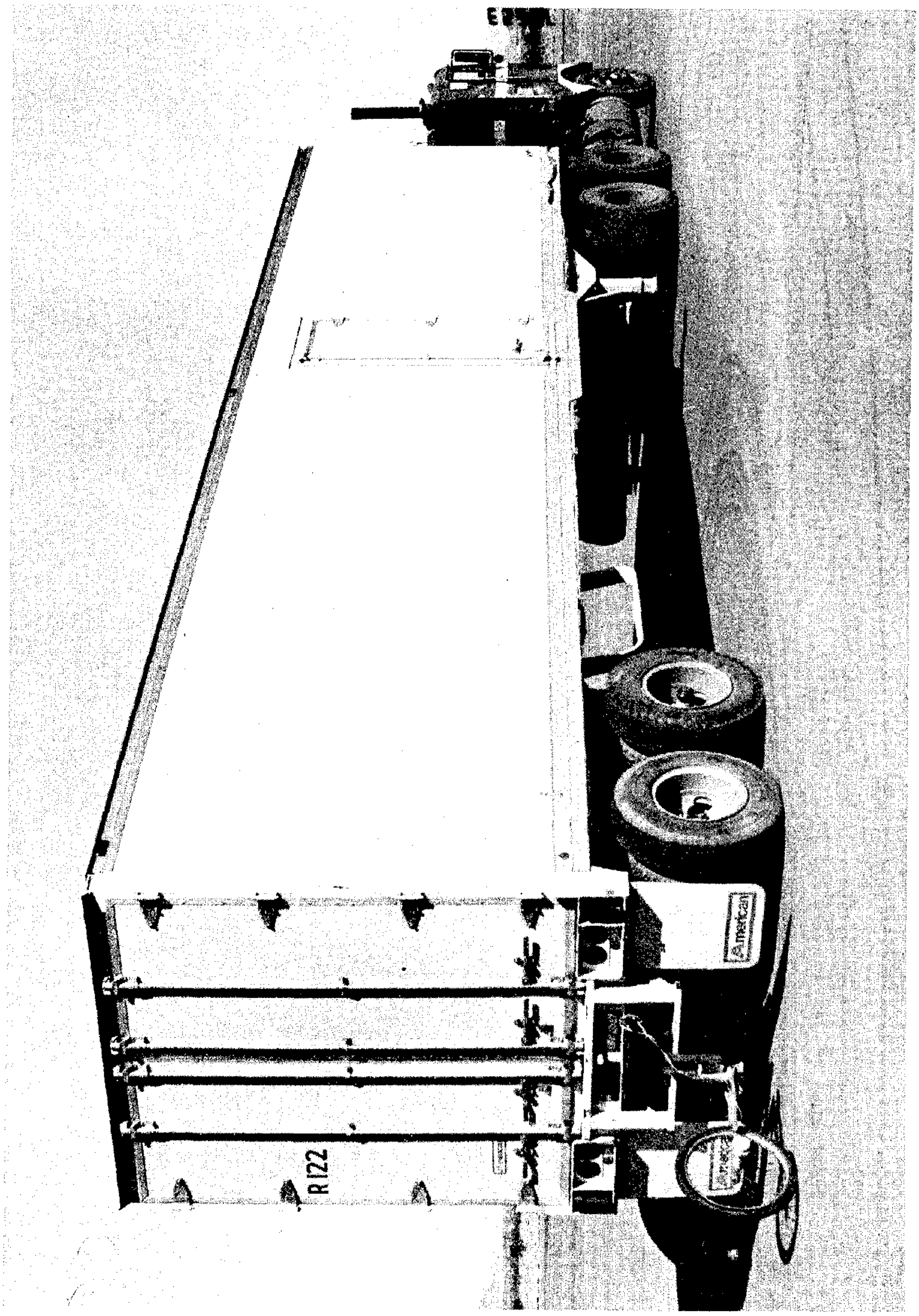


Figure 1. Refrigerated van.

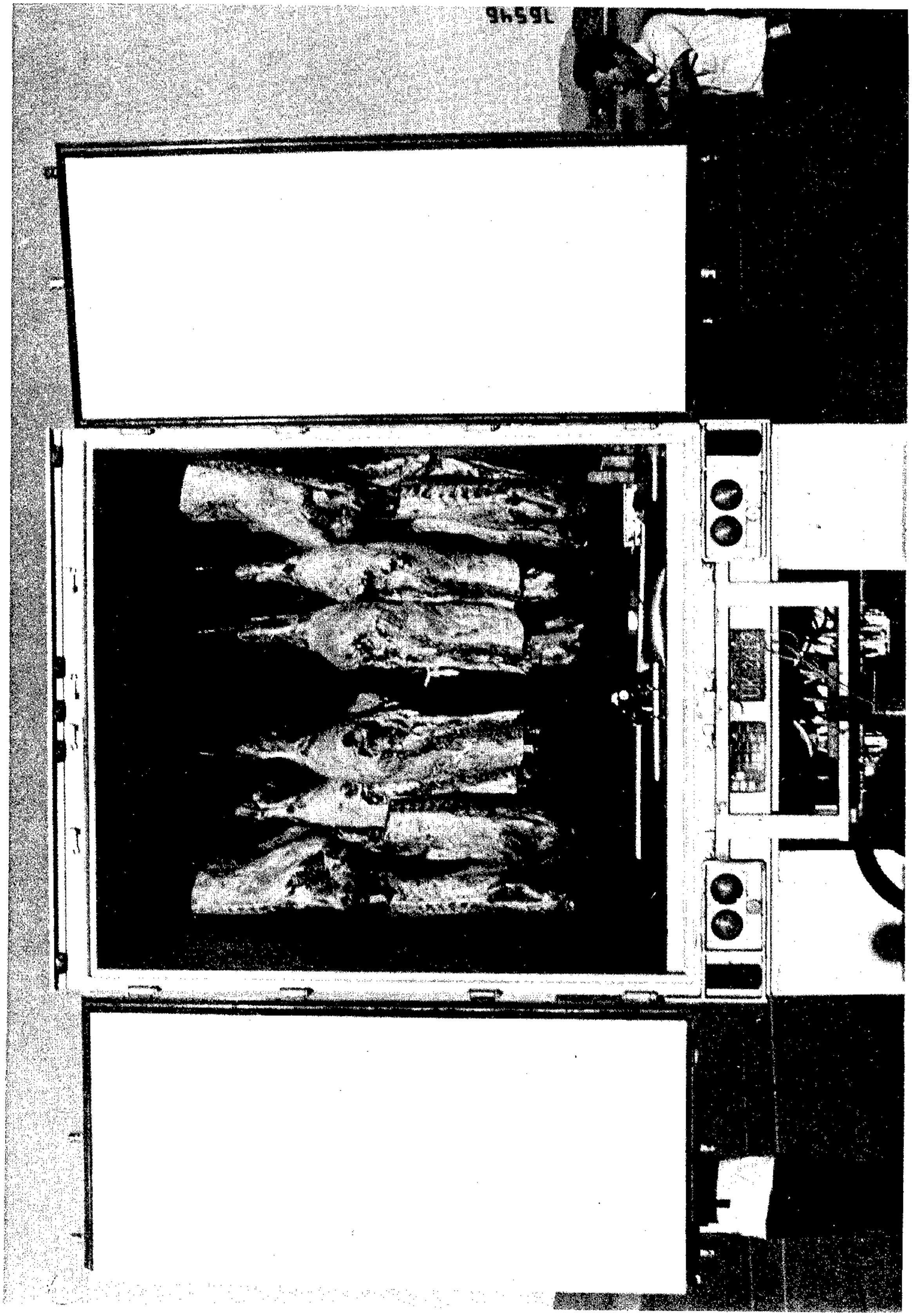


Figure 2. Hanging meat load.

Empty weight of trailer: 9,650 lb

Tractor/trailer weight by wheel (lb):

	Empty	3/4 Load (6,000 gal)
Tractor:		
Right front	3,765	4,020
Left front	3,765	4,020
Right front driver	2,930	9,215
Left front driver	2,930	9,215
Right rear driver	2,075	7,275
Left rear driver	2,075	7,275
Trailer:		
Right front	1,195	7,415
Left front	1,195	7,415
Right rear	2,255	10,090
Left rear	2,255	10,090
Total Vehicle Weight:	24,440	76,030

Wheelbase length (tractor 5th wheel to center of dual rear axles): 328.5 in.

Track width:

Inside duals 58.5 in.

Outside duals 85 in.

Frame width: 38 in.

Tank width: 95 in.

Number of axles: 2

Number of tires per axle: 4

Type of tires:

All eight trailer tires - 10.00x20 Goodyear "Custom Hi-Miler"

Inside dimensions of trailer cargo area:

Tank overall length:	404 in.
Elliptical cross-section:	
Width:	95 in.
Height:	62.5 in.
Compartment lengths and capacities from front to rear:	
#1	132 in.; 2,500 gallons
#2	56 in.; 1,200 gallons
#3	48 in.; 1,000 gallons
#4	60 in.; 1,300 gallons
#5	108 in.; 2,000 gallons

Dimension, weight, and location of load:

Loaded with water weighing 8.4 lb/gallon to the following volume load:

3/4 vol:	6,000 gal; 51,590 lb; 44 in. fluid in tank

Description of baffles:

Compartment No. 1 - 2 baffles located at 24 in. and at 75 in. aft of front tank bulkhead.

Compartment No. 5 - 1 baffle located at 48 in. forward of rear tank bulkhead.

Baffles conformed to elliptical shape of tank and had a 20-in. diameter hole in their centers.

Figure 3 shows the MC-306 cargo tanker.

2.3.5 High-Density Cargo Tanker With Baffles Specification

The following trailer was used:

Tank Trailer With Baffles/Freightliner Tractor

1969 Beall - 40-foot, single compartment, cylindrical-tank type, 4,700-gallon capacity, 2-axle semitrailer, Type MC-312, Model 137, Serial Number D 280 69 701.

Empty weight of trailer:	10,920 lb

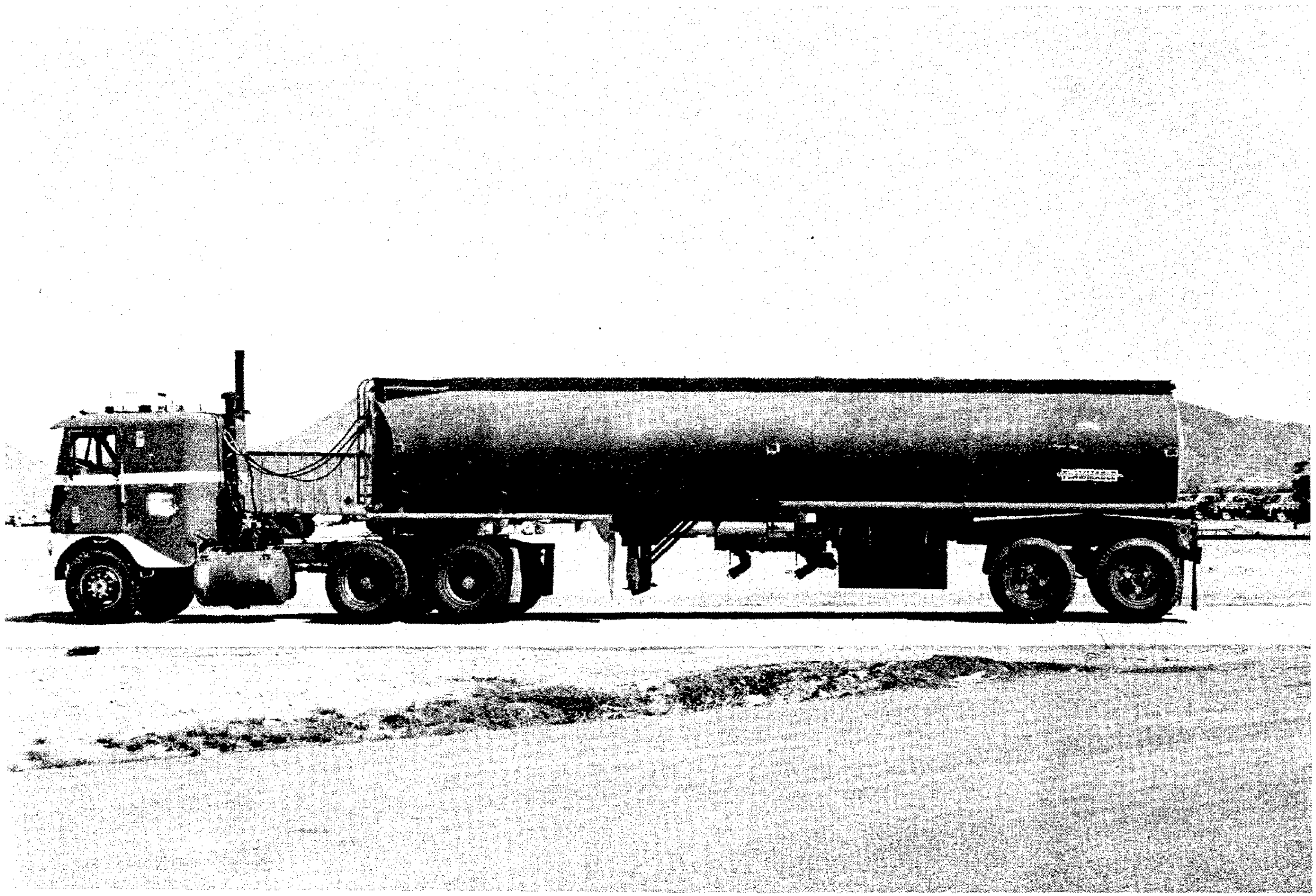


Figure 3. Liquid cargo tanker (MC-306).

Tractor/trailer weight by wheel (lb):

	Empty	1/2 Load (2,350 gal)	3/4 Load (3,525 gal)	7/8 Load (4,113 gal)
Tractor:				
Right front	3,710	3,855	4,005	3,785
Left front	3,710	3,855	4,005	3,785
Right front driver	3,035	5,735	6,835	7,805
Left front driver	3,035	5,735	6,835	7,805
Right rear driver	2,225	4,010	5,555	6,005
Left rear driver	2,225	4,010	5,555	6,005
Trailer:				
Right front	1,770	4,305	5,295	6,030
Left front	1,770	4,305	5,295	6,030
Right rear	2,115	4,925	6,450	7,040
Left rear	2,115	4,925	6,450	7,040
Total Vehicle Weight	25,710	45,660	56,280	61,330

Wheelbase length (tractor 5th wheel to center of dual rear axles):	385 in.
Track width:	
Inside duals	59 in.
Outside duals	84.75 in.
Frame width:	42 in.
Tank width:	56 in.
Number of axles:	2
Number of tires per axle:	4

Type of tires:

All eight trailer tires - 10.00x20 Goodyear "Custom Hi-Miler"

Inside dimensions of trailer cargo area:

Tank length:	473.5 in.
Diameter:	56 in.

Dimension, weight, and location of load:

Loaded with water weighing 8.4 lb/gallon to the following volume loads:

1/2 vol:	2,350 gal; 19,740 lb; 28.0 in. fluid in tank
3/4 vol:	3,525 gal; 29,619 lb; 39.3 in. fluid in tank
7/8 vol:	4,113 gal; 34,549 lb; 45.8 in. fluid in tank

Horizontal centers of gravity (distance from front tractor axle):

	Unloaded	1/2 Load	3/4 Load	7/8 Load
Tractor	95.6 in.	116.4 in.	124.2 in.	128.4 in.
Trailer	327.9 in.	351.3 in.	352.7 in.	351.9 in.

Description of baffles:

2 baffles located at 150 in. and 330 in. forward of rear tank bulkhead. Baffles were 56 inches in diameter with a 20-inch diameter hole in the center.

Figure 4 shows the MC-312 cargo tanker with baffles.

2.3.6 High-Density Cargo Tanker Without Baffles Specification

The following trailer was used:

Tank Trailer Without Baffles/Freightliner Tractor

1975 Fruehauf - 44-foot, single compartment, cylindrical-tank type, 3,850-gallon capacity, 2-axle semitrailer; Type MC-312, Serial Number OMW 717002.

Empty weight of trailer: 12,950 lb

Tractor/trailer weight by wheel (lb):

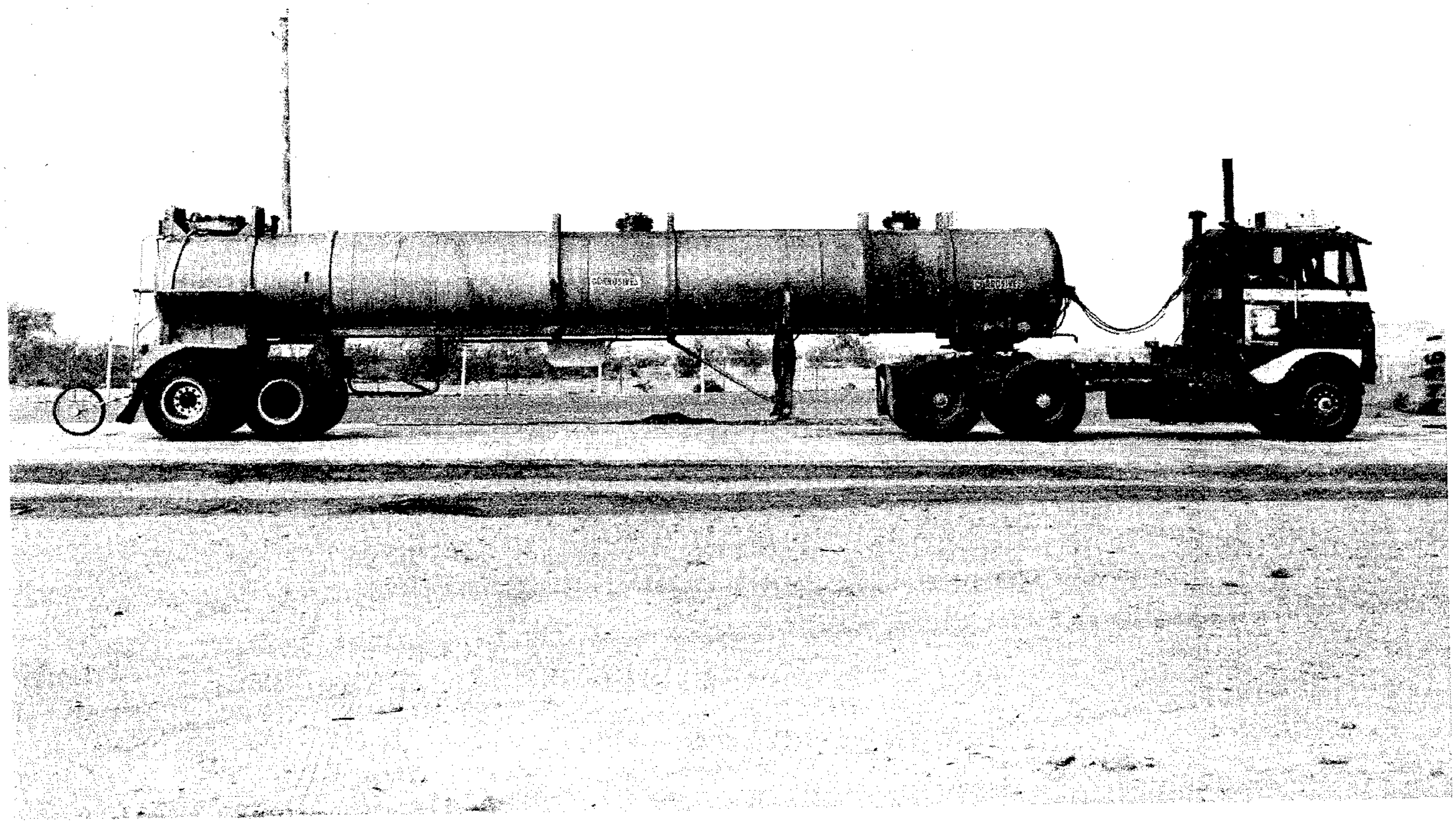


Figure 4. Liquid cargo tanker with baffles (MC-312).

	Empty	1/2 Load (1,925 gal)	3/4 Load (2,888 gal)	7/8 Load (3,369 gal)
Tractor:				
Right front	3,810	3,850	3,990	3,780
Left front	3,810	3,850	3,990	3,780
Right front driver	3,235	5,790	6,625	7,740
Left front driver	3,235	5,790	6,625	7,740
Right rear driver	2,560	4,000	5,310	5,530
Left rear driver	2,560	4,000	5,310	5,530
Trailer:				
Right front	1,590	4,430	4,380	7,815
Left front	1,590	4,430	4,380	7,815
Right rear	2,675	3,885	5,935	3,515
Left rear	2,675	3,885	5,935	3,515
Total Vehicle Weight	27,740	43,910	52,480	56,760

Wheelbase length (tractor 5th wheel to center of dual rear axles):	434 in.
Track width:	
Inside duals	58.63 in.
Outside duals	84 in.
Frame width:	38.25 in.
Tank width:	49 in.
Number of axles:	2
Number of tires per axle:	4

Type of tires:

All eight trailer tires - 10.00x20 Goodyear "Custom Hi-Miler"

Inside dimensions of trailer cargo area:

Tank length	521 in.
Diameter	49 in.

Dimension, weight, and location of load:

Loaded with water weighing 8.4 lb/gallon to the following volume loads:

1/2 vol:	1,925 gal; 16,170 lb; 24.5 in. fluid in tank
3/4 vol:	2,888 gal; 24,259 lb; 34.4 in. fluid in tank
7/8 vol:	3,369 gal; 28,300 lb; 40.0 in. fluid in tank

Figure 5 shows the MC-312 cargo tanker without baffles.

2.4 TASK A-4 - TEST PROGRAM DEVELOPMENT

Requirement: Prepare a test program prescribing required speeds and including at least the following four maneuvers:

1. Braking
2. Cornering
3. Lane changing
4. Cornering with braking.

All maneuvers shall be performed at limit conditions with appropriate safety margins, as required by an experienced driver. Each maneuver is to be performed at a minimum of three loading conditions and be repeated at least three times. The expected number of tests is therefore at least:

> 4 maneuvers x 3 loads x 3 repetitions x 2 surface conditions (dry and wet) x 4 vehicle types (the van is to be used as a baseline vehicle while loaded with non-shifting cargo), i.e., 288 tests. Provide for up to 25 percent additional tests as may be needed.

The effect of cargo shifting was determined by subjecting the test vehicles to four closed-loop, manually-controlled maneuvers. The maneuvers were:

- Straight-line Braking
- Trapezoidal Steer (cornering)
- Sinusoidal Steer (lane changing)
- Braking in a Turn (cornering with braking)

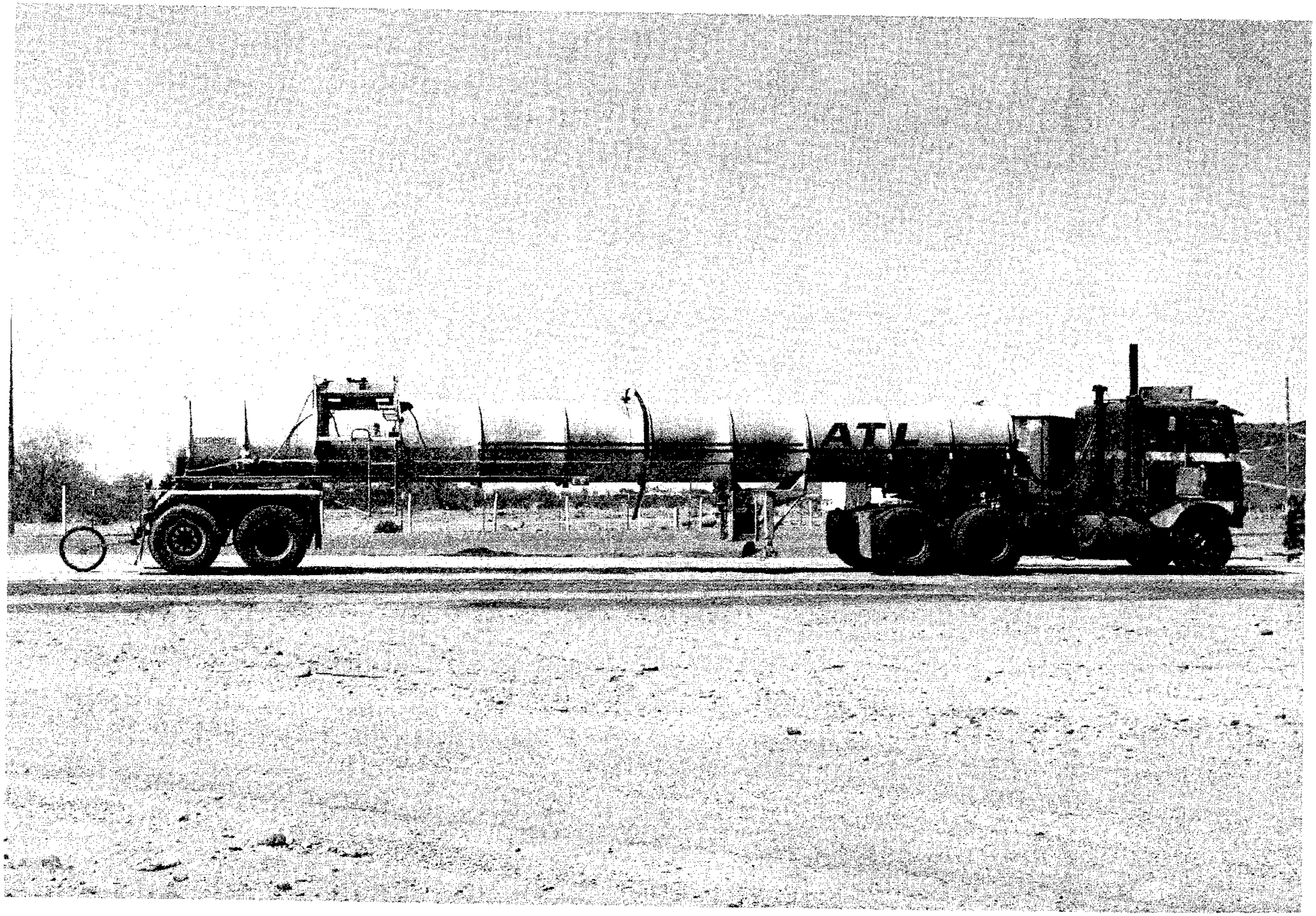


Figure 5. Liquid cargo tanker without baffles (MC-310).

The test series was performed on a high skid number surface (65 to 85) and a low skid number surface (20 to 40) except that the trapezoidal steer was performed only on the high skid number surface. A brief description of each maneuver follows.

Straight-line Braking

This maneuver was designed to determine the braking capability of the vehicle. The test consisted of determining the minimum stopping distance from an initial speed of 40 mph.

Trapezoidal Steer

This maneuver was designed to examine the cornering capability of the vehicle. The test consisted of determining the maximum speed at which a fixed curved course can be traversed.

Sinusoidal Steer

This maneuver was designed to determine the lane changing capability or obstacle avoidance capability of the vehicle. The test consisted of determining the maximum speed at which a given lane change can be performed.

Braking in a Turn

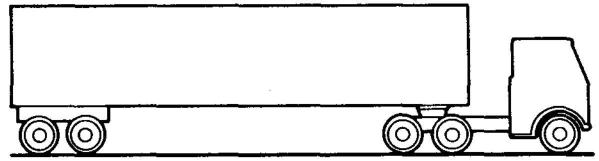
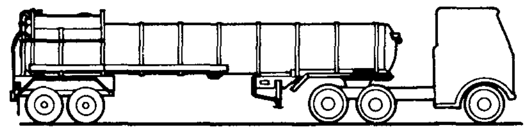
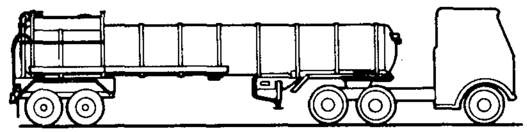
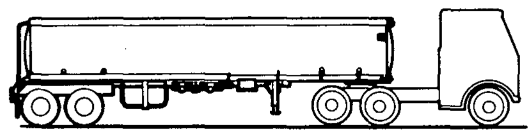
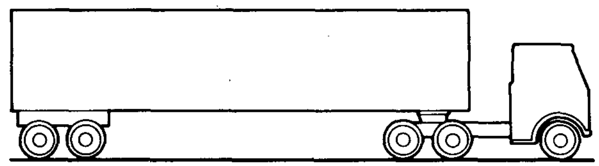
This maneuver was designed to determine the stopping capability and directional control stability of a vehicle that is turning. The test consisted of determining the minimum stopping distance when the vehicle is in a given turn at 40 mph.

The overall scope of the testing for each tractor/trailer loading condition is summarized in Figure 6, the test vehicle matrix. Table 2 shows the total test maneuver requirements.

2.5 TASK A-5 - INSTRUMENTATION, FACILITIES, AND DATA ACQUISITION

Requirement: Select the required instrumentation for measuring:

1. Vehicle acceleration, at least longitudinal and transverse.
2. Dynamic wheel loads on all wheels, at least in the vertical direction (normal load).
3. Field instrumentation for measuring speeds, trajectories, and stopping distances.
4. Instrumentation for filming the motion of the hanging load.

TEST VEHICLE		EMPTY	1/2 FULL	3/4 FULL	7/8 FULL	FULL
		LOADING CONDITION				
BASELINE VAN TRAILER WITH NON-SHIFTING CARGO		X	X			X
HIGH DENSITY TANK TRAILER WITHOUT BAFFLES			X	X	X	
HIGH DENSITY TANK TRAILER WITH BAFFLES			X	X	X	
LOW DENSITY TANK TRAILER WITH COMPARTMENTS				X		
MEAT TRAILER WITH MEAT						X

80301305

Figure 6. Test matrix.

Table 2. Test matrix.

Maneuver	Test Condition	Test Variable	Repetition	Test Surfaces	Total No. Tests
Straight-line Braking	40 mph	Stopping Distance	4	2	8
Trapezoidal Steer	420-ft radius curve	Velocity	4	1	4
Sinusoidal Steer	1 lane change	Velocity	4	2	8
Braking in a Turn - Dry Surface	420-ft radius curve at 40 mph	Stopping Distance	4	1	4
Braking in a Turn - Wet Surface	300-ft radius curve at 30 mph	Stopping Distance	4	1	4
			Total minimum tests per tractor combination and load condition		28

2.5.1 Instrumentation

The basic instrumentation requirements were as follows:

Driver Variables:

Steering Wheel Torque

Steering Wheel Angle

Brake Pedal Force.

Vehicle Variables:

Trailer Roll Position

Trailer Longitudinal Acceleration

Tractor Lateral and Longitudinal Acceleration

Tractor/Trailer Angle

Loads at Each Wheel

Vehicle Speed

Stopping Distance

Vehicle Trajectory (tractor)

Meat Motion.

Table 3 is a list of instrumentation used to accomplish these measurements. Figure 7 is a schematic showing typical instrumentation locations on the tractor. Figure 8 shows instrumentation locations on the trailer.

The first three parameters measured the level of driver input during the maneuver. The steering wheel torque was measured by strain gauges attached to the steering wheel shaft (Figure 9). Steering wheel angle was measured by a string potentiometer and pedal force was measured by a load cell (Figure 9).

Vehicle dynamics were documented by the remaining instrumentation. The trailer roll was measured by a gyro (Figure 10). Acceleration was measured by accelerometers. These instruments were part of a self-contained Humphrey gyro package (Figure 11) which was attached to the underside of the trailer and later to the tractor. The tractor/trailer angle was measured by a string potentiometer.

Wheel loads were calculated from a measurement of spring displacement and unsprung mass acceleration. The displacement and acceleration were measured by string potentiometers and accelerometers, respectively. Vehicle speed and stopping distance were obtained from a fifth wheel (Figure 12) in conjunction with an integrating circuit to obtain stopping distance which was digitally displayed for the driver.

Vehicle trajectory was calculated from tractor yaw position and acceleration after the data were digitized. Originally, it was planned to measure trajectory directly on the track from a physical marker attached to the vehicle, but this proved too time-consuming because of the large number of test runs required, so, with approval of the Government Contract Manager, the trajectory was calculated as just explained. A motion picture (64 frames per second) camera documented motion of the meat during the swinging meat tests. Real-time motion pictures (24 frames per second) documented representative testing of each type. Black-and-white photographs and color slides also documented the test vehicles, instrumentation, test configurations, and unusual occurrences.

2.5.2 Facilities

The tests were performed on the skid pad and the high and low skid number braking lanes of the Dynamic Science Facility (see Figure 13).

Table 3. Instrumentation list.

Item	Measurand	Transducer	Manufacturer and Model	Full Scale	Accuracy
1	Steering Wheel Wheel Torque	Strain Gauge	Dynamic Science	500 in./lb	±.5%
2	Front Wheel Angle (outside wheel)	Displacement Potentiometer	Celesco PT-101-15C	0.5 in.	±.1% F.S.*
3	Pedal Force	Pedal Force Load Cell	GSE 3000	300 lb	±2 lb
4	Tractor-Trailer Angle	Displacement Potentiometer	Celesco PT-101-30C	30 in.	±.1% F.S.
5-14	Wheel Displacement	Displacement Potentiometer	Celesco PT-101-30C	30 in.	±.1% F.S.
15-19	Axle Acceleration	Strain Gauge Accelerometer	Bell & Howell 4-202-0001	5G	±.65% F.S.
20	Roll Rate**	Gyro Position	Humphrey 18-0902-1	45 deg	±.5 deg
21	Velocity	Fifth Wheel with Digital Meter	DD 2.1	100 mph	.5 mph
22	Longitudinal Acceleration**	Force Balance Accelerometer	Kistler 3036	1.0G	±0.01G
23	Longitudinal Acceleration	Strain Gauge Accelerometer	Bell & Howell 4-202-0001	5G	±0.65% F.S.
24	Yaw Rate Gyro**	Rate Gyro	Humphrey	40 deg	±0.5 deg
25	Roll Rate	Rate Gyro	Humphrey 36128VA	45 deg	±0.5 deg
26	Lateral Acceleration**	Force Balance Accelerometer	Kistler 3036	1.0G	±0.01G
C	Stopping Distance	Fifth Wheel with Digital Meter	DD 1.1	1000 ft	.5%
E	Swinging Load Dynamics	Camera	Milliken 5A	64 frames/ second	NA

*F.S. = Full scale.
**Part of Humphrey gyro package Model CF18-0900 series.

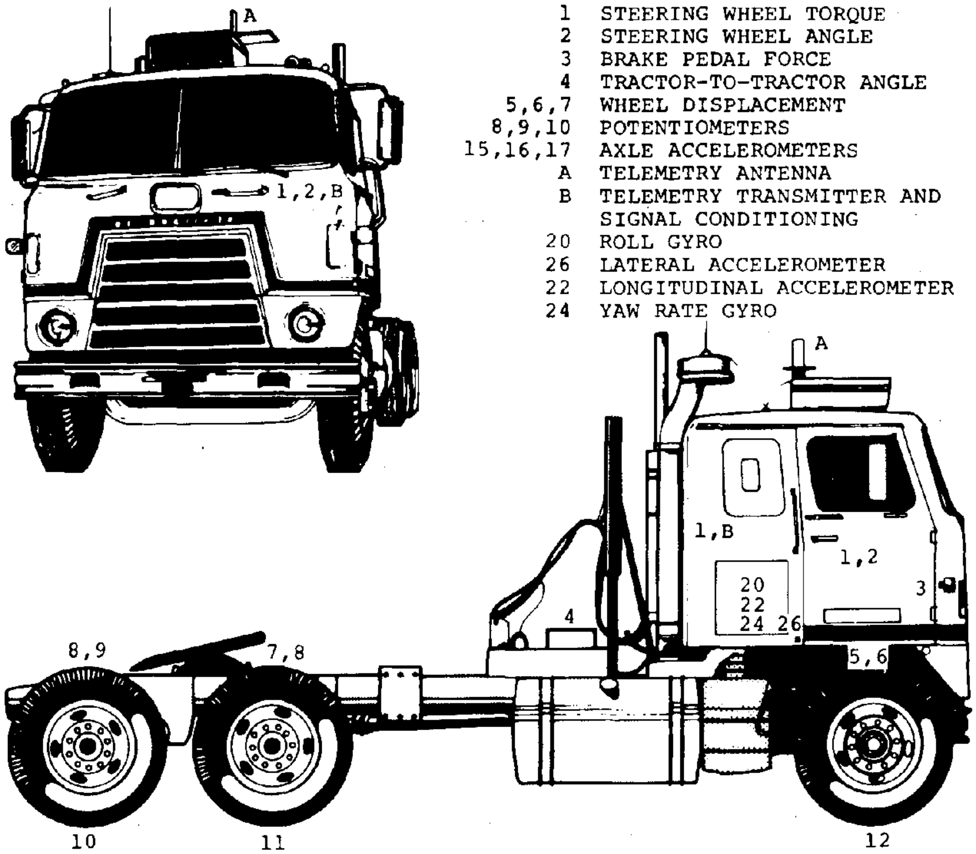
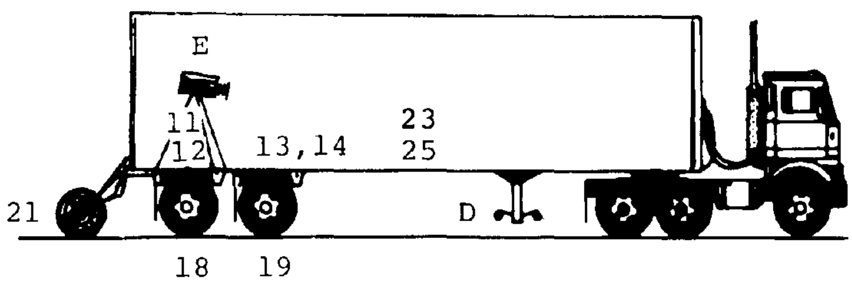


Figure 7. Tractor instrument locations.



11,12,13,14	WHEEL DISPLACEMENT
18,19	AXLE ACCELEROMETERS
21	FIFTH WHEEL
23	LONGITUDINAL ACCELEROMETER
D	TRAJECTORY MARKER
E	CAMERA
25	ROLL GYRO

Figure 8. Trailer instrument locations.

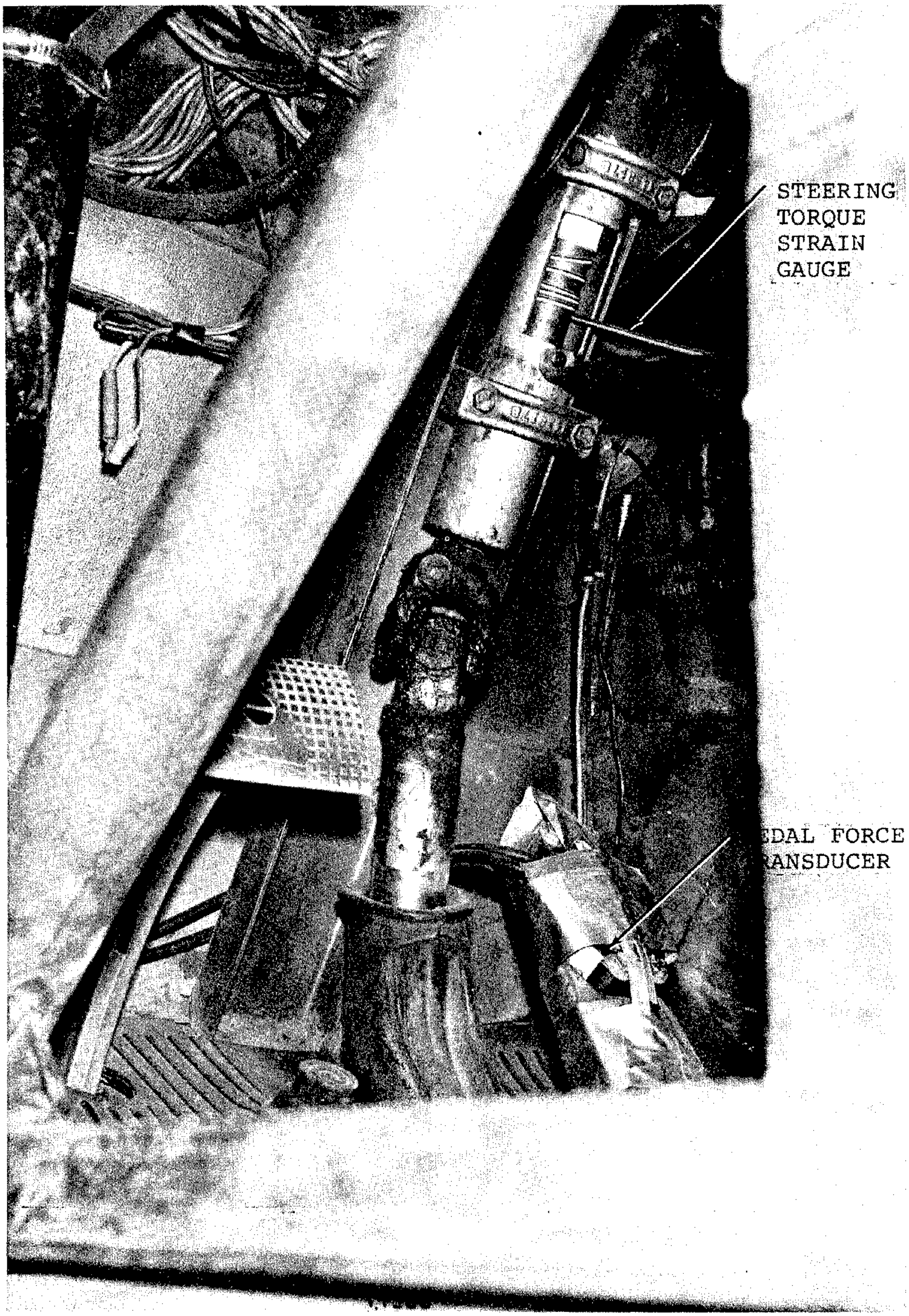


Figure 9. Steering instrumentation.

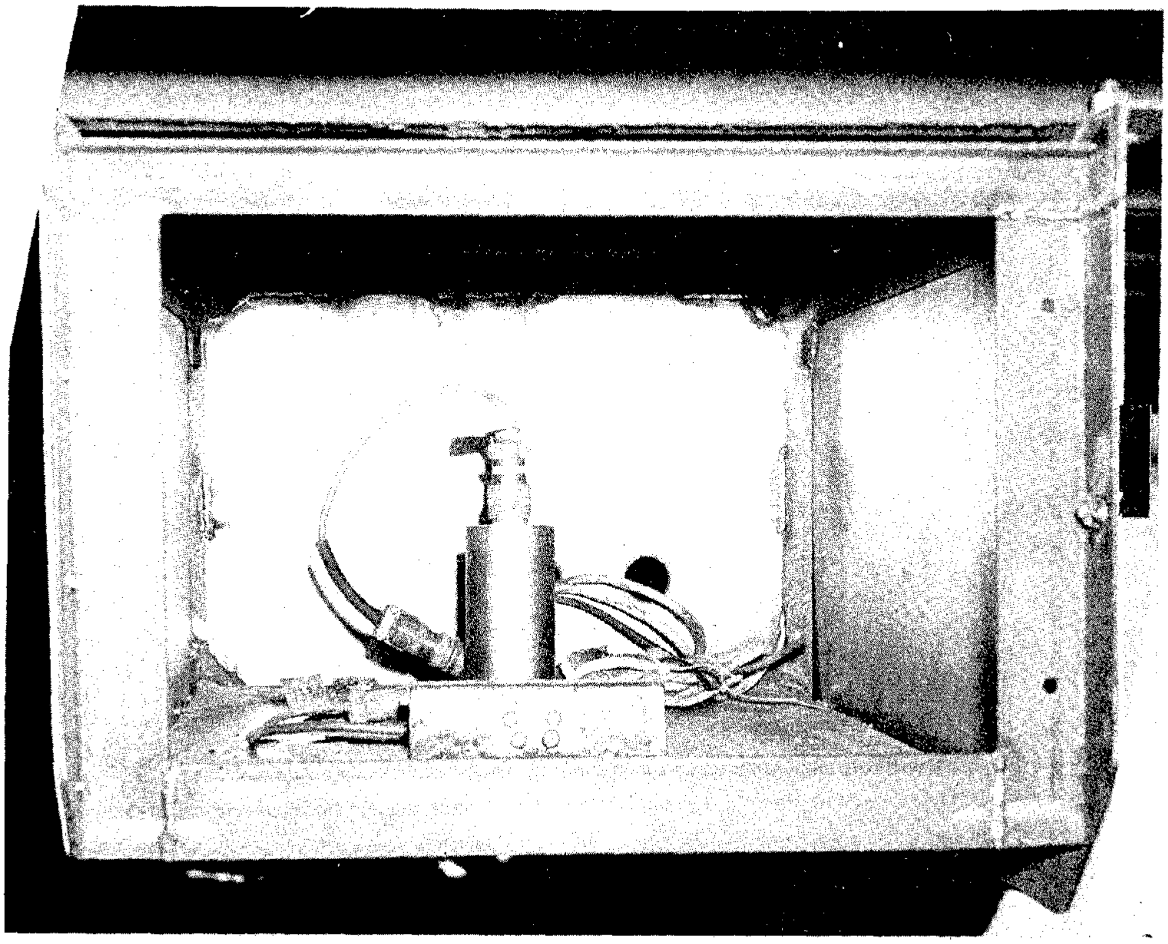


Figure 10. Gyro installation.

2.5.3 Data Acquisition System

The data acquisition system is shown schematically in Figure 14. Instrumentation and signal conditioning were mounted on board the vehicle. All data except camera data were transmitted to a ground-based data recording station via a telemetry system. At the data receiving station, the data were recorded on a tape recorder for a permanent record of the test as well as for access at a future date. The data were also discriminated and played out on a line-type recorder for the purpose of obtaining quick-look evaluation data. This quick-look data served to give a check as to whether test conditions had been achieved, and also provided a view of the critical test parameters to ensure that good data were obtained during the test period. Data from selected test runs were then converted from analog to digital in the Dynamic Science data reduction facility. Trajectories, wheel loads, roll angles, yaw angles, and tractor-trailer angles were calculated and the data were written on a magnetic tape for more detailed evaluation and comparison with computer simulation work.

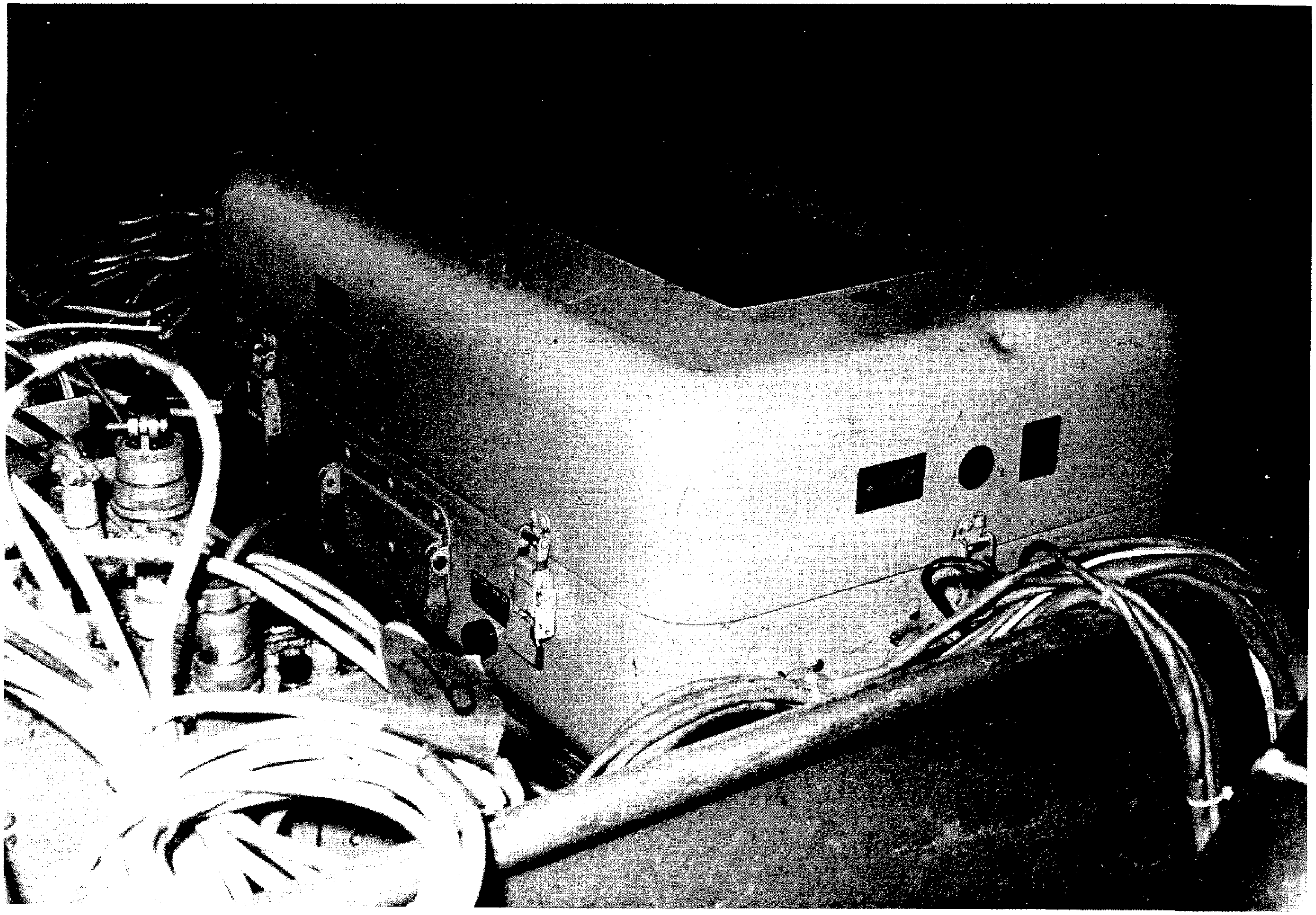


Figure 11. Humphrey package.

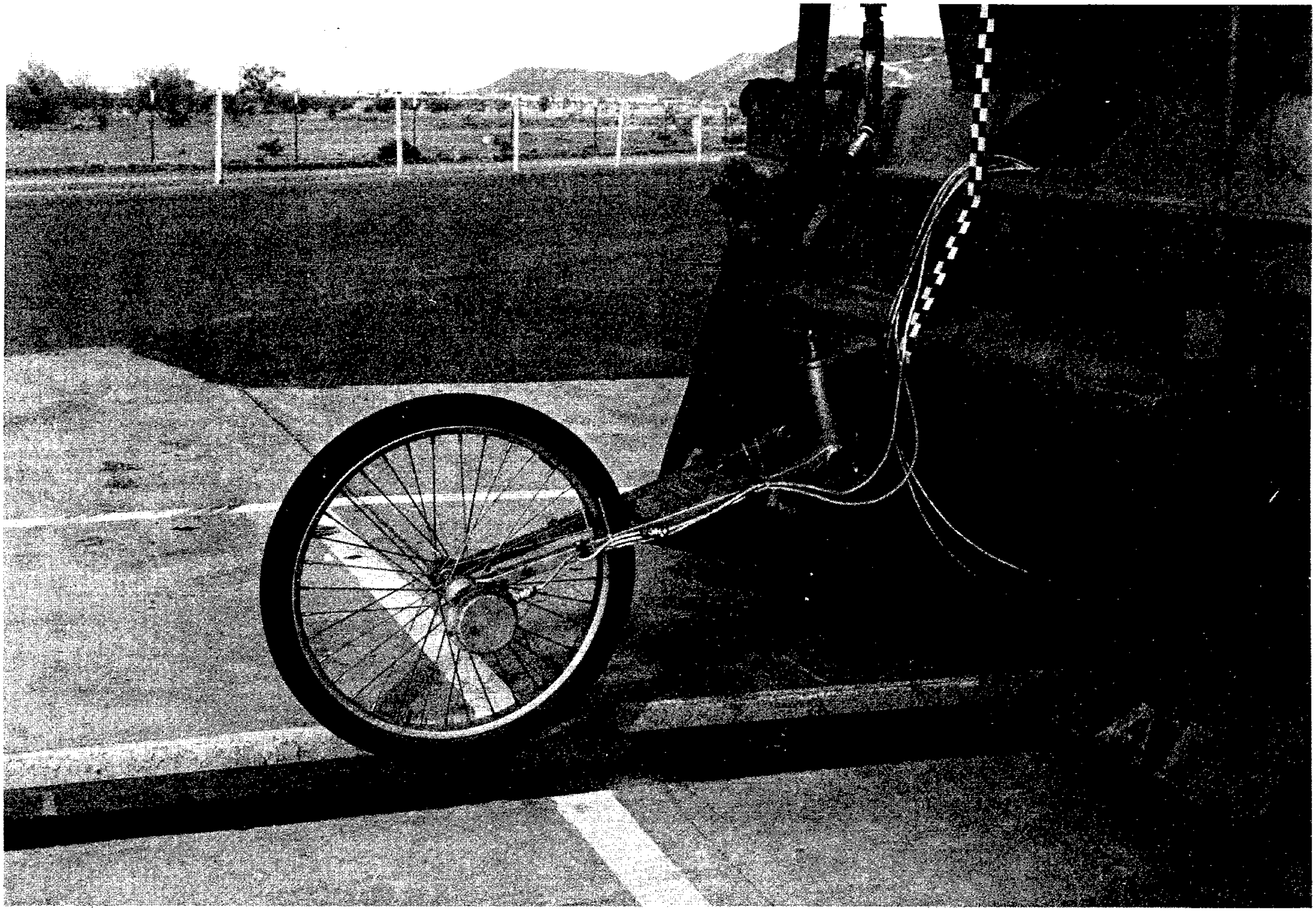
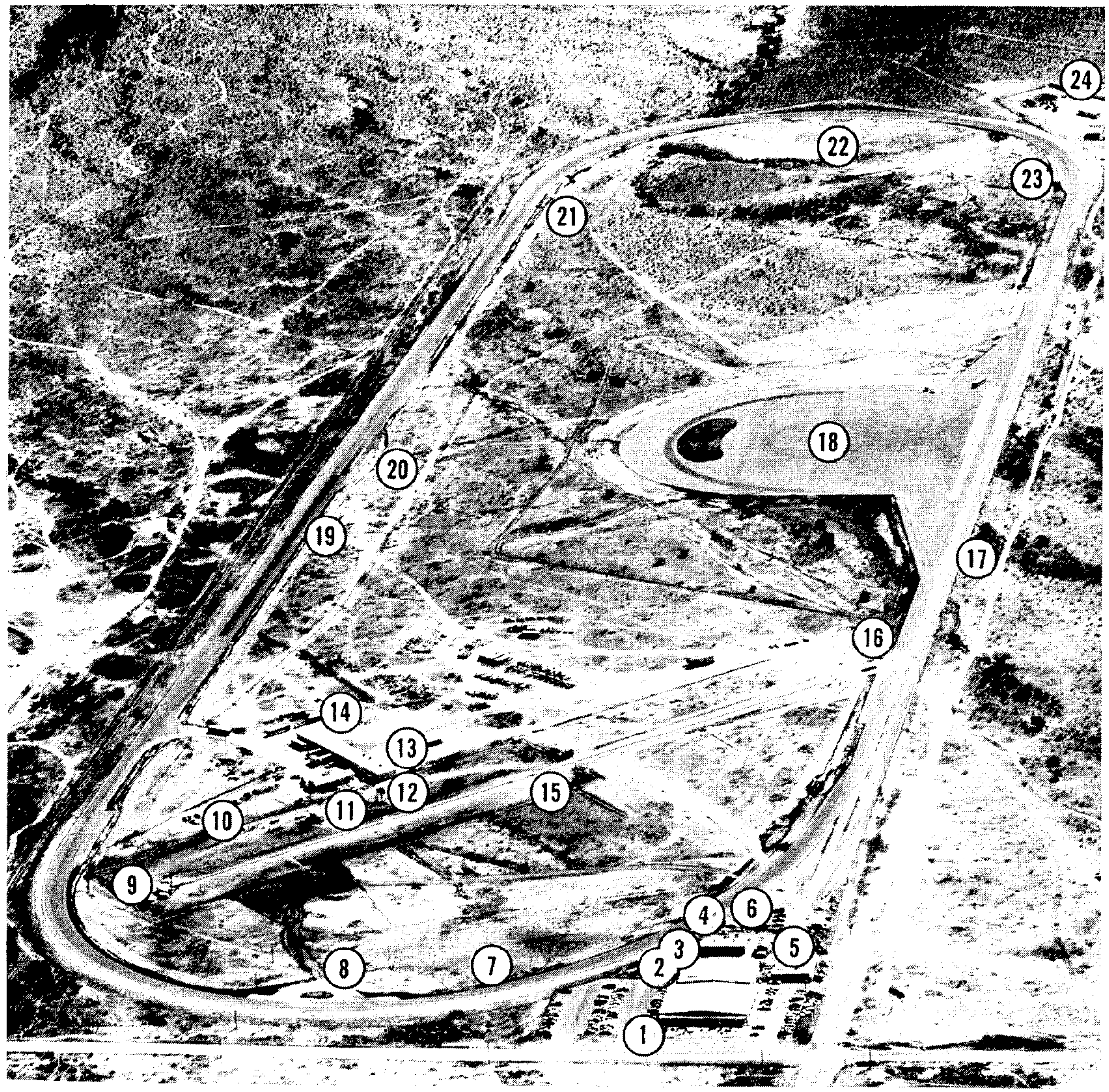


Figure 12. Fifth wheel installation.



1. ENGINEERING/ADMINISTRATION CENTER
2. MECHANICAL/INSTRUMENTATION SHOPS
3. DUMMY CALIBRATION LABORATORY
4. GARAGE/MAINTENANCE SHOP
5. ENVIRONMENTAL CHAMBER
6. STATIC CRUSH FACILITY
7. TWO-MILE OVAL
8. TURNAROUND (TYPICAL OF TWO)
9. BARRIER IMPACT FACILITY
10. DROP TOWER/SLED TEST FACILITY
11. CENTRAL DATA ACQUISITION AND CONTROL STATION
12. PENDULUM FACILITY
13. NONMETALLICS LABORATORY
14. TEST SERVICE FACILITY
15. VEHICLE-TO-VEHICLE TEST FACILITY
16. ROLLOVER TEST FACILITY
17. RIDE QUALITY COURSE
18. SKID PAD
19. HIGH AND LOW SKID NUMBER BRAKING LANES
20. SALT WATER TROUGH
21. BELGIAN BLOCK
22. PARKING BRAKE TEST RAMP
23. PULL-OFF AREA (TYPICAL OF THIRTEEN)
24. BALLISTIC TEST RANGE

Figure 13. Aerial view of Dynamic Science, Inc. Deer Valley Facility.

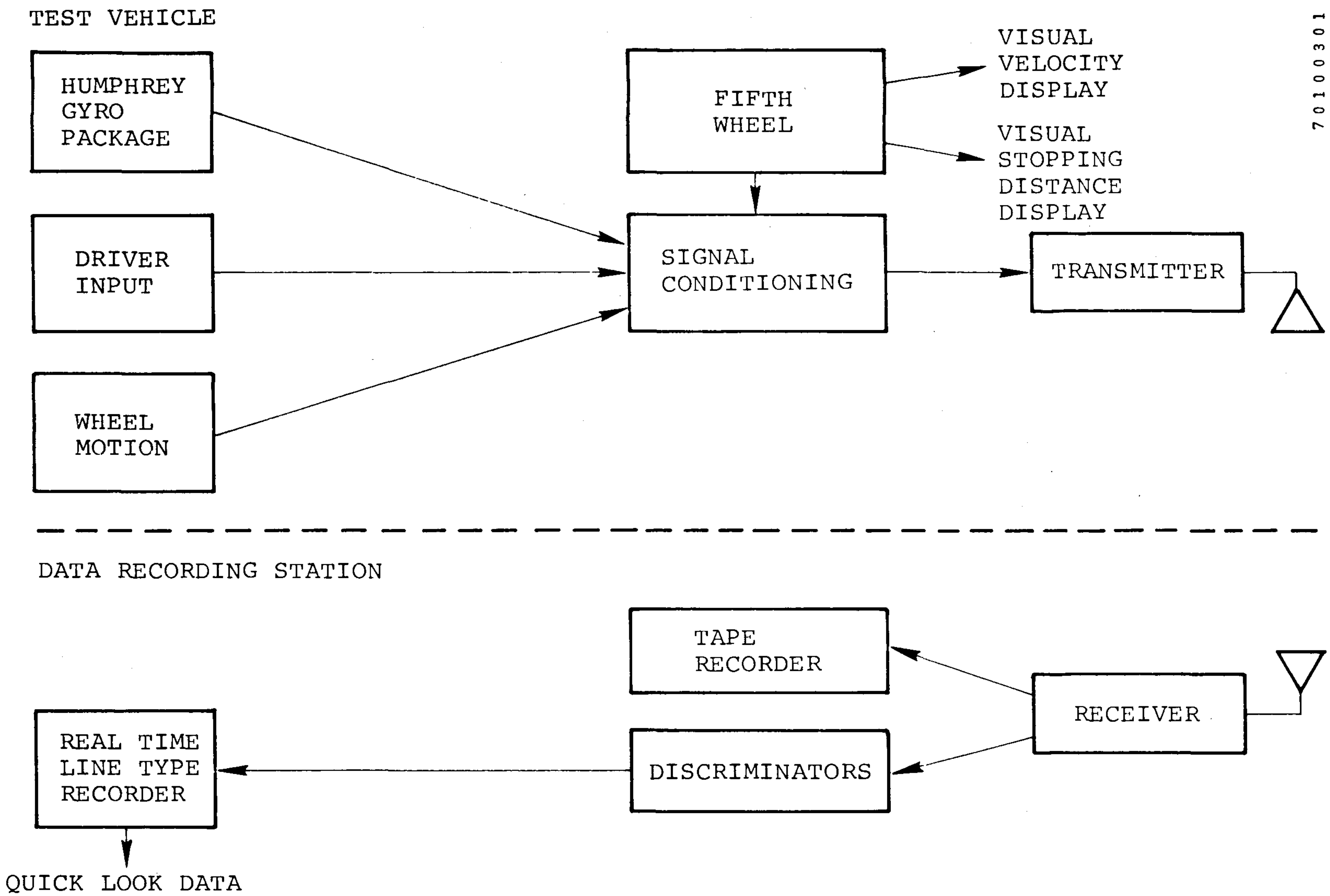


Figure 14. Data acquisition system schematic.

3.0 TASK B - CONDUCT OF TESTS

Task B was devoted to preparing the vehicles and instrumentation; mounting the instrumentation and performing the necessary calibrations; driver selection, training, and systems orientation; conducting the tests; and data acquisition and analysis.

3.1 TASK B-1 - VEHICLE AND INSTRUMENTATION PREPARATIONS

Requirement: Prepare the vehicles and the required instrumentation.

Each test vehicle was inspected when received, and the Vehicle Description Sheet shown in Figure 15 was completed.

A Vehicle Log was then initiated and maintained to collect the completed forms during the testing program. The log was kept current by performing the following tasks:

- Include copies of all completed forms.
- Enter activity in Chronological Log (Figure 16).
- Enter repairs in Maintenance Log (Figure 17).
- Enter modifications in Modification Log (Figure 18).

Prior to receipt of the vehicles, preliminary data system design was accomplished and effort was taken to provision the necessary instrumentation supplies and support logistics (tractor fuel, fabrication metals, etc.).

3.2 TASK B-2 - ON-VEHICLE INSTRUMENTATION INSTALLATION AND CALIBRATION

Requirement: Mount the instruments on the vehicles and position the field instruments. Perform calibrations and record calibration data. Check for reliability.

Each vehicle was prepared for installation of instruments by fabricating brackets and fixtures to mount and secure the instruments, cables, signal conditioning, and transmitters as listed in Tables 4 and 5. Typical instrument installations were provided in Figures 9 through 12.

The equipment for determining the motion of the meat was installed immediately after the loaded trailer was received. The motion of five selected carcasses was determined from two LED light sources attached six inches apart on each carcass. These

VEHICLE DESCRIPTION SHEET

Date Received: ____________

Program Vehicle Identification: ____________ Contract#: ____________

VIN: ____________ Make: ____________

Year: ________ Color: ____________ Model: ____________

Auto Trans: yes ☐ no ☐ Pwr Steering: yes ☐ no ☐ Seats: (front) Bench: ______

Pwr Brakes: yes ☐ no ☐ Auto Speed Cont: yes ☐ no ☐ Bucket: ______

Pwr Seats: yes ☐ no ☐ Anti Skid Brake: yes ☐ no ☐ Split Bench: ______

Pwr Window: yes ☐ no ☐ Air Conditioning: yes ☐ no ☐

Tinted Glass: yes ☐ no ☐ Rear Window Def.: yes ☐ no ☐ Split Back Bench: ______

Radio: yes ☐ no ☐ Brakes: drum ______ disc ______

Clock: yes ☐ no ☐

Tire Size: ________ Ply Rating: ________ Mfg. & Line: ____________

Bias Ply: ______ Belted: ______ Radial: ______/Eng. HP: ______ Cylinders: ______ Total Displ: ______

Trans. # Fwd. Speeds: ________ Shipping Weight: ________ Odometer: ________

Vehicle As-Received Weights (lb)

RF: ________ LF: ________

RR: ________ LR: ________

Total: ________

Date Purchased: ________ Purchase Order #: ________ Purchase Price: ________

Wholesale Price: ____________ Suggested Ret. Price: ____________

Remarks; (list additional accessories not listed above): ____________

Figure 15. Vehicle description sheet.

CHRONOLOGICAL LOG

70100302

VEHICLE NO.	DATE

TIME	ODOMETER	INITIAL	EVENT

DSEO Form 1342

Figure 16. Vehicle chronological log.

MAINTENANCE						
BODY	CHASSIS	ENGINE	DATE	ODOM-ETER	INITIAL	WORK DONE

70100304

DSEO Form 1344

Figure 17. Vehicle maintenance log.

MODIFICATIONS						
BODY	CHASSIS	ENGINE	DATE	ODOM-ETER	INITIAL	WORK DONE

DSEO Form 1343

Figure 18. Vehicle modification log.

Table 4. Vehicle preparation log.

PROJECT________ VEHICLE IDENTIFICATION:

SPEC: Tractor MAKE________ YEAR______ MODEL______

TASK:________ S/N________ TEST NO.______

SUBTASK NUMBER	SUBTASK DESCRIPTION	DONE BY	DATE	SPECIAL INSTRUCTIONS/COMMENTS
1	Install roll cage, bucket seat, and an aircraft type four-point restraint system.			
2	Mount visual display of fifth wheel velocity and stopping distance in easy view of driver.			
3	Install instrumentation as shown in Figure 7.			
4	Install data acquisition system which consists of 2 RSCMs.			
4a	Determine and record the calibration value for the measurements.			Use instrumentation configuration list for Handling/ Braking/Ride Form.
5	Paint stripe on wheel tc aid in viewing wheel rotation.			
6	Determine weight of vehicle with full fuel tanks.			Front______ Rear______ Total______
7	Put copies of all completed forms in the Vehicle Log.			
8	Determine suspension rate by adding weight and recording suspension deflection using string potentiometer and scales.			Use Suspension Test Form in Figure 19.

Table 5. Vehicle preparation log.

PROJECT ____________________ VEHICLE IDENTIFICATION:

SPEC: Trailer ____________________ MAKE __________ YEAR ______ MODEL ______

TASK: ____________________ S/N __________ TEST NO. ______

SUBTASK NUMBER	SUBTASK DESCRIPTION	DONE BY	DATE	SPECIAL INSTRUCTIONS/COMMENTS
1	Determine weight of empty trailer/ tractor.			Front ______ Rear ______ Total ______
2	Build cables for connecting instrumentation with RSCM on tractor.			
3	Mount fifth wheel on rear bumper.			
4	Install instrumentation as shown in Figure 8.			
4a	Measure and record location of Humphrey package and trajectory marker.			
5	Determine and record the calibration values for the measurements.			Use Instrumentation Configuration List for Handling/ Braking/Ride Form.
6	Paint stripes on wheel to aid in viewing wheel rotation.			
7	Determine weight of trailer/tractor.			Front ______ Rear ______ Total ______
8	Determine suspension rate by adding weight and recording suspension deflection using string potentiometer and scales.			Use Suspension Test Form in Figure 19.

SPECIFICATION ______________________________

MAKE ______________ YEAR __________ MODEL ______________

FRONT WHEELS

LOAD	WHEEL ___ LOAD (LB)	DISPLACE-MENT (IN.)	WHEEL ___ LOAD (LB)	DISPLACE-MENT (IN.)	WHEEL ___ LOAD (LB)	DISPLACE-MENT (IN.)	WHEEL ___ LOAD (LB)	DISPLACE-MENT (IN.)
Normal								
#1								
#2								
#3								
#4								
#5								
#6								
#7								

REAR WHEELS

LOAD	WHEEL ___ LOAD (LB)	DISPLACE-MENT (IN.)	WHEEL ___ LOAD (LB)	DISPLACE-MENT (IN.)	WHEEL ___ LOAD (LB)	DISPLACE-MENT (IN.)	WHEEL ___ LOAD (LB)	DISPLACE-MENT (IN.)
Normal								
#1								
#2								
#3								
#4								
#5								
#6								
#7								

Figure 19. Suspension test form.

light sources were the only light in the van except for a time-of-day clock, a timer clock, and a small correlation light that signalled start of test. Figure 20 shows LED light sources attached to meat carcasses, which were viewed by the camera shown in Figure 21.

On a daily basis, the calibration of the primary instruments was checked physically. For instance, known reference weights were placed on the brake pedal load cell, the string potentiometers were displaced to accurately-measured distances, moments were applied to the steering wheel to calibrate torque by applying known weights at precise distances, and the fifth wheel was spun at a known speed by a synchronous motor with an independent speed readout which accurately counts revolutions. The longitudinal acceleration was checked by decelerating the vehicle and dividing the velocity change (ΔV) by the corresponding change in time (Δt). Velocity, lateral acceleration, and yaw rate were correlated with each other by driving the vehicle around a 100-foot radius circle at constant speed. The correlation equations are

$$A_y = V^2/R$$

$$W = V/R$$

where A_y = lateral acceleration

V = vehicle velocity

R = radius of circle (100 ft)

W = yaw rate

This check was also used to check the computer simulation. The physical check was documented using the forms presented in Figures 22 and 23 for the tractor and trailer, respectively. Electrical calibration was generated and recorded prior to each day's testing.

3.3 TASK B-3 - DRIVER SELECTION AND SYSTEM CHECKOUT

Requirement: Select a driver experienced in operating the vehicles and cargoes in the program and make sure he understands the test program and his role in it. The same driver is to be used throughout the program. Conduct one day of exploratory tests to verify that the program can be conducted as planned.

After some driver changes due to conflict with schedule commitments, Mr. Patrick Ryan was selected as the test driver. Mr. Ryan was selected because of his experience in compliance driving to controlled R&D test conditions in the service. Most of this experience was gained as a heavy-vehicle operator before retiring

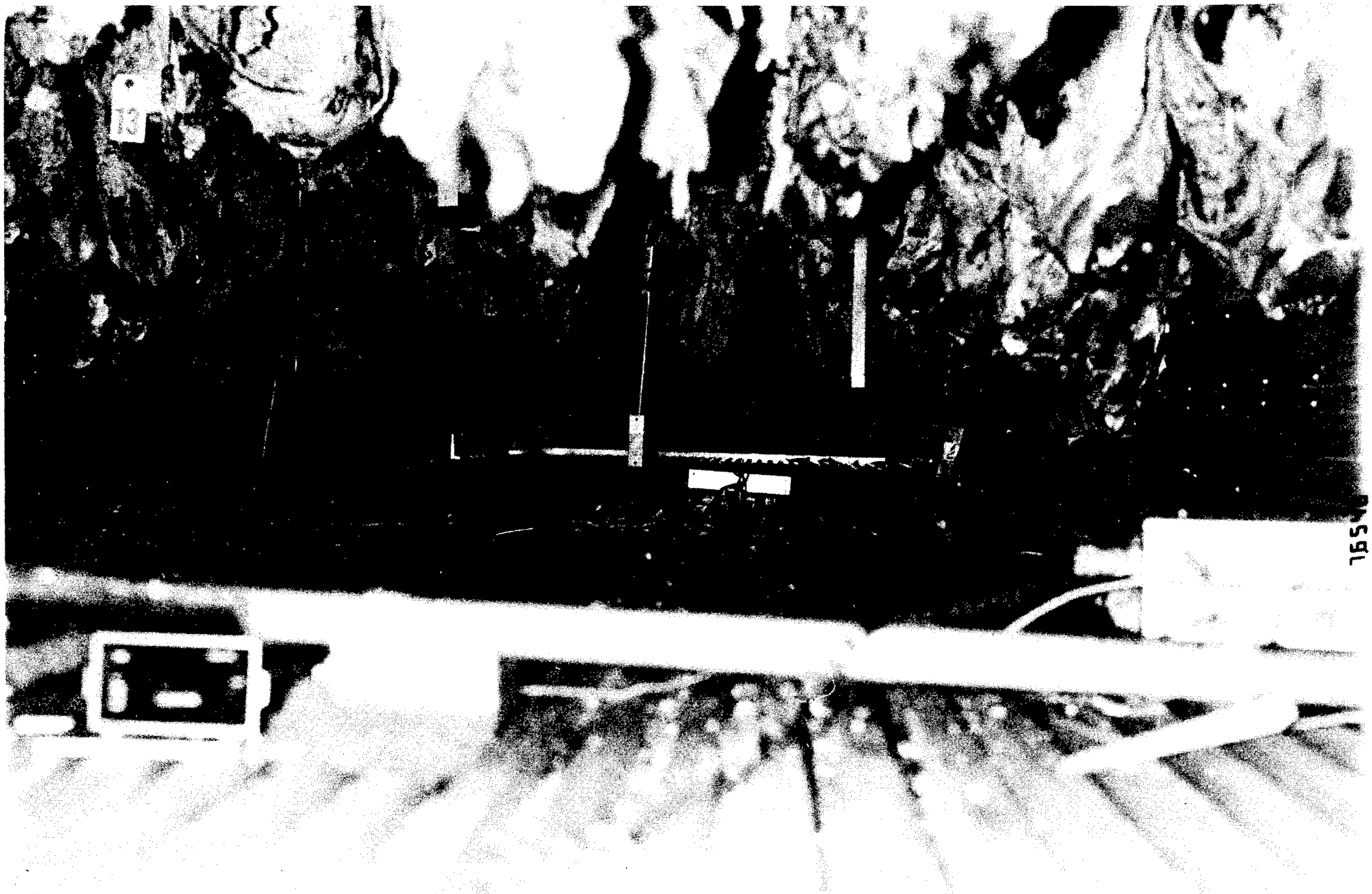


Figure 20. LED light sources attached to meat carcasses.

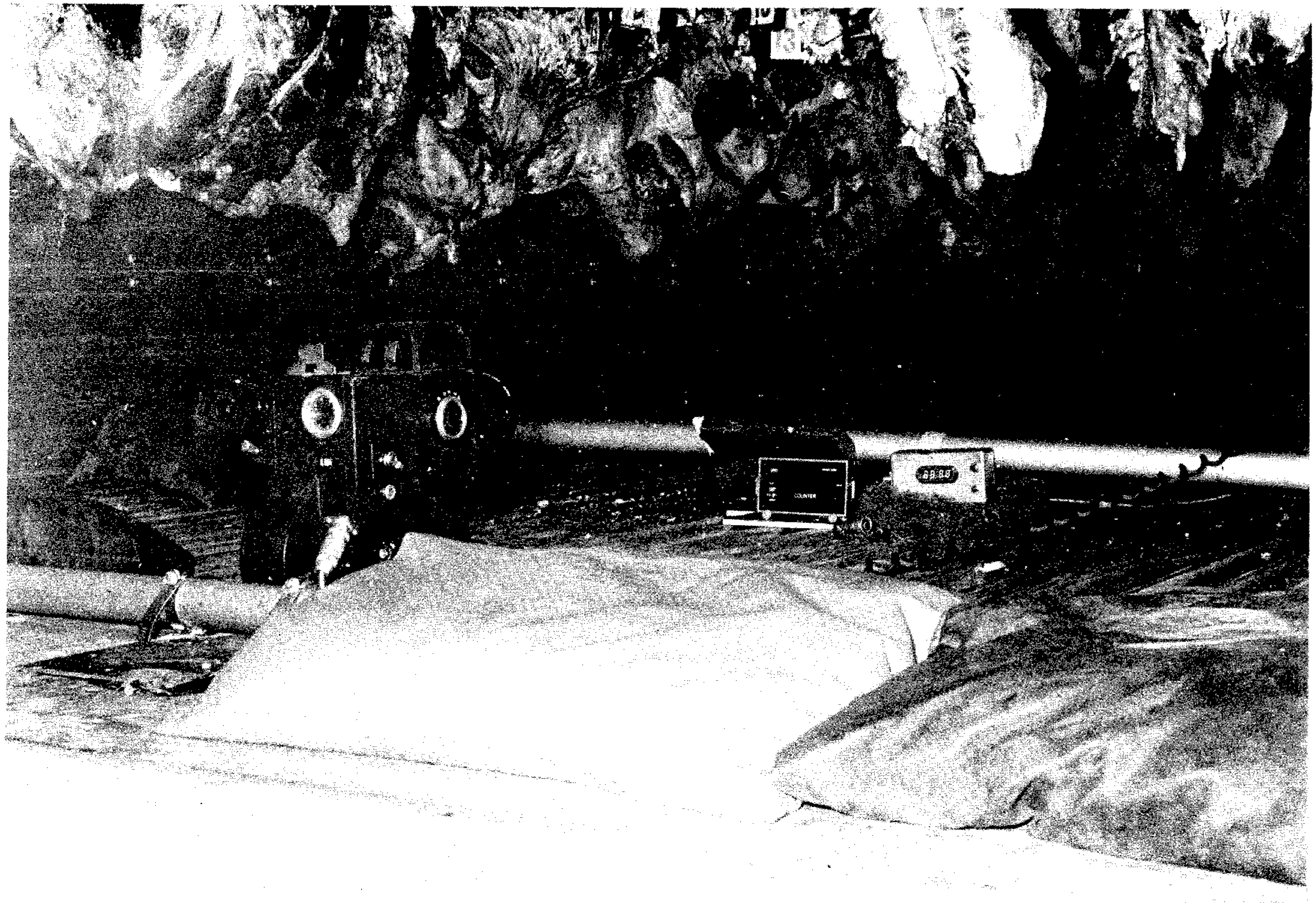


Figure 21. Camera installation in meat van.

CALIBRATION CHECK SHEET

VEHICLE Tractor ______ TEST TYPE ______ DATE ______

Data Channel	Measurement Description	How to Perform Physical Check	Measurement Value Desired	Measurement Value Measured
1	Steering wheel torque	Apply moment		
2	Steering wheel angle	Rotate wheel	±360°	
3	Brake pedal force	Apply force		
4	Tractor/trailer angle	Displace string Potentiometer		
5	Wheel displacement	None	-	-
6	Wheel displacement	None	-	-
7	Wheel displacement	None	-	-
8	Axle acceleration	None	-	-
9	Axle acceleration	None	-	-
10	Axle acceleration	None	-	-
11				
12				
13				
14				

Comments: ______

Checks performed by: ______

Figure 22. Calibration check sheet.

CALIBRATION CHECK SHEET

VEHICLE Trailer TEST TYPE ____________ DATE ____________

Data Channel	Measurement Description	How to Perform Physical Check	Measurement Value Desired	Measurement Value Measured
1	Vehicle velocity	Calibration motor	52.95 mph	
2	Lateral acceleration	100-ft circle, compute $A_V = V^2/R$		
3	Longitudinal acceleration	Stop vehicle, compute $a = (\Delta V)/(\Delta t)$		
4	Yaw rate	100-ft circle, compute $W = V/R$		
5	Wheel displacement	None	-	-
6	Wheel displacement	None	-	-
7	Wheel displacement	None	-	-
8	Axle acceleration	None	-	-
9	Axle acceleration	None	-	-
10	Axle acceleration	None	-	-
11	Roll	None	-	-
12				
13				
14				

Comments: ____

Checks performed by: ______________________

Figure 23. Calibration check sheet.

from the Air Force in 1974, and included involvement in fuel transport, hanging meat delivery, and all types of military munitions transport, both overseas and in the continental U.S.A. Since retirement, he has driven for R. T. Platka Fuels in Vermont; he is presently living in Mesa, Arizona and is employed as a line haul driver for Professional Drivers, Operators, and Pilots Service (PDOPS) out of Phoenix.

Because of his in-service experience in R&D test driving, Mr. Ryan was able to perform the required vehicle maneuvers of the cargo shift program with relative ease. He was thoroughly briefed on his responsibilities, including emphasis on his discretion in determining braking and steering input limits. He was required to use the tractor restraint system and wear a crash helmet at all times. In addition, an observer was positioned at a safe distance from the testing to witness vehicle response (in particular, signs of imminent limit conditions).

The exploratory testing was conducted using the baseline configuration (tractor and van with non-shifting cargo) after verifying data system function and limit responses.

3.4 TASK B-4 - TEST PROCEDURES, CONDITIONS, AND DATA OPERATIONS

Requirement: Conduct the tests as planned and keep accurate records of test results and conditions during testing, including photographic records. Temperature, weather, and surface conditions should be reasonably constant during testing. Make sure vehicle conditions do not change. Inflation pressures, brake, and tire conditions should be checked.

The tests were conducted using the vehicles specified in Section 2.3 to perform the maneuvers outlined in the Test Matrix presented in Table 2. The test vehicle configurations were:

- Tractor and van trailer with non-shifting cargo (baseline).
- Tractor and compartmented, low-density liquid cargo tanker with baffles (MC-306).
- Tractor and high-density liquid cargo tanker with baffles (MC-312).
- Tractor and high-density liquid cargo tanker without baffles (MC-312).
- Tractor and refrigerated van trailer with hanging meat.

Basic determinations for each configuration were:

- Braking
- Cornering
- Lane Changing
- Cornering With Braking.

3.4.1 Test Procedures

On each test day, the skid pad and braking lanes were cleaned as required, and the high and low skid number surfaces were measured. Typical data are presented in Appendix B. Following this, the test course was laid out, using traffic cones as shown in Figure 24.

Before each test run, a check procedure was followed to make sure all personnel (driver, observer, photographer, and data monitor) and the test vehicle were ready for test (see Figure 25). The procedure also accounted for post-test activity on a check-off basis. Daily copies of the procedure checklist were filed in the Vehicle Log Book, along with the Daily Operating Log Sheet (Figure 26) which served to record individual vehicle performance and maintenance.

3.4.1.1 Braking Test

The procedure for Straight-line Braking and Braking in a Turn is outlined below:

1. The vehicle is driven to approach the test course.
2. The stopping distance and initial speed display units are reset.
3. The vehicle speed is stabilized at 40 mph and the Central Data Acquisition and Control Station is notified of start of test.
4. The vehicle is accelerated to slightly above test speed and the clutch is disengaged.
5. The vehicle is driven through the course:
   - At the initiation point, when the test speed is reached, the brakes and clutch are applied to try and stop the vehicle in the shortest distance.
   - The vehicle is steered to stay within the lane.

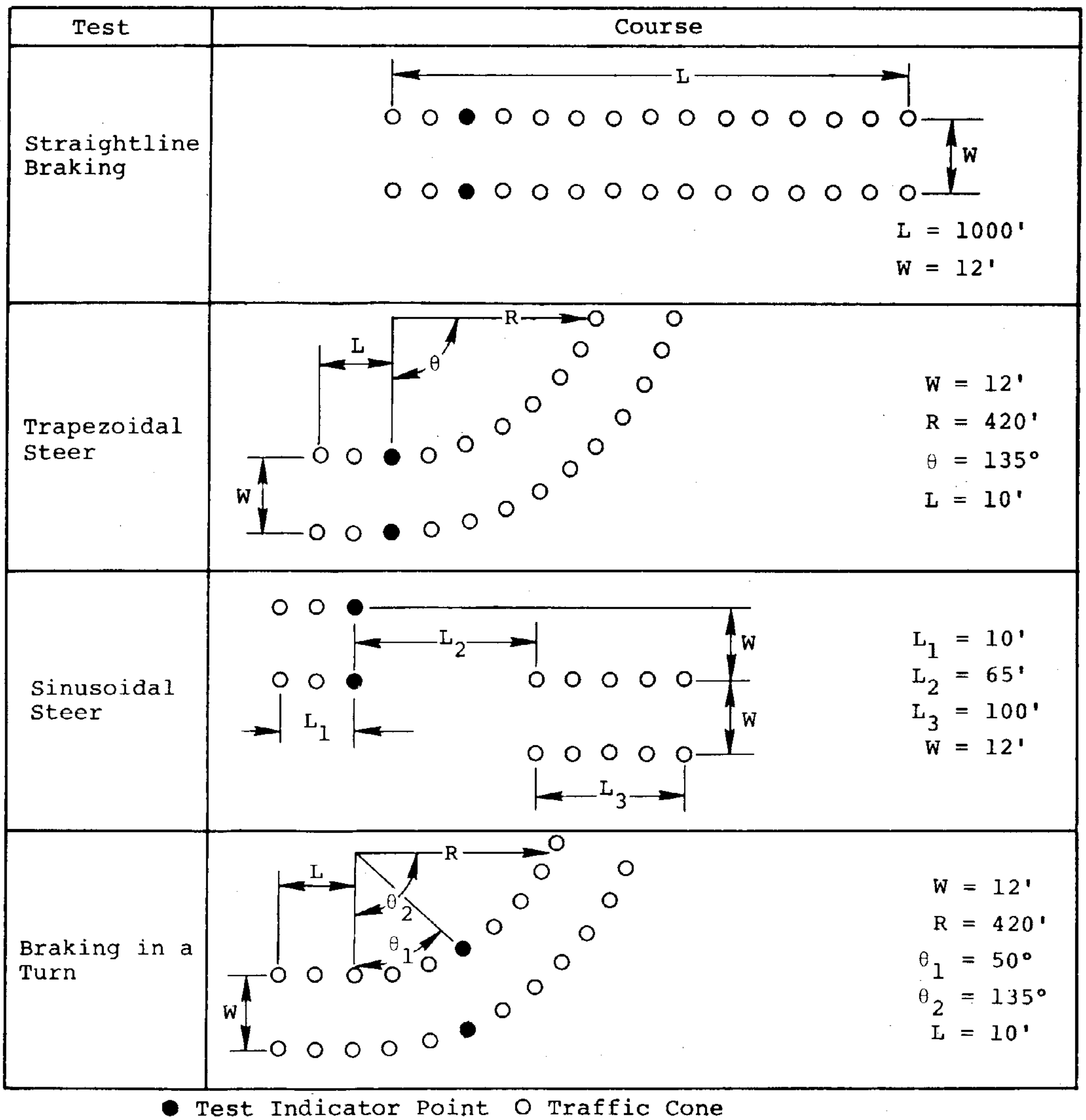


Figure 24. Test course reference markers.

Task	Checked by	Time
Record test conditions	________	________
Perform calibration of instruments	________	________
Check driver instructions	________	________
Check speed setting	________	________
Check tire pressure	________	________
Take pre-test photo	________	________
Position photographer	________	________
Alert observers	________	________
Verify recorders operational	________	________
Perform test	________	________
Take post-test photos	________	________
Take post-test comments and measurements	________	________
Check post-test condition of vehicle and prepare for next test	________	________

The test conditions recorded will include:

- Vehicle
- Weight (loading condition)
- Run direction
- Date
- Time
- Temperature
- Wind velocity
- Tire pressure
- Tire type (and condition)
- Surface conditions (wet or dry)
- Test speed
- Driver comments
- Observer comments

Figure 25. Pre-test checklist.

DAILY OPERATING LOG SHEET

TEST VEHICLE ______________________ DATE ______________

TEST ______________________

SHIFT ______________________

	START	FINISH
Temperature		
Wind		
Weather		

	ODOMETER
Finish	
Start	
Total	

Fluids added during start-up inspection:

- Fuel ______________ gal
- Ensure that the following fluid levels are as specified by the manufacturer

  engine oil ______________ transmission oil ______________

  brake fluid ______________ power steering ______________

  radiator ______________ battery ______________

Corrective action for deficiencies noted on previous day's log:

____

____

____

Fluids added at finish fill-up: Fuel ______________ gal

Deficiencies at end of day needing corrective action:

____

____

____

Operable: Yes __________ No __________

Operator ______________________

Figure 26. Daily operating log sheet.

6. Upon stopping the following items are recorded:
   - Stopping distance
   - Initial velocity
   - Number of cones knocked over
   - Driver's comments on vehicle stability
   - Observer's comments on vehicle stability
   - Stopping distance, d is corrected

$$d_{corrected} = d_{test} \text{ (40 mph/initial test speed)}^2$$

7. Two laps around the track are made before the next stop.

8. Steps 1 through 7 are repeated 3 additional times. The best performance is indicated by the stop that yields the smallest corrected stopping distance and stays within the lane.

9. For the Braking in a Turn on the wet surface the radius of the turn is 300 feet and the initiation speed is 30 mph.

3.4.1.2 Non-Braking Tests

The procedure for Trapezoidal Steer and Sinusoidal Steer is outlined below:

1. The vehicle is driven to approach the test course.

2. The vehicle speed is stabilized at the desired test speed and the Central Data Acquisition and Control Station is notified of start of test.

3. The vehicle is driven through the course maintaining speed and steered to stay within the lane.

4. Upon traversing the complete course, the vehicle is stopped and the following items are recorded:
   - Average speed through the course from the real-time line-type recorder.
   - Number of cones knocked over.
   - Driver's comments on vehicle stability.
   - Observer's comments on vehicle stability.
   - Trajectory measurements.

5. Steps 1 through 4 are repeated 3 additional times at higher initial velocity or until an unsafe vehicle response is observed.

3.4.2 Test Conditions

Tests were conducted on days with environmental conditions conducive to good photographic coverage and low winds.

Water was used as ballast for the liquid cargo tankers, and gallonage was removed or added as necessary to achieve desired volume for the various test configurations.

Ballast for the hanging meat tests was an actual meat load which was obtained from a local processor.

Ballast for the baseline van tests was concrete block, loaded as shown in Figure 27. These blocks have a greater density than typical cargo, resulting in a lower center of gravity for the baseline van. Thus the baseline results are biased toward non-stable performance, and comparisons between baseline and other vehicles tested should be evaluated with this in mind.

3.4.3 Data Operations

Each test run was documented on the Tape Data Log Sheet shown in Figure 28.

3.4.3.1 Data Reduction and Analysis

The test variables of interest included:

- Test speed
- Number of cones knocked over
- Stopping distance (braking tests)
- Peak steering wheel torque
- Number of steering reversals
- Front steering wheel angle in both directions
- Pedal force (braking tests)
- Longitudinal acceleration
- Lateral acceleration
- Yaw rate

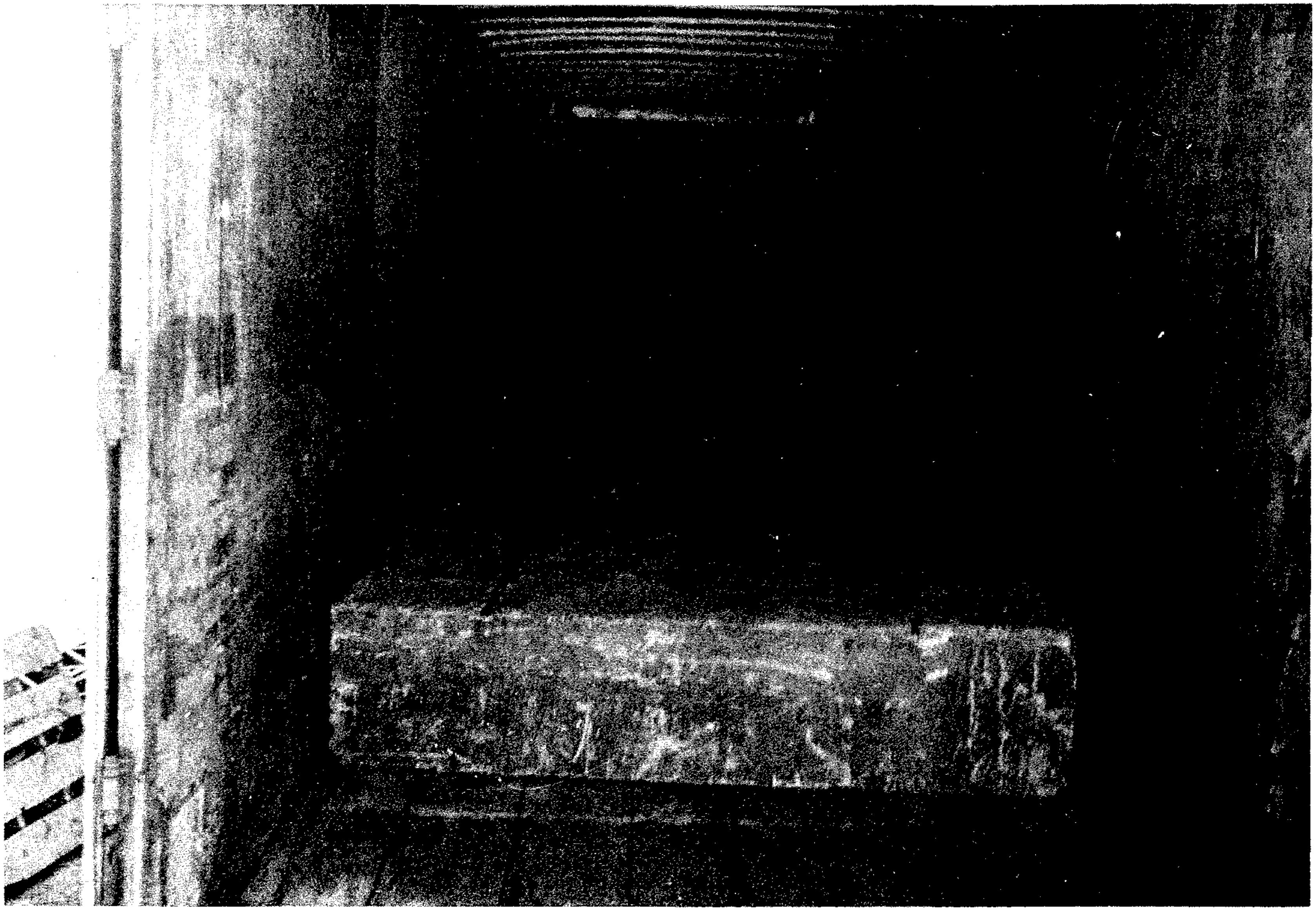


Figure 27. Ballast for baseline van tests.

TAPE DATA LOG

Vehicle: ______________ Project: ______________ Tape No: ______________

Vehicle Weight: ______________ Test Type: ______________ RSCM: ______________

Ambient Temperature: ______________ Wind Velocity: ______________ Test Date: ______________

Run Number	Chronological Description	Time Code Day	Hour	Min.	Sec.	Run Dir.	Sur. Cond.	Test Speed	No. Cones Hit		Observer Comments		Driver Comments	

DS Form 4065

Figure 28. Tape data log sheet.

- Roll rate and angle
- Tractor/trailer angle
- Wheel loads.

These data were tabulated and compared between vehicles, and an assessment of the magnitude of the effect of the shifting type cargo was made.

3.4.3.2 Input to Digital Analysis

The data generated during the testing (except camera data and stopping distance) were input to the Dynamic Science Accident Avoidance Computer Program (AVOID). The flow of the data is shown in Figure 29. The test data were converted from analog to digital form using a Hewlett-Packard 2100A minicomputer. A pre-sample filter of 6.3 Hz and a sample rate of 20 samples per second for each data channel were used. The digital data were then processed using the AVOID program.

<u>AVOID PROGRAM</u>

The AVOID program performed the following analysis on the test data:

- Converted the output of each instrument to engineering units.
- Computed trajectory parameters of the tractor using the following equations:

$$V_y = - \int (A_y + V_{xr})\, dt$$

$$V_x = V_{x_o} + \int (A_x + V_{yr})\, dt$$

and

$$y = \int (V_y \cos\psi + V_x \sin\psi)\, dt$$

$$x = \int (-V_y \sin\psi + V_x \cos\psi)\, dt$$

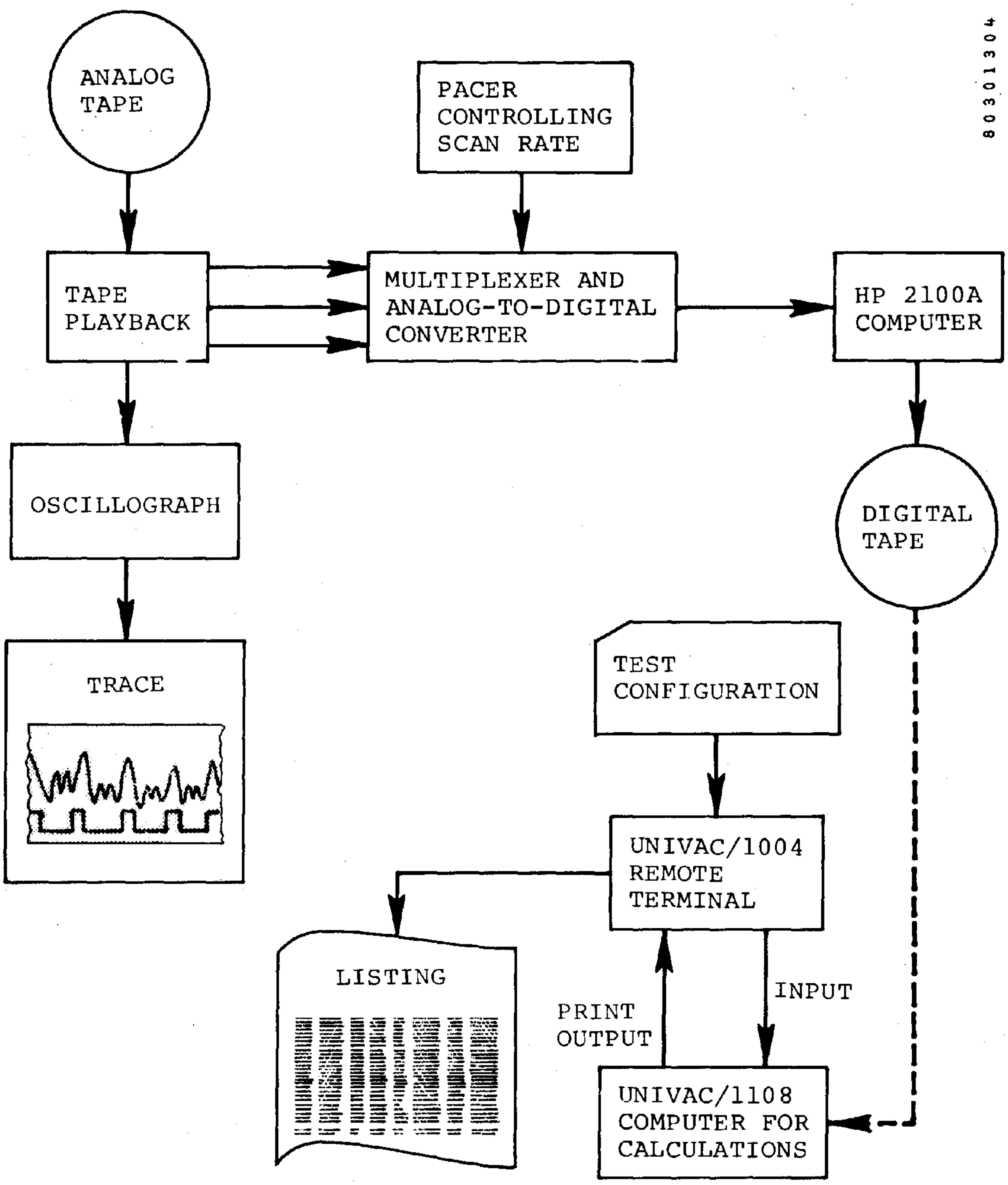


Figure 29. Data schematic.

where A_x = tractor longitudinal acceleration

A_y = tractor lateral acceleration

r = tractor yaw rate

ψ = tractor yaw position relative to some fixed time in the maneuver

V_x = tractor longitudinal velocity

V_y = tractor lateral velocity

x = longitudinal displacement of tractor from reference point

y = lateral displacement of tractor from reference point

V_{x_o} = the value of the fifth wheel at the reference point

Note: The reference points for the various maneuvers are:

Sinusoidal steer, wet and dry	
Trapezoidal steer, wet and dry	Initiation of Steer
Braking in a turn, dry	
Straight-line braking, wet and dry	Initiation of Braking
Braking in a turn, wet	2 Sec Before Initiation of Braking

- Tractor/trailer angle using the tractor/trailer displacement reading and the installation configuration of the displacement transducer.
- Front wheel angle using the front wheel displacement reading and the installation configuration of the displacement transducer.
- Trailer roll angle by integrating the trailer roll rate.

- The changes in the wheel loads on the pavement (relative to the steady state value for the particular load) using the following equation:

$$\text{Force on pavement generated by an axle side} = (Amass_i)(A_i) - (AK_i)(P_{ij})$$

where: $Amass_i$ = the mass of axle i

A_i = the acceleration of axle i

AK_i = the spring constant of the suspension for axle i

P_{ij} = the change in deflection (relative to steady state) for side j of axle i

Note: Three groups of axle parameters were used (front tractor, rear tractor, and trailer).

- To compensate for instrumentation drift, some of the instruments were zeroed at the following times for each test:

Just before reference point	Front wheel angle
At reference point	Yaw position
At end of test after vehicle is stopped	Fifth wheel velocity, yaw rate, longitudinal and lateral acceleration, suspension deflections, axle accelerations, tractor roll angle.

DATA PROCESSING

Two runs were processed for each maneuver for a load/trailer configuration; one run to represent a low effort case and the other to represent the limit case. Selected instrumentation check runs were also processed. The instrumentation check runs consisted of the following types of tests:

- Straight-line braking at a low level of pedal force.
- Traveling around an approximate 100-foot circle at constant speed.

The measured data and computed data were divided into two groups (one for each Remote Signal Conditioning Module [RSCM]*) and printed for each data point digitized during a test. Samples of computed data for each RSCM are included in Appendix C.

The first group was for instruments on the first RSCM and consisted of the following:

- Time (sec)
- Longitudinal acceleration of tractor (G)
- Lateral acceleration of tractor (G)
- Yaw rate of tractor (deg/sec)
- Heading of tractor (deg)
- Fifth wheel velocity at rear of trailer (ft/sec)
- Computed tractor longitudinal velocity (ft/sec)
- Computed tractor lateral velocity (ft/sec)
- Computed tractor longitudinal displacement referenced to vehicle coordinate system at time = 0 (ft)
- Right front wheel steer transducer displacement (in.)
- Right front wheel steer angle (deg)
- Tractor-trailer angle transducer displacement (in.)
- Tractor-trailer angle (deg)
- Roll angle of tractor (deg)
- Trailer roll rate (deg/sec)
- Trailer roll angle (deg)
- Steering wheel torque applied (ft/lb)
- Tractor right front axle vertical displacement (in.)
- Tractor left front axle vertical displacement (in.)
- Tractor front axle vertical acceleration (G)

*A Remote Signal Conditioning Module provides signal conditioning (amplifier) and frequency modulation (voltage controlled oscillator) for 14 data channels.

- Change from steady state in tractor right front wheel dynamic force (lb)
- Change from steady state in tractor left front wheel dynamic force (lb)
- Event marker (near 850 when activated).

The second group was for instruments on the second RSCM and consisted of the following:

- Time matched to RSCM #1 (sec)
- Tractor brake pedal force (lb)
- Trailer longitudinal acceleration (G)
- Tractor right front drive axle vertical displacement (in.)
- Tractor left front drive axle vertical displacement (in.)
- Tractor front drive axle vertical acceleration (G)
- Change from steady state in tractor right front drive wheels dynamic force (lb)
- Change from steady state in tractor left front drive wheels dynamic force (lb)
- Right rear drive axle vertical displacement (in.)
- Left rear drive axle vertical displacement (in.)
- Tractor rear drive axle vertical acceleration (G)
- Change from steady state in tractor right rear drive wheels dynamic force (lb)
- Change from steady state in tractor left rear drive wheels dynamic force (lb)
- Trailer right front axle vertical displacement (in.)
- Trailer left front axle vertical displacement (in.)
- Trailer front axle vertical acceleration (G)
- Change from steady state in trailer right front wheels dynamic force (lb)

- Change from steady state in trailer left front wheels dynamic force (lb)
- Trailer right rear axle vertical displacement (in.)
- Trailer left rear axle vertical displacement (in.)
- Trailer rear axle vertical acceleration (G)
- Change from steady state in trailer right rear wheels dynamic force (lb)
- Change from steady state in trailer left rear wheels dynamic force (lb)
- Event marker (correlated with RSCM #1).

The printout of each test was put on tape and sent to JHU/APL for validation of their computer model of the cargo shift dynamics. The tractor and trailer parameters were also sent to define each tractor/trailer configuration.

4.0 TEST RESULTS

The test maneuvers described in Section 3.4 were used to obtain information on longitudinal and lateral stability. The object of each of the test runs was to drive the tractor-trailer to a maximum performance limit within the confines of a twelve-foot-wide course laid out on the test track. The variable, then, was the driver's ability to drive as fast as possible around the turns (trapezoidal steer) and through the lane changes (sinusoidal steer), and to stop as quickly as possible in the braking maneuvers. As a result of the driver's opinions and those of outside observers as to when they felt the truck had performed to its maximum limit, and by using the electronic transducer information from the trailer, the testing was accomplished at or near the limits of the trucks' capabilities. Deviations from the course which knocked marker cones down was considered disqualifying, hence no mention is made in the results on the number of cones knocked over.

Typically, four runs were performed for each trailer-maneuver-load condition. The first run was at a low performance level for the purpose of driver familiarization, the second was at an intermediate level, and the last two runs were performed at what the driver and observers felt was a maximum performance level. The best results of these last two runs are presented in this section.

For the braking maneuvers, the stopping distance is shown in the tables, followed by a value in parentheses. This value is the ratio of the theoretically achievable stopping distance (in a sliding stop on that particular surface) to the measured stopping distance. The theoretically achievable value is determined by equating work done during the stop to kinetic energy dissipated:

$$Fd = \frac{1}{2} mV^2$$

where $F = mg\ C_f$ (that is, the product of the weight [mg] of the vehicle and the coefficient of friction)

d = stopping distance

m and V = mass and velocity of the vehicle

By making the substitutions shown and simplifying the equation, stopping distance becomes:

$$d = \frac{V^2}{2g\ C_f}$$

It should be noted that this is not a highly refined theoretical value of stopping distance, since it does not consider driver or system delay times. It should also be noted that C_f is the coefficient of sliding friction, and most stops are made without sliding the wheels but are made at incipient lockup, where a coefficient of static friction would be more applicable. There may be a significant difference between the coefficient of sliding and that of static friction, particularly on the low coefficient surfaces.

With these qualifications in mind, the parenthetical values can be considered quasi-braking efficiency which is useful in providing an approximate comparison of stopping with the different vehicle configurations and at different speeds. For braking tests, stopping distance and the braking efficiency factor were taken as the principal evaluation factors. Considering possible variations in driver actions and other variables common to such test procedure, a variation of ±10 percent in results is not considered significant, and evaluations and comparisons among the vehicles and vehicle configurations are made on this basis.

For the trapezoidal and sinusoidal steer maneuvers, two principal criteria are presented: (1) the maximum speed that the vehicle could be driven successfully through the course (with related driver comments and subjective evaluation) and (2) trailer roll angle. As in the braking tests, differences of less than 10 percent are not considered significant.

Data are presented in several formats:

- Section 4.1 presents a summary of performance for each vehicle as a function of load for each of the test maneuvers (Tables 6 through 10).
- Section 4.2 presents a summary of performance in each test maneuver for all vehicles in each of their respective configurations (Table 11 through Table 17 and graphical data in Figures 30 through 36).
- Section 4.3 presents a summary of all results, providing a convenient means of comparing vehicle performance (Table 18).

4.1 TEST PERFORMANCE LEVELS BY VEHICLE TYPE

Results of all tests for each vehicle are presented in this Section. Definitive test results such as stopping distance or attainable speed are presented, together with driver comments and observed control difficulties. The reader may find it convenient to refer to Figures 30 through 36 in Section 4.2 which provide graphical representations of the key evaluation parameters.

4.1.1 Baseline Van Trailer With Non-Shifting Ballast

The maximum levels of performance of the baseline trailer are presented in Table 6. A discussion of each of the maneuvers and a comparison of performance versus loading is contained in the following subsections.

Straight-line Braking - Dry and Wet Surface

Stopping distances at the different loads were within ±10 percent of the average. This is the variation that can be expected in a group of stops all conducted under the same condition. For this reason, the performance in all straight-line braking steps is considered to be equivalent and not a function of load.

No directional control problems were encountered with the baseline trailer when performing the dry surface stops. However, some directional control problems were encountered on the wet surface, with the truck at incipient jackknife with the brakes locked. The stopping distances on the wet surface were about double those obtained on the dry surface due to the reduced coefficient of friction.

Braking in a Turn - Dry and Wet Surface

Stopping distances again are within 10 percent of the average and can thus be considered equivalent. No directional control problems were encountered on the dry surface.

On the wet surface, some tendency towards jackknifing was encountered but was controlled by modulating the brakes. The wet surface stops were made with more efficient utilization of the roadway friction (achievable stopping distance divided by the actual stopping distance). As discussed in the introduction to this section, however, this is at least partially attributable to the coefficient of static friction being higher than the coefficient of sliding friction on this surface.

As noted earlier, the initiation speed for the wet surface stops was ten miles per hour slower than on the dry surface, and the turn radius was 300 feet rather than 420 feet.

Sinusoidal Steer - Dry Surface

The maximum speed at which the driver was able to negotiate the maneuver was essentially constant for the three load conditions. No directional control problems were experienced.

Table 6. Maximum performance levels for baseline trailer.

Test Maneuver	Nominal Test Initiation Speed (mph)	Pavement Condition and Skid Number	Maximum Performance — Loading (Total Vehicle Weight - lb) Unloaded (26,050)	One Half (46,440)	Full (66,160)
Straight-line Braking	40	Dry-78.1	159.8 feet (.44)	146.6 feet (.47)	142.1 feet (.49)
	40	Wet-20.4	302.5 feet (.95)	360.2 feet (.73)	337.1 feet (.78)
Braking While in a Turn	40	Dry-74.5	169.5 feet (.42)	140.8 feet (.50)	147.8 feet (.48)
	30	Wet-26.4	180.8 feet (.59)	167.1 feet (.68)	145.7 feet (.73)
Sinusoidal Steer	Note 1	Dry-78.1	47.7 mph	47.0 mph	47.2 mph
	Note 1	Wet-20.4	43.0 mph	40.8 mph	43.1 mph
Trapezoidal Steer	Note 1	Dry-74.5	47.6 mph	50.4 mph	47.7 mph

Note 1: The purpose of this test was to determine the maximum speed at which the maneuver could be performed.

Sinusoidal Steer - Wet Surface

The maximum speeds obtained were about equal for all loading conditions and about ten percent lower than the speeds obtained for the same maneuver on the dry surface. A small amount of fish-tailing was encountered as the vehicle completed the last turn in the maneuver.

Trapezoidal Steer - Dry Surface

No significant variation in maximum attainable speed as a function of load was encountered. No abnormal directional control problems were encountered.

4.1.2 High-Density Tank Trailer With Baffles

The maximum levels of performance of the high-density tank trailer with baffles are presented in Table 7. The maneuvers and a comparison of performance versus loading are discussed in the following subsections.

Straight-line Braking - Dry and Wet Surface

The stopping distance at 7/8 load was approximately 30 percent greater than at 1/2 load. Comparison with the baseline shows a slightly lower braking efficiency.

The measured stopping distances increased slightly with load due to small speed differences in the stops. The normalized (efficiency) values are approximately the same for each stop but about 20 percent lower than in the baseline stops. Some directional control problems were encountered with the truck tendency to jackknife if the brakes were locked on the wet surface.

Braking in a Turn - Dry Surface

The stopping distance increased slightly with increasing load but is not significantly different than baseline stops. No directional control problems were experienced.

Braking in a Turn - Wet Surface

The stopping distances tended to increase as the load was increased. Braking efficiencies are approximately the same as the straight-line wet surface runs with this vehicle configuration. Some jackknifing was encountered but was corrected by modulating the brakes. In general, the heavier the load, the more difficult it was to stop.

Table 7. Maximum performance levels for high-density tank trailer with baffles.

Test Maneuver	Nominal Test Initiation Speed (mph)	Pavement Condition and Skid Number	Maximum Performance Loading (Total Vehicle Weight - lb) One Half (45,660)	Three Quarters (56,280)	Seven Eighths (61,330)
Straight-line Braking	40	Dry-78.1	134.5 feet (.49)	165.8 feet (.42)	176.6 feet (.42)
	40	Wet-20.4	379.0 feet (.67)	409.8 feet (.67)	411.4 feet (.66)
Braking While in a Turn	40	Dry-74.5	145.3 feet (.53)	155.2 feet (.49)	162.7 feet (.46)
	30	Wet-26.4	165.8 feet (.72)	164.1 feet (.78)	192.5 feet (.64)
Sinusoidal Steer	Note 1	Dry-78.1	43.6 mph	45.5 mph	49.8 mph
	Note 1	Wet-20.4	40.6 mph	48.3 mph	46.7 mph
Trapezoidal Steer	Note 1	Dry-74.5	41.4 mph	46.7 mph	46.0 mph

Note 1: The purpose of this test was to determine the maximum speed at which the maneuver could be performed.

Sinusoidal Steer - Dry Surface

The maximum speed attained through the maneuver increased as the weight of the vehicle was increased. No directional control problems were encountered. The driver commented that the load felt more stable as the vehicle's weight was increased, and hence he could drive faster through the maneuver.

Sinusoidal Steer - Wet Surface

The performance with the three-quarter and seven-eighths loads was about equal, with the maximum speed from 15 to 20 percent higher than in the half-loaded condition. The driver indicated that a more stable feel with the two fuller loads allowed him to drive faster.

Trapezoidal Steer - Dry Surface

The performance with the three-quarter and seven-eighths loads was about equal. The half-loaded condition produced results about fifteen percent lower. The driver indicated that the half-load felt less stable.

4.1.3 High-Density Tank Trailer Without Baffles

The maximum levels of performance of the high-density tank trailer without baffles are presented in Table 8. A discussion of each of the maneuvers and a comparison of performance versus loading is contained in the following subsections.

Straight-line Braking - Dry Surface

The stopping distances were lowest (and most efficient) at the 1/2 load condition but, in general, approximated those made with the tank equipped with baffles. No directional control problems occurred during the performance of this maneuver.

Straight-line Braking - Wet Surface

The stopping distances decreased with increasing load with braking efficiencies approximating (except for 1/2 load) those obtained in the baseline test and better than obtained with the tank with baffles. Some directional control problems were encountered with the truck trying to jackknife if the brakes were locked.

Braking in a Turn - Dry Surface

The stopping distance decreased with increasing load but can be considered equivalent. No directional control problems were encountered.

Table 8. Maximum performance levels for high-density tank trailer without baffles.

Test Maneuver	Nominal Test Initiation Speed (mph)	Pavement Condition and Skid Number	Maximum Performance — Loading (Total Vehicle Weight - lb): One Half (43,910)	Three Quarters (52,480)	Seven Eighths (56,760)
Straight-line Braking	40	Dry-78.1	145.7 feet (.51)	177.8 feet (.41)	164.7 feet (.42)
	40	Wet-20.4	383.6 feet (.72)	367.6 feet (.77)	338.2 feet (.85)
Braking While in a Turn	40	Dry-74.5	163.5 feet (.48)	160.5 feet (.47)	147.0 feet (.49)
	30	Wet-26.4	184.7 feet (.66)	196.7 feet (.63)	204.7 feet (.62)
Sinusoidal Steer	Note 1	Dry-78.1	44.0 mph	47.8 mph	44.9 mph
	Note 1	Wet-20.4	46.6 mph	46.0 mph	45.5 mph
Trapezoidal Steer	Note 1	Dry-74.5	45.8 mph	47.7 mph	47.5 mph

Note 1: The purpose of this test was to determine the maximum speed at which the maneuver could be performed.

Braking in a Turn - Wet Surface

The stopping distance became slightly longer as the load was increased with braking efficiencies at all three load conditions being lower than for the tank with baffles. Some tendency towards jackknifing was encountered but was corrected by modulating the brakes.

Sinusoidal Steer - Dry Surface

The maximum speed at which the driver was able to negotiate the maneuver was approximately the same for the one-half and seven-eighths loaded conditions. The speed attained for the three-quarter load was about eight percent higher. No directional control problems were experienced.

Sinusoidal Steer - Wet Surface

The maximum attainable speeds were about equal for all loading conditions and were approximately the same as the speeds obtained for the same maneuver on the dry surface. Some fishtailing was encountered as the vehicle completed the last turn in the maneuver.

Trapezoidal Steer - Dry Surface

The maximum speeds attained were approximately equal for all loading conditions. No abnormal directional control problems were encountered.

4.1.4 Low-Density Tank Trailer With Baffles

The maximum levels of performance of the low-density tank trailer are presented in Table 9. The maneuvers are discussed in the following subsections.

Straight-line Braking - Dry Surface

The stopping distance was essentially the same as with the high-density tank trailer with baffles. No directional control problems were encountered.

Straight-line Braking - Wet Surface

The stopping distance was the shortest measured with any vehicle configuration under this condition. Some directional control problems occurred due to a tendency for the truck to jackknife with the brakes locked.

Table 9. Maximum performance levels for low-density tank trailer with baffles.

Test Maneuver	Nominal Test Initiation Speed	Pavement Condition and Skid Number	Maximum Performance Loading - Three Quarters (76,030 lb - Total Vehicle Weight)
Straight-line Braking	40	Dry-78.1	166.7 feet (.43)
	40	Wet-20.4	310.7 feet (.87)
Braking While in a Turn	35	Dry-74.5	118.3 feet (.49)
	30	Wet-26.4	176.7 feet (.68)
Sinusoidal Steer	Note 1	Dry-78.1	36.0 mph
	Note 1	Wet-20.4	37.8 mph
Trapezoidal Steer	Note 1	Dry-74.5	37.5 mph

Note 1: The purpose of this test was to determine the maximum speed at which the maneuver could be performed.

Braking in a Turn - Dry Surface

Test initiation speed was from 35 mph rather than 40 mph due to the vehicle's inability to negotiate the 420-foot radius turn at a greater speed. Braking efficiency was the same as with the high-density tank with baffles. No directional control problems were experienced.

Braking in a Turn - Wet Surface

The stopping distance was within 8 percent of that achieved in stops with the high density tank with baffles.

Some jackknifing was encountered but was corrected by modulating the brakes.

Sinusoidal Steer - Dry Surface

No directional control problems were encountered when performing this maneuver. The attainable speed was lower than that for the baseline vehicle and that of the other tankers.

Sinusoidal Steer - Wet Surface

Some fishtailing occurred as the vehicle completed the second turn in the maneuver. Attainable speed was about equal to that of the baseline vehicle and the other tankers.

Trapezoidal Steer - Dry Surface

No significant directional control problems occurred. The driver felt that this load was relatively unstable and tailored his performance accordingly. The vehicle tended to roll considerably.

4.1.5 Refrigerated Trailer With Hanging Meat

The maximum levels of performance of the refrigerated trailer containing hanging meat are presented in Table 10. The maneuvers are discussed in the following subsections.

Table 10. Maximum performance levels for refrigerated trailer with hanging meat.

Test Maneuver	Nominal Test Initiation Speed (mph)	Pavement Condition and Skid Number	Maximum Performance: Loading - Full (69,690 lb - Total Vehicle Weight)
Straight-line Braking	40	Dry-78.1	184.2 feet (.37)
	40	Wet-20.4	322.7 feet (.87)
Braking While in a Turn	27	Dry-74.5	79.8 feet (.43)
	22	Wet-26.4	94.7 feet (.68)
Sinusoidal Steer	Note 1	Dry-78.1	27.2 mph
	Note 1	Wet-20.4	26.6 mph
Trapezoidal Steer	Note 1	Dry-74.5	31.6 mph

Note 1: The purpose of this test was to determine the maximum speed at which the maneuver could be performed.

Straight-line Braking - Dry Surface

Braking efficiency was the lowest of any recorded, indicating low utilization of the available friction.

No directional control problems were encountered when performing this maneuver.

Straight-line Braking - Wet Surface

Braking efficiencies were on the same order as those measured with the other vehicle configurations. Some directional control problems occurred due to a tendency for the truck to jackknife with the brakes locked.

Braking in a Turn - Dry Surface

Test initiation speed was from 27 mph rather than 40 mph due to the vehicle's inability to negotiate the 420-foot radius turn used for dry surface tests at a greater speed. As in the dry surface straight-line stops, braking efficiencies were the lowest recorded. No significant directional control problems were experienced.

Braking in a Turn - Wet Surface

Test initiation speed was from 22 mph rather than 30 mph due to the vehicle's inability to negotiate the 300-foot radius curve used for wet surface tests at a greater speed. Braking efficiencies were on the same order as those measured with previous vehicle configurations. During the maximum performance test run, the vehicle jackknifed slightly to the right while traversing the left-hand curve.

Sinusoidal Steer - Dry Surface

No directional control problems were encountered at the speed at which this maneuver was performed. Considerable sway of the trailer resulted during the maximum limit test run.

Sinusoidal Steer - Wet Surface

No directional control problems were experienced. The maximum speed attained was approximately the same as that for the dry surface. There was less trailer sway than during the same maneuver performed on the dry surface. The driver felt that the load was slightly more stable when going through the wet maneuver as compared to the dry maneuver at the same speed.

Trapezoidal Steer - Dry Surface

The vehicle rolled considerably during this maneuver. The driver had to make a significant correction in steering wheel angle during the maximum performance test run in order to avert wheel lift-off and a possible tipover.

4.2 COMPARISON OF VEHICLE PERFORMANCE BY TEST MANEUVER

The following sections summarize the test data for each of the seven maneuvers performed during the program. These sections contain tables for each maneuver which compare the results of all five of the test vehicles at their various loading conditions. Graphs are provided for convenient comparison of vehicle performance for each test.

The tables containing the data for the braking maneuvers list the following test variables:

- Loading
- Total vehicle weight
- Estimated center of gravity height
- Test run number
- Test initiation speed
- Minimum stopping distance.
- Peak brake pedal force
- Peak tractor deceleration
- Peak trailer deceleration
- Peak tractor roll
- Peak trailer roll
- Peak tractor-trailer angle
- Peak steering wheel torque.

The tables with the data for the trapezoidal and sinusoidal steer maneuvers list the following test variables:

- Loading
- Total vehicle weight
- Estimated center of gravity height
- Test run number
- Maximum velocity attained
- Peak tractor lateral acceleration
- Peak tractor yaw rate
- Peak tractor-trailer angle
- Peak tractor front wheel angle
- Peak tractor roll
- Peak trailer roll
- Peak steering wheel torque.

All data were filtered with analog filters (cutoff frequency 6.3 Hz), then digitized. Analyses and values presented were all taken from the digital data. Peak values presented are instantaneous peak values from the digital data.

4.2.1 Straight-line Braking - Dry Surface

Test vehicle data for the straight-line braking maneuver on a dry surface are presented in Table 11 and Figure 30.

Comparisons of stopping distances and brake efficiency factors between vehicles and loads indicate that the vehicles with shifting cargoes had poorer braking performance with their larger loads than did the baseline trailer with non-shifting cargo at equivalent loads. The trailer with hanging meat performed poorest of all vehicles.

The films of the five pieces of hanging meat in the refrigerated trailer showed them to move forward in unison as the braking was begun. They remained there until the stop was completed, at which time they swung back to a vertical position.

4.2.2 Straight-line Braking - Wet Surface

Test vehicle data for maximum performance runs of the straight-line braking maneuver on a wet surface are presented in Table 12 and Figure 31.

Table 11. Data for straight-line braking - dry surface.

Vehicle	Baseline Trailer With Non-Shifting Ballast			Refrigerated Trailer With Hanging Meat	Low-Density Petroleum Tank Trailer	High-Density Tank Trailer With Baffles			High-Density Tank Trailer Without Baffles		
Loading	Empty	1/2	Full	Full	3/4	1/2	3/4	7/8	1/2	3/4	7/8
Total Vehicle Weight (lb)	26,050	46,440	66,160	69,690	76,030	45,660	56,280	61,330	43,910	52,480	56,760
Estimated Center of Gravity Height (in.)	57	67	68	98	73	64	67	71	68	72	74
Test Run Number	71	39	122	8	17	11	91	150	24	106	148
Initiation Speed (mph)	40.5	39.95	40.2	40.0	40.9	39.1	40.4	41.5	41.7	41.3	40.4
Minimum Stopping Distance (ft)	159.8	146.6	142.1	184.2	166.7	134.5	165.8	176.6	145.7	177.8	164.7
Braking "Efficiency" Factor	.44	.47	.49	.37	.43	.49	.42	.42	.51	.41	.42
Peak Brake Pedal Force (lb)	55.0	95.3	90.4	29.4	95.0	81.3	67.4	103.8	71.6	57.3	77.9
Peak Tractor Deceleration (G)	.6	.65	.63	.45	.53	.88	.64	.49	.78	.49	.6
Peak Trailer Deceleration (G)	.55	.58	.59	.7	.46	.81	.48	.42	.67	.46	.44
Peak Tractor Roll (deg)	No Gyro	1.0	.7	.8	.5	1.2	.7	.8	.8	.5	.8
Peak Trailer Roll (deg)	1.5	1.1	3.7	.7	.6	1.1	.4	.8	1.0	1.3	1.0
Peak Tractor-Trailer Angle (deg)	1.0	1.2	.3	1.0	.5	.1	.2	.2	.1	.6	.1
Peak Steering Wheel Torque (ft-lb)	7.0	6.0	2.5	7.6	4.7	2.5	2.9	2.5	.7	1.7	1.4

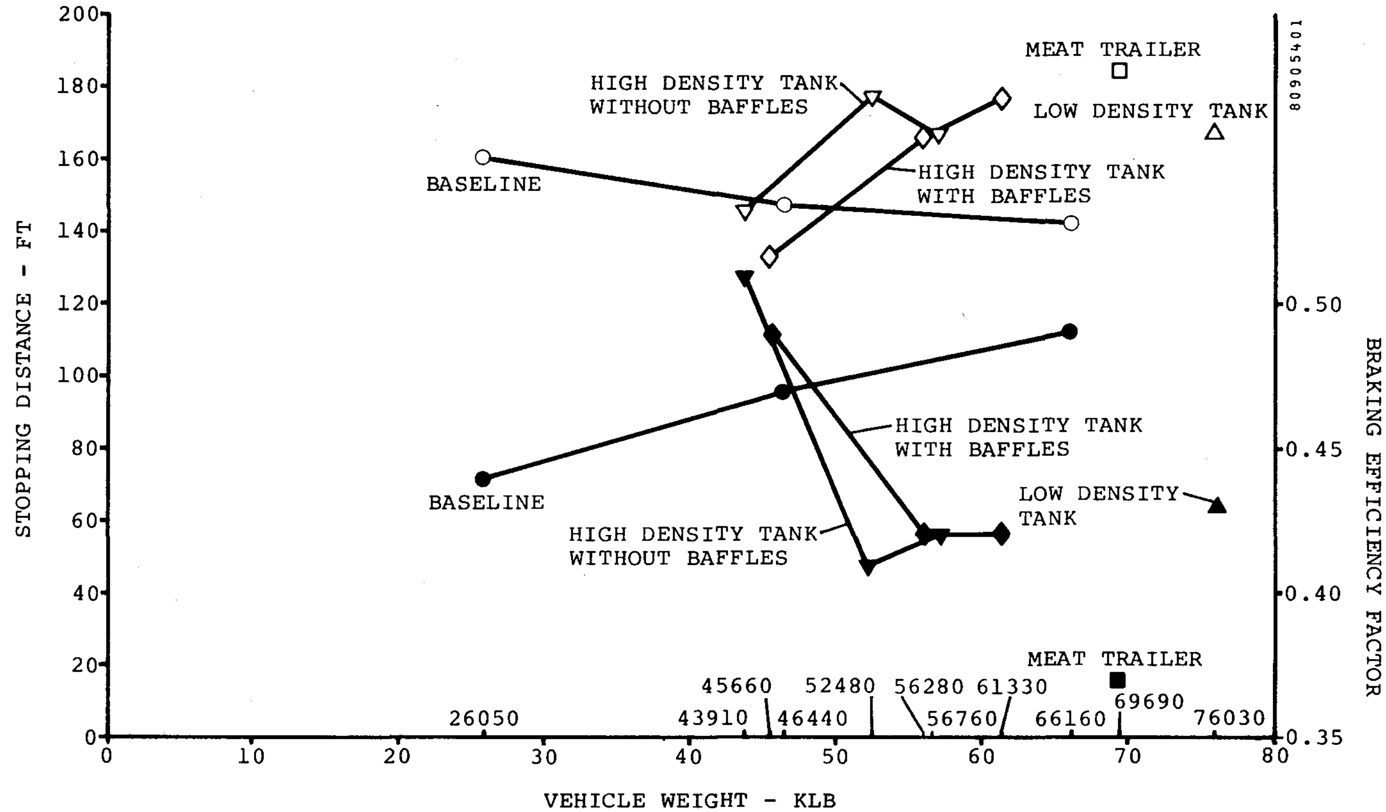


Figure 30. Braking (dry surface) results.

Table 12. Data for straight-line braking - wet surface.

Vehicle	Baseline Trailer With Non-Shifting Ballast			Refrigerated Trailer With Hanging Meat	Low-Density Petroleum Tank Trailer	High-Density Tank Trailer With Baffles			High-Density Tank Trailer Without Baffles		
Loading	Empty	1/2	Full	Full	3/4	1/2	3/4	7/8	1/2	3/4	7/8
Total Vehicle Weight (lb)	26,050	46,440	66,160	69,690	76,030	45,660	56,280	61,330	43,910	52,480	56,760
Estimated Center of Gravity Height (in.)	57	67	68	98	73	64	67	71	68	72	74
Test Run Number	85	90	174	36	34	45	130	174	59	93	138
Initiation Speed (mph)	41.8	40.0	40.0	41.3	40.6	39.3	41.1	40.6	41.2	41.7	41.8
Minimum Stopping Distance (ft)	302.5	360.2	337.1	322.7	310.7	379.0	409.8	411.4	383.6	367.6	338.2
Braking "Efficiency" Factor	.95	.73	.78	.87	.87	.67	.67	.66	.72	.77	.85
Peak Brake Pedal Force (lb)	58.0	43.9	51.4	57.3	40.0	60.3	68.8	68.3	31.8	51.3	66.5
Peak Tractor Deceleration (G)	.3	.35	.38	.37	.39	.35	.35	.38	.37	.43	.5
Peak Trailer Deceleration (G)	.32	.35	.31	.33	.35	.37	.34	.33	.26	.36	.35
Peak Tractor Roll (deg)	No Gyro	.9	1.0	1.1	.6	1.0	.8	.6	1.8	.7	.9
Peak Trailer Roll (deg)	.5	1.0	2.5	1.1	4.4	.9	.8	.7	1.8	2.2	2.0
Peak Tractor-Trailer Angle (deg)	4.0	.8	.6	4.0	.6	.5	.2	.9	.7	.2	.4
Peak Steering Wheel Torque (ft-lb)	8.9	3.2	1.7	16.0	5.9	2.5	3.6	2.7	2.5	1.2	3.1

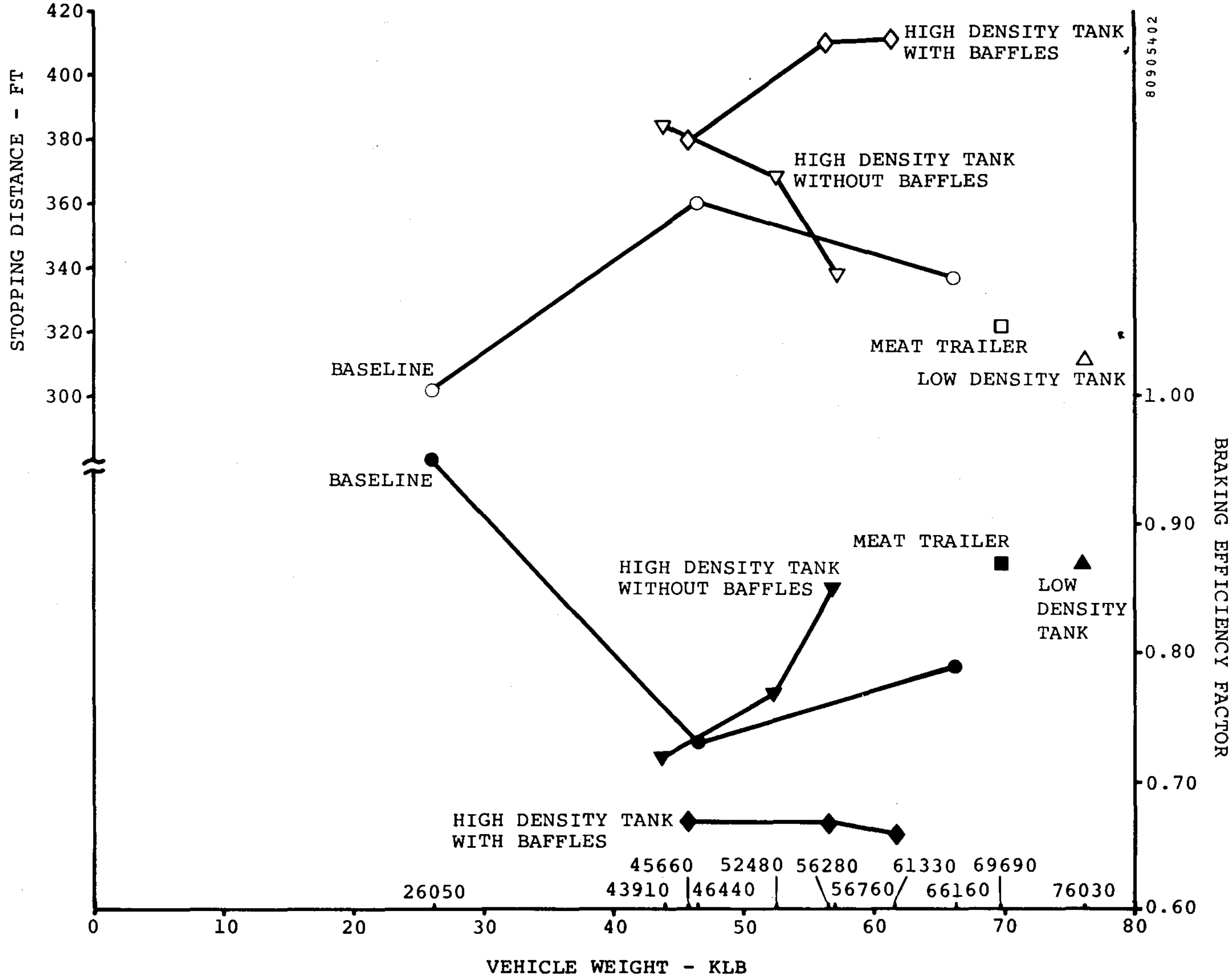


Figure 31. Braking (wet surface) results.

At higher loads the tanker trailers and meat trailer performed within 10 percent of the baseline vehicle except that the high density tanker with baffles was significantly poorer in performance (in both stopping distance and brake efficiency factors). This difference cannot be explained from the test results. For all vehicles, brake efficiency factor was better for the wet surface than for the dry surface.

The films of the hanging meat in the refrigerated trailer showed it to behave as it had for dry surface braking.

4.2.3 Braking in a Turn - Dry Surface

Test vehicle data for the braking in a turn maneuver on a dry surface are presented in Table 13 and Figure 32.

The baffled and unbaffled high-density tank trailers had somewhat the same stopping distance trend as they did in the previous maneuver - the unbaffled tank stopping slightly faster the heavier it was, and the baffled tank stopping in a greater distance as the load increased. Both, however, took approximately the same distance as the correspondingly loaded baseline trailer. With the unbaffled tank there would be a reduced tendency for sloshing cargo when the tank carries a higher volume of liquid.

Direct comparisons between the low-density tank trailer or refrigerated trailer with hanging meat and the baseline trailer cannot be made due to the fact that neither of these vehicles with shifting cargoes could negotiate the 420-foot radius course at the desired test initiation speed. The amount of speed reduction necessary to stay on the course is indicative of the degree of instability induced by the shifting cargo.

The trailer containing the load of hanging meat had a significantly higher initial center of gravity than the other vehicles and the films indicate a shift in the center of gravity of about eight inches laterally and one to two inches vertically due to the turn. During braking, the meat swung forward and as the vehicle speed was reduced with the corresponding decrease in centrifugal force, it moved back inward toward the center of the turn.

The low-density tank trailer had an estimated center of gravity height of 73 inches which was only five inches above that of the correspondingly loaded baseline trailer. Its performance during braking was not unusual, but the reduced speed around the course was necessitated by a substantial shift of its center of gravity to the outside of the turn. It is estimated that the shift was about five inches laterally.

Table 13. Data for braking in a turn - dry surface.

Vehicle	Baseline Trailer With Non-Shifting Ballast			Refrigerated Trailer With Hanging Meat	Low-Density Petroleum Tank Trailer	High-Density Tank Trailer With Baffles			High-Density Tank Trailer Without Baffles		
Loading	Empty	1/2	Full	Full	3/4	1/2	3/4	7/8	1/2	3/4	7/8
Total Vehicle Weight (lb)	26,050	46,440	66,160	69,690	76,030	45,660	56,280	61,330	43,910	52,480	56,760
Estimated Center of Gravity Height (in.)	57	67	68	98	73	64	67	71	68	72	74
Test Run Number	51	44	144	31	31	26	111	169	40	126	166
Initiation Speed (mph)	39.9	39.8	39.6	27.6	36.0	41.6	41.3	40.9	41.8	40.9	40.2
Minimum Stopping Distance (ft)	169.5	140.8	147.8	79.8	118.3	145.3	155.2	162.7	163.5	160.5	147.0
Braking "Efficiency" Factor	.42	.50	.48	.43	.49	.53	.49	.46	.48	.47	.49
Peak Brake Pedal Force (lb)	64.0	66.1	88.2	53.5	72.3	68.7	65.2	73.6	65.0	70.8	76.2
Peak Tractor Deceleration (G)	.45	.58	.61	.7	.56	.67	.55	.51	.7	.59	.61
Peak Trailer Deceleration (G)	.44	.51	.53	.47	.48	.61	.49	.41	.59	.58	.5
Peak Tractor Roll (deg)	No Gyro	3.5	3.3	4.1	1.9	3.8	4.3	4.8	2.5	2.6	2.9
Peak Trailer Roll (deg)	1.2	2.7	5.4	4.1	8.7	6.3	3.0	4.2	2.0	2.8	2.5
Peak Tractor-Trailer Angle (deg)	2.2	3.2	4.7	4.9	3.9	4.0	4.5	4.0	4.1	3.5	4.0
Peak Steering Wheel Torque (ft-lb)	6.1	5.9	5.7	21.7	10.0	4.4	5.9	6.1	2.7	5.0	2.5

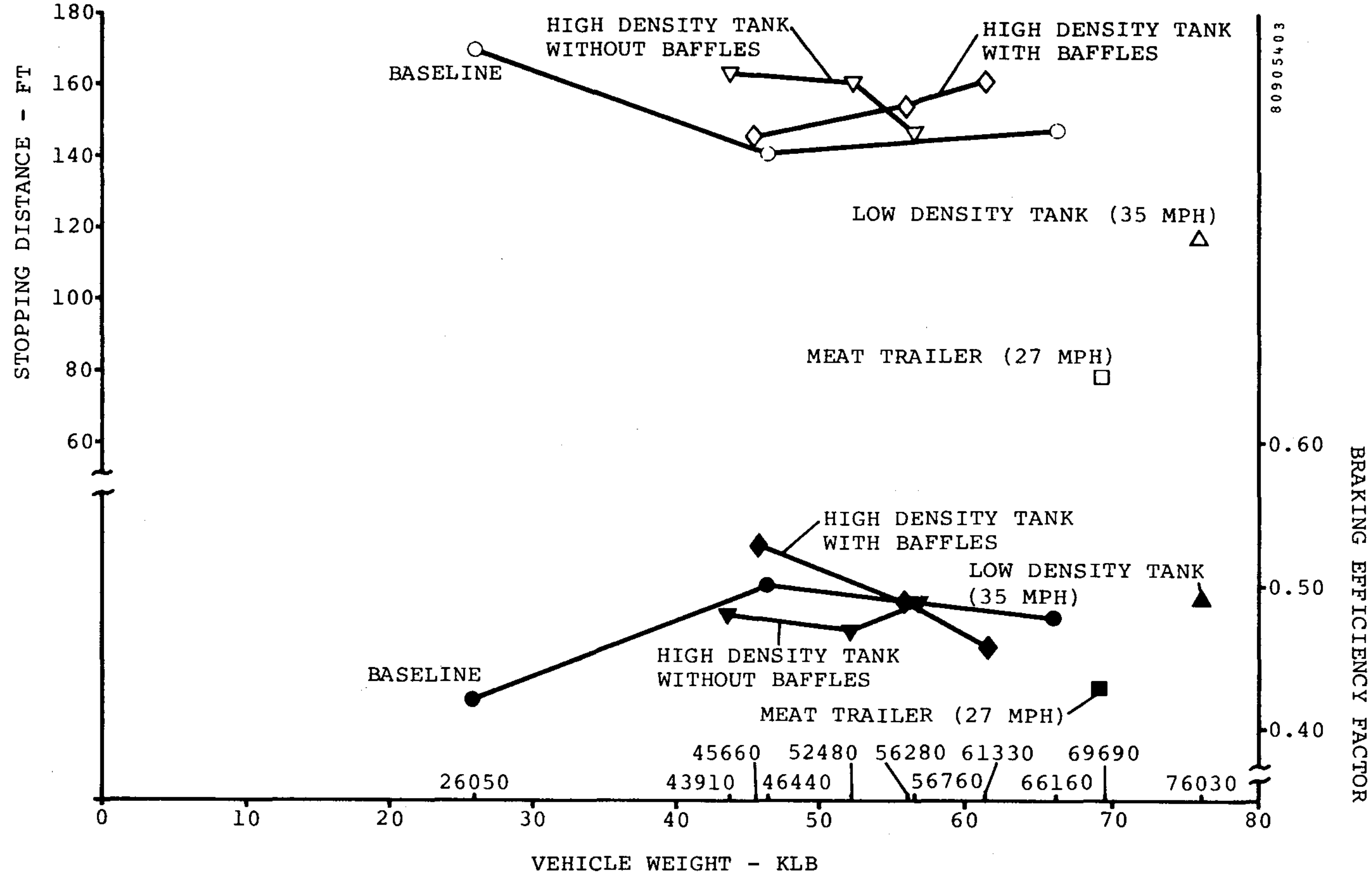


Figure 32. Braking in a turn (dry surface) results.

4.2.4 Braking in a Turn - Wet Surface

Test vehicle data for maximum performance runs of the braking in a turn maneuver on a wet surface are presented in Table 14 and Figure 33.

The baffled and unbaffled high-density tank trailers had similar stopping distance trends in this maneuver. That is, they both tended to take longer to stop as the loads became heavier. At the highest load, they both performed approximately the same. At the lower loads, however, the baffled tank produced the shortest stopping distances.

The low density tank truck stopped in an uneventful manner during this maneuver and had a stopping distance commensurate with its load.

The refrigerated trailer with hanging meat was unable to negotiate the 300-foot radius course used for wet surface tests at the desired speed of 30 mph due to instability. It successfully performed the maneuver from an initial speed of 22 mph. During the stop with this vehicle, the meat swung forward and stayed as in previously described braking maneuvers. The tractor brakes locked momentarily and the vehicle started a slight jackknife to the right. As the vehicle had been traversing a left-hand course, the sudden change in direction of the trailer to the right caused the beef to swing left relative to the inside of the trailer and consequently, towards the inside of the turn. This maneuver was apparently stabilized by this motion.

4.2.5 Sinusoidal Steer - Dry Surface

Test vehicle data for maximum performance runs of the sinusoidal steer maneuver on a dry surface are presented in Table 15 and Figure 34.

The maximum speeds attained by the baseline trailer through the course for all three of its loading conditions were about equal. The driver felt that the change in load with the corresponding small increase in height of vehicle center of gravity had no significant effect on stability.

The two high-density tank trailers had centers of gravity factors similar to the baseline vehicle for their larger loads. They attained test speeds close to that of the baseline with no directional control problems or instabilities noted.

The peak roll angles for the high density tank trailers were 56 to 100 percent higher than that of the baseline trailer. Suspension spring rates may influence roll, and comparison of roll angles could be normalized to spring rates; however, suspension properties were not available so absolute roll angles will be compared here with this caution in mind.

Table 14. Data for braking in a turn - wet surface.

Vehicle	Baseline Trailer With Non-Shifting Ballast			Refrigerated Trailer With Hanging Meat	Low-Density Petroleum Tank Trailer	High-Density Tank Trailer With Baffles			High-Density Tank Trailer Without Baffles		
Loading	Empty	1/2	Full	Full	3/4	1/2	3/4	7/8	1/2	3/4	7/8
Total Vehicle Weight (lb)	26,050	46,440	66,160	69,690	76,030	45,660	56,280	61,330	43,910	52,480	56,760
Estimated Center of Gravity Height (in.)	57	67	68	98	73	64	67	71	68	72	74
Test Run Number	98	111	187	47	43	55	142	189	80	86	133
Initiation Speed (mph)	29.1	30.0	29.0	22.5	30.9	30.7	31.8	31.2	31.0	31.3	31.6
Minimum Stopping Distance (ft)	180.8	167.1	145.7	94.7	176.7	165.8	164.1	192.5	184.7	196.7	204.7
Braking "Efficiency" Factor	.59	.68	.73	.68	.68	.72	.78	.64	.66	.63	.62
Peak Brake Pedal Force (lb)	41.5	37.6	70.0	39.4	37.1	41.0	46.3	59.8	52.1	58.7	46.7
Peak Tractor Deceleration (G)	.25	.36	.39	.35	.34	.37	.43	.33	.39	.41	.4
Peak Trailer Deceleration (G)	.26	.33	.43	.33	.38	.33	.41	.4	.3	.39	.3
Peak Tractor Roll (deg)	No Gyro	3.1	2.9	3.2	3.1	3.4	3.9	3.0	3.1	3.8	3.0
Peak Trailer Roll (deg)	1.8	2.8	4.9	2.4	4.6	2.2	3.5	2.3	1.4	1.3	5.2
Peak Tractor-Trailer Angle (deg)	4.6	2.9	2.3	3.0	3.3	4.0	2.2	4.1	2.6	4.1	3.7
Peak Steering Wheel Torque (ft-lb)	8.8	4.8	3.9	9.8	16.0	4.9	4.5	4.3	5.5	3.9	3.3

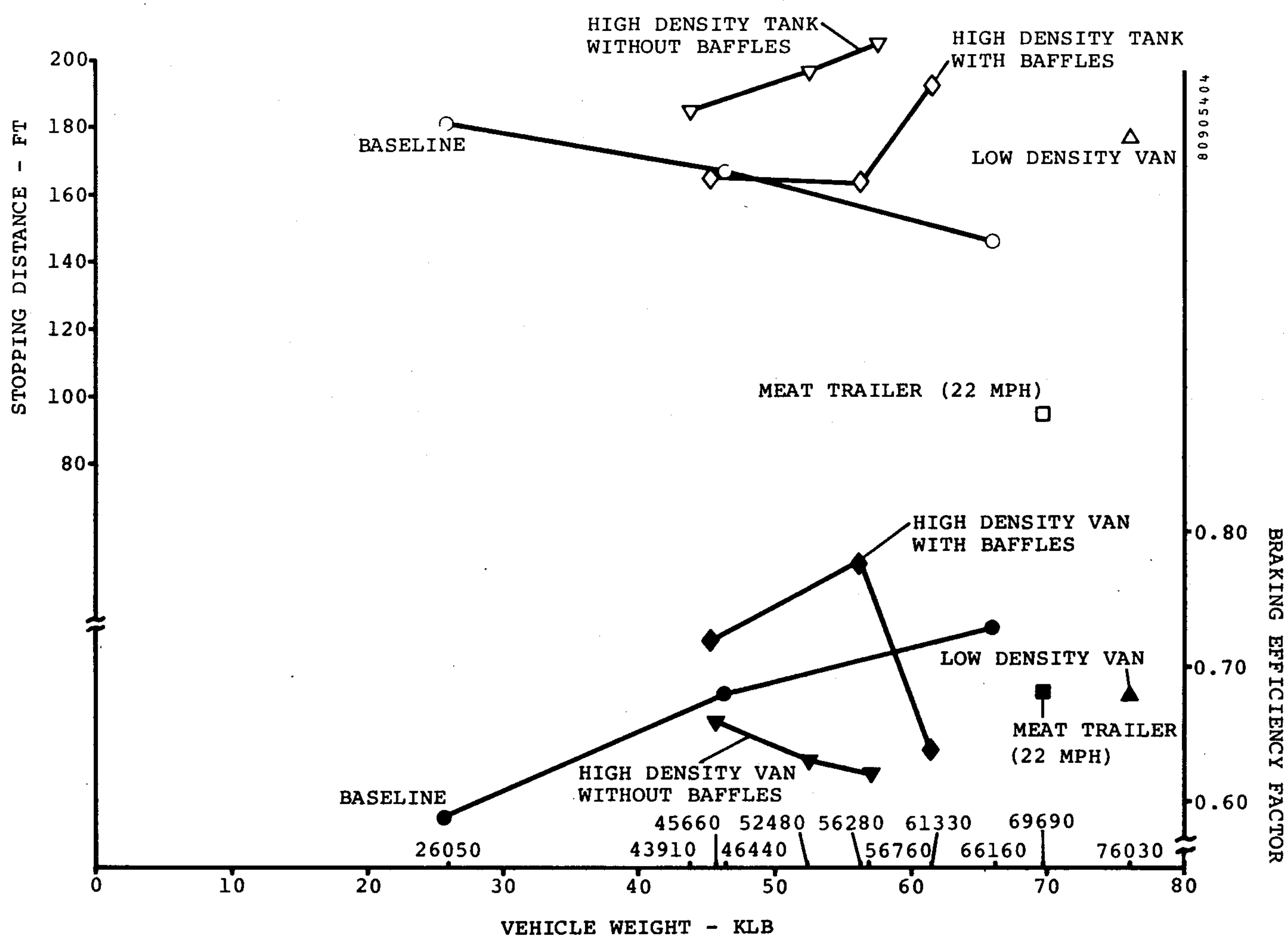


Figure 33. Braking in a turn (wet surface) results.

Table 15. Data for sinusoidal steer - dry surface.

Vehicle	Baseline Trailer With Non-Shifting Ballast			Refrigerated Trailer With Hanging Meat	Low-Density Petroleum Tank Trailer	High-Density Tank Trailer With Baffles			High-Density Tank Trailer Without Baffles		
Loading	Empty	1/2	Full	Full	3/4	1/2	3/4	7/8	1/2	3/4	7/8
Total Vehicle Weight (lb)	26,050	46,440	66,160	69,690	76,030	45,660	56,280	61,330	43,910	52,480	56,760
Estimated Center of Gravity Height (in.)	57	67	68	98	73	64	67	71	68	72	74
Test Run Number	8	17	127	22	20	17	76	159	29	115	154
Maximum Velocity (mph)	47.7	47.0	47.2	27.6	36.0	43.6	45.5	49.8	44.0	47.8	44.9
Peak Tractor Lateral Acceleration (G)	.41*	.38	.39	.24	.3	.25	.22	.3	.31	.35	.32
Peak Tractor Yaw Rate (deg/sec)	9.5*	11.9	10.6	10.5	12.4	9.7	7.4	11.1	10.7	12.5	11.4
Peak Tractor-Trailer Angle (deg)	4.1	3.8	4.5	5.8	5.8	5.9	5.8	6.8	5.6	5.3	5.9
Peak Tractor Front Wheel Angle (deg)	4.1	4.4	4.6	5.0	4.7	3.1	2.7	3.7	3.9	4.2	4.2
Peak Tractor Roll (deg)	No Gyro	3.1	3.0	2.4	2.4	2.8	2.2	2.7	2.8	3.2	2.9
Peak Trailer Roll (deg)	2.0	1.5	1.7	5.9	6.2	3.3	2.5	3.2	1.6	2.8	2.6
Peak Steering Wheel Torque (ft-lb)	13.0	5.5	4.8	21.6	20.0	4.5	6.0	5.3	5.8	6.1	5.5

*Trailer data prior to relocation of gyros to tractor.

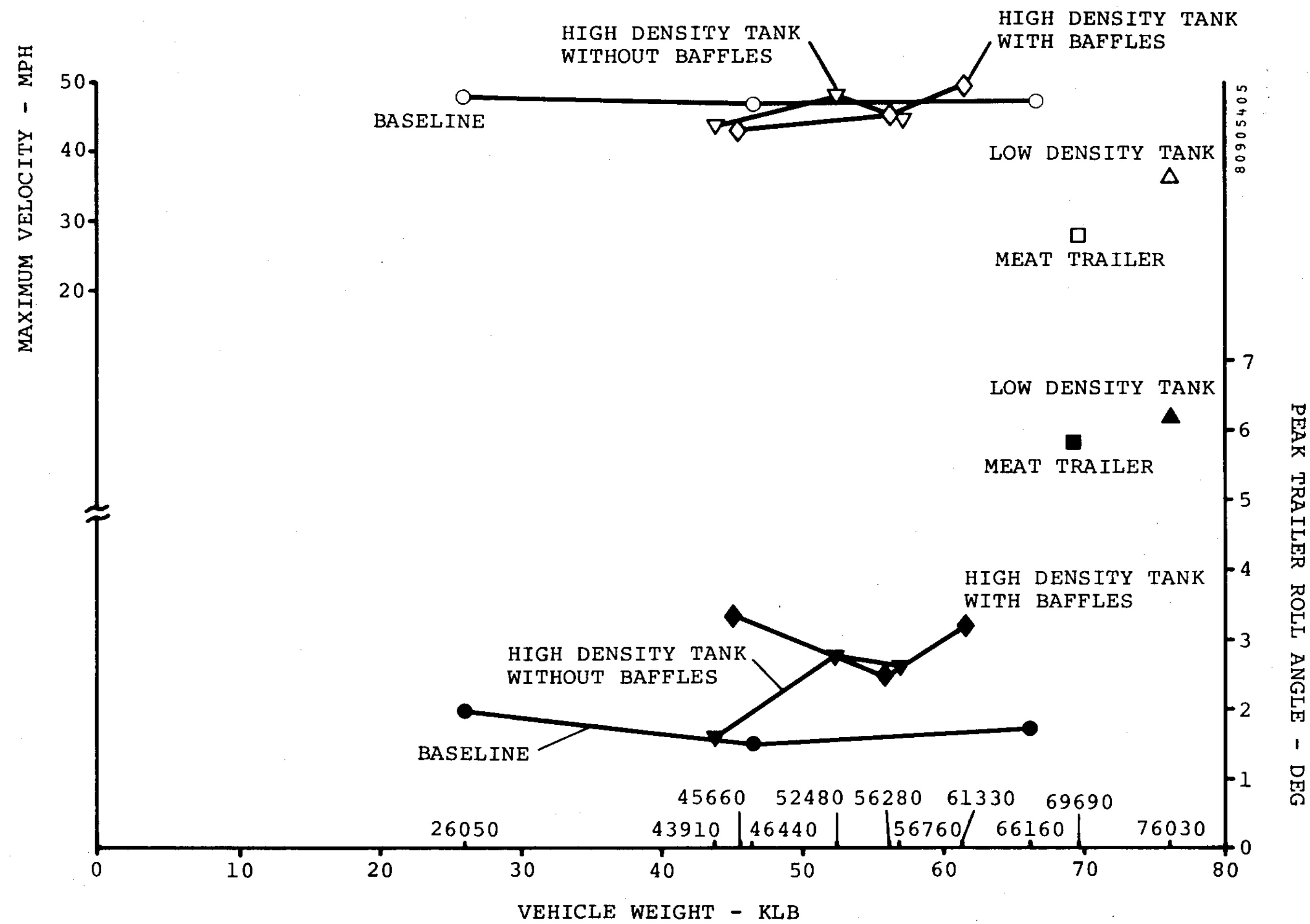


Figure 34. Sinusoidal steer (dry surface) results.

The low-density tank trailer's speed through the maneuver was 24 percent lower than that of the baseline trailer. Its center of gravity was about 7 percent higher and some allowance must be given due to its somewhat higher total weight. The peak trailer roll angle experienced by this vehicle was three times that of the baseline vehicle. The steering wheel torque was also higher. These measurements indicate that stability was less than in the baseline vehicle and that more driver effort was required to control the vehicle through the maneuvers.

The maximum speed at which the meat trailer was able to negotiate the lane change maneuver was 41 percent lower than that of the baseline trailer. The center of gravity of the baseline trailer was approximately 31 percent lower than that of the meat trailer. The films of the behavior of the hanging meat showed that as the vehicle first turned to the right at the beginning of the maneuver, the meat came off of the right wall and compressed together against the left wall. As soon as the turn was reversed back to the left to complete the lane change, the meat came off of the left wall and compressed together against the right wall. When the vehicle straightened at the end of the maneuver, the meat settled back to the vertical position. The driver felt that after the initial turn to the right, the load shifts during subsequent turns back to the left and to straighten the vehicle did not greatly influence vehicle stability.

Peak vehicle roll angle was over three times that of the baseline and over twice that of the high density tank trailers. Peak steering wheel torque was also highest for the meat trailer. These results indicate greater instability and greater effort required by the driver to negotiate the course.

4.2.6 Sinusoidal Steer - Wet Surface

The test vehicle data for maximum performance runs of the sinusoidal steer maneuver on a wet surface are presented in Table 16 and Figure 35.

Little difference was noted in the attainable speeds for the baseline and high density trailers on the wet surface compared to the dry surface. The baseline experienced a greater roll angle on the wet surface and high density tankers experienced roll angles two to three times greater on the wet surface. The low density tanker and the meat trailer performed about the same as on the dry surface. Thus they were less stable than the other vehicles. (Note, however, that the high density tanker with baffles had a higher peak roll angle at its highest load.)

Table 16. Data for sinusoidal steer - wet surface.

Vehicle	Baseline Trailer With Non-Shifting Ballast			Refrigerated Trailer With Hanging Meat	Low-Density Petroleum Tank Trailer	High-Density Tank Trailer With Baffles			High-Density Tank Trailer Without Baffles		
Loading	Empty	1/2	Full	Full	3/4	1/2	3/4	7/8	1/2	3/4	7/8
Total Vehicle Weight (lb)	26,050	46,440	66,160	69,690	76,030	45,660	56,280	61,330	43,910	52,480	56,760
Estimated Center of Gravity Height (in.)	57	67	68	98	73	64	67	71	68	72	74
Test Run Number	90	64	182	42	39	51	137	186	64	98	144
Maximum Velocity (mph)	43.0	40.8	43.1	26.6	37.8	40.6	48.3	46.7	46.6	46.0	45.5
Peak Tractor Lateral Acceleration (G)	.35*	.31	.23	.16	.26	.23	.24	.17	.3	.3	.24
Peak Tractor Yaw Rate (deg/sec)	7.5*	10.2	7.2	7.7	9.0	8.3	7.7	9.5	9.7	10.5	7.5
Peak Tractor-Trailer Angle (deg)	5.8	4.4	4.0	5.0	4.4	5.1	4.0	4.9	5.9	6.1	5.8
Peak Tractor Front Wheel Angle (deg)	5.0	5.1	3.8	4.4	5.0	4.1	4.0	4.8	4.7	3.1	5.0
Peak Tractor Roll (deg)	No Gyro	2.8	2.3	2.5	2.0	2.5	3.2	3.2	2.9	2.4	2.3
Peak Trailer Roll (deg)	2.1	2.7	3.2	5.6	5.5	5.8	6.0	7.7	3.8	4.3	5.1
Peak Steering Wheel Torque (ft-lb)	10.1	5.2	5.7	18.7	17.0	5.1	4.8	5.0	4.5	4.6	5.1

*Trailer Data prior to relocation of gyros to tractor.

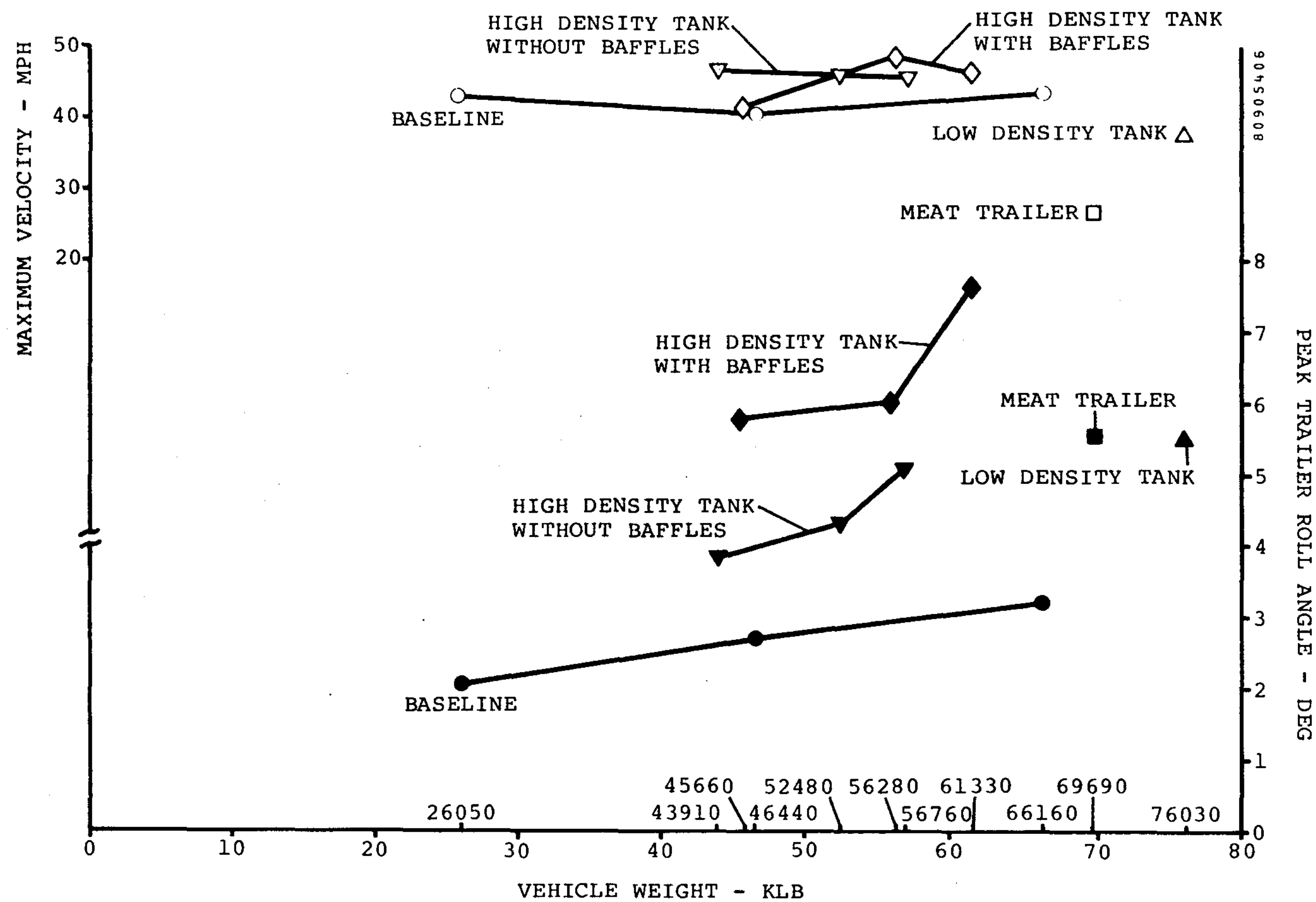


Figure 35. Sinusoidal steer (wet surface) results.

The trailer with meat appeared to sway less through the maneuver and the film record of the hanging meat showed the same behavior as described in the previous section but with slightly less swinging.

4.2.7 Trapezoidal Steer - Dry Surface

The test vehicle data for maximum performance runs of the trapezoidal steer maneuver on a dry surface are presented in Table 17 and Figure 36.

The maximum speeds attained by the baseline trailer through the course were about equal for the empty and fully loaded condition.

As with the sinusoidal steer on the dry surface, the two high-density tank trailers had speeds and centers of gravity similar to the baseline vehicle for their larger loads. Their maximum attainable speeds were slightly lower than for the baseline but their peak roll angles were two to three times higher than the baseline.

The low density tank trailer's speed through the maneuver was about 21 percent lower than that of the baseline trailer. Its center of gravity was about seven percent higher. The peak steering wheel torque and the amount of peak trailer roll angle experienced were significantly higher for this vehicle than for the baseline. These measurements indicate that stability was less and that more driver effort was required to control the low density trailer through the maneuver.

The maximum speed that the meat trailer was able to negotiate the trapezoidal steer maneuver was 34 percent lower than the baseline trailer's speed. The center of gravity of the baseline trailer was approximately 31 percent lower than that of the meat trailer. The films of the behavior of the hanging meat showed that as the vehicle entered the 420-foot radius left-hand turn from the straight course, the meat came off of the left wall of the trailer, compressed together against the right wall, and stayed there throughout the maneuver. Some of the pieces of meat originally adjacent to the left wall swung as much as 16 degrees to the right before being stopped by the compressed stack of the other pieces. An analysis of the film for the maximum performance run resulted in an estimate that the center of gravity moved 9.7 inches to the right and 2.1 inches upward. This horizontal and vertical movement would contribute significantly to an unstable condition. During the maximum performance run at the point of greatest center of gravity change, the driver felt that a significant steer angle change towards reducing the rate of turn was necessary to keep the trailer wheels on the pavement. The driver made the correction to the right and continued successfully along the trapezoidal course. The film shows the piece of meat which was

Table 17. Data for trapezoidal steer - dry surface.

Vehicle	Baseline Trailer With Non-Shifting Ballast			Refrigerated Trailer With Hanging Meat	Low-Density Petroleum Tank Trailer	High-Density Tank Trailer With Baffles			High-Density Tank Trailer Without Baffles		
Loading	Empty	1/2	Full	Full	3/4	1/2	3/4	7/8	1/2	3/4	7/8
Total Vehicle Weight (lb)	26,050	46,440	66,160	69,690	76,030	45,660	56,280	61,330	43,910	52,480	56,760
Estimated Center of Gravity Height (in.)	57	67	68	98	73	64	67	71	68	72	74
Test Run Number	38	53	138	24	25	32	126	164	35	121	162
Maximum Velocity (mph)	47.6	50.4	47.7	31.6	37.5	41.4	46.7	46.0	45.8	47.7	47.5
Peak Tractor Lateral Acceleration (G)	.48*	.54	.38	.21	.31	.29	.35	.3	.35	.4	.45
Peak Tractor Yaw Rate (deg/sec)	10.0*	15.8	10.0	7.5	8.5	9.5	11.2	11.6	9.3	13.2	11.5
Peak Tractor-Trailer Angle (deg)	4.2	6.0	4.7	5.9	3.8	6.7	4.0	4.5	4.0	4.5	4.5
Peak Tractor Front Wheel Angle (deg)	3.5	5.4	2.8	2.5	2.2	3.0	4.0	3.0	3.1	4.0	2.9
Peak Tractor Roll (deg)	No Gyro	8.6	5.8	5.0	4.0	4.1	5.0	5.8	5.0	5.9	3.3
Peak Trailer Roll (deg)	2.3	3.7	6.7	7.9	10.0	6.0	12.9	15.7	3.3	8.7	9.0
Peak Steering Wheel Torque (ft-lb)	12.2	7.1	6.3	9.6	12.9	3.5	5.6	3.8	5.6	6.0	5.1

*Trailer data prior to relocation of gyros to tractor.

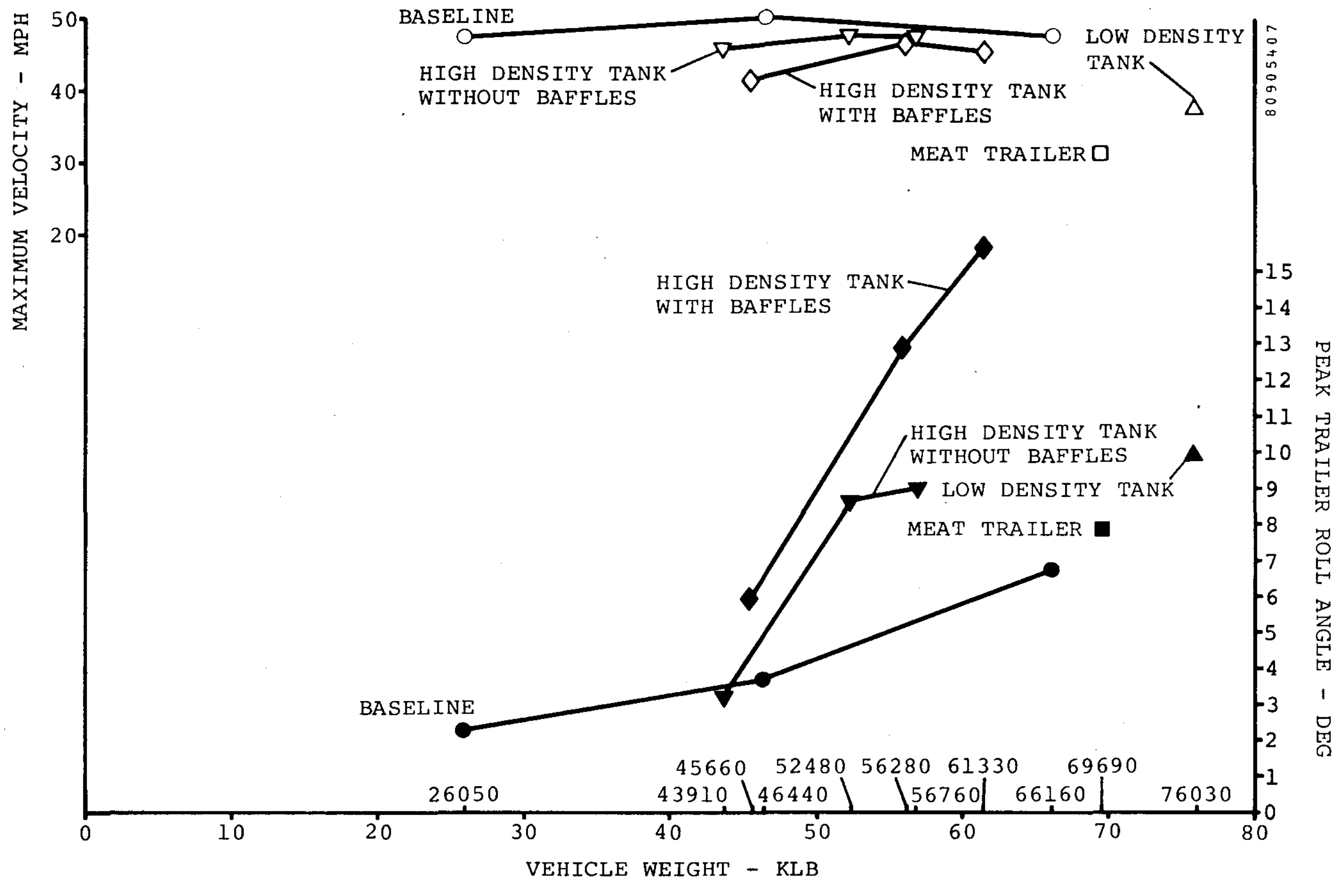


Figure 36. Trapezoidal steer (dry surface) results.

displaced farthest (16 degrees), swinging back to 6 degrees and then returning to a relatively steady state position of approximately 10 degrees displacement for the remainder of the maneuver. This piece of meat was in the aft section of the trailer which had a very loosely packed configuration (there were no pieces hanging from the center rail) and could therefore swing considerably. The forward section of the trailer was packed tightly and the piece adjacent to the left wall swung only 12 degrees initially, moved to about 7 degrees displacement after the driver took corrective action, and subsequently returned to about 10 degrees displacement for the remainder of the maneuver.

Peak steering wheel torque and trailer roll angle measured during the maneuver were significantly greater than those of the baseline trailer and were indicative of increased instability and extra driver effort needed to control the vehicle.

4.3 SUMMARY AND DISCUSSION OF RESULTS

In the two previous sections, detailed quantitative results were presented by discussing the test results for each vehicle and then by comparing vehicle performance in each of the seven tests to which they were subjected.

To put results into proper relative perspective, the significant findings are summarized in Table 18. These findings are discussed on a test-by-test basis in this section.

4.3.1 Braking Test Results

All vehicles with shifting types of cargo experienced a longitudinal kick or surge at initial brake application, caused by the cargo shifting as the vehicle begins to stop and before the cargo is restrained by forward bulkheads (liquid cargo) or hook swing travel (hanging cargo). Initially, these vehicles' deceleration rates are relatively high, become noticeably reduced when the load catches up, and then behave like vehicles carrying non-shifting cargo for the remaining major portion of the stopping period. This phenomenon indicates that during braking maneuvers, the shifting cargoes move forward against their restraints or bulkheads and remain there until the stop is completed. (This was verified by the films in the case of the trailer with hanging meat.) A sloshing fore and aft condition is not indicated during this type of maneuver.

The effect of the surge on overall stopping distance and hence vehicle safety is thought to be minimal. During this test program, it was our opinion that longitudinal surge during the braking maneuvers primarily affected the driver's willingness to stop in a minimum distance. The driver remarked that he could feel the surge, and to counteract this, reduced his braking effort.

Table 18. Summary of results.

	Baseline	High Density Tank With Baffles	High Density Tank Without Baffles	Low Density Tank With Baffles	Meat Trailer
Dry Braking					
Variation with load	No significant variation	Improved as load increased	Improved as load increased	Not applicable	Not applicable
Vehicle comparison	Best at higher loads	Tankers and meat trailer within 12%	Tankers and meat trailer within 12%	Tankers and meat trailer within 12%	Tankers and meat trailer within 12%
Directional control	No difficulty	No difficulty	No difficulty	No difficulty	Jackknife tendency when brakes lock
Wet Braking					
Comparison to dry	More efficient	More efficient	More efficient	More efficient	More efficient
Variation with load	Performance decreased as load increased	Performance decreased as load increased	Performance improved as load increased	Not applicable	Not applicable
Vehicle comparison	Less efficient than other vehicles except high density tank with baffles	Least efficient of all vehicles	Higher efficiency than baseline	Higher efficiency than baseline	Higher efficiency than baseline
Directional control	Jackknife tendency	Jackknife tendency	Jackknife tendency	Jackknife tendency	Jackknife tendency
Dry Braking in a Turn					
Variation with load	Improvement for higher loads	Slight improvement for higher load	Slight degradation for higher loads	Not applicable	Not applicable
Vehicle comparison	Better than high density tankers	Performance slightly less than baseline	Performance slightly less than baseline	Efficiency close to other vehicles; stopping distance less due to lower initial speed	Efficiency close to other vehicles; stopping distance less due to lower initial speed
Directional control	No difficulty	No difficulty	No difficulty	No difficulty	No difficulty
Stability	No difficulty	No difficulty	No difficulty	Speed reduced to 35 mph in order to negotiate turn	Speed reduced to 27 mph in order to negotiate turn

Table 18. Summary of results (contd).

	Baseline	High Density Tank With Baffles	High Density Tank Without Baffles	Low Density Tank With Baffles	Meat Trailer
Wet Sinusoidal Steer					
Comparison to Dry	More roll, lower attainable speed	More roll, lower attainable speed	More roll, lower attainable speed	More roll, lower attainable speed	More roll, lower attainable speed
Variation with load	None	Attainable speed constant, roll angle increased with load	Attainable speed constant, roll angle increased with load	Not applicable	Not applicable
Vehicle comparison	Attainable speed close to high density trailers	Attainable speed close to baseline	Attainable speed close to baseline	Attainable speed lower than baseline	Lowest attainable speed
Directional control	Slight fishtailing	No difficulty	Fishtail tendency	Fishtail tendency	No difficulty
Stability	Lowest roll angle, most stable	Greatest roll angle	Roll angle close to low density tanker and meat trailer	Roll angle close to high density tanker without baffles	Roll angle close to high density tanker without baffles
Dry Trapezoidal Steer					
Variation with load	Attainable speed constant, roll angle increased with load	Attainable speed constant, roll angle increased with load	Attainable speed constant, roll angle increased with load	Not applicable	Not applicable
Vehicle comparison	Attainable speed close to high density tankers, lowest roll angle	Attainable speed close to baseline, greatest roll angle	Attainable speed close to baseline, intermediate roll angle	Attainable speed slightly lower than baseline, intermediate roll angle	Lowest attainable speed, intermediate roll angle
Directional control	No difficulty	No difficulty	No difficulty	No difficulty	No difficulty
Stability	Lowest roll angle, most stable	Greatest roll angle	Intermediate stability	Intermediate stability	Intermediate stability

Table 18. Summary of results (contd).

	Baseline	High Density Tank With Baffles	High Density Tank Without Baffles	Low Density Tank With Baffles	Meat Trailer
Wet Braking in a Turn					
Comparison to dry	More efficient	More efficient	More efficient	More efficient	More efficient
Variation with load	Improvement for higher loads	Slight degradation for higher loads	Slight degradation for higher loads	Not applicable	Not applicable
Vehicle comparison	Better than tankers	Close to other tankers	Close to other tankers	Close to other tankers	Efficiency close to other vehicles; stopping distance less due to lower initial speed
Directional control	Jackknife tendency	Jackknife tendency	Jackknife tendency	Jackknife tendency	Jackknife tendency
Stability	No difficulty	No difficulty	No difficulty	No difficulty	Speed reduced to 22 mph in order to negotiate turn
Dry Sinusoidal Steer					
Variation with load	None	None	None	Not applicable	Not applicable
Vehicle Comparison	Attainable speed higher than high density tankers	Attainable speed lower than baseline	Attainable speed lower than baseline	Attainable speed lower than baseline high roll angle	Lowest attainable speed high roll angle
Directional control	No difficulty	No difficulty	No difficulty	No difficulty	No difficulty
Stability	Lowest roll angle, most stable	Greater roll angle than baseline, less stable than baseline	Greater roll angle than baseline, less stable than baseline	Greatest roll angle, least stable	Roll angle almost equal to low density tanker; stability slightly better than low density tanker

For dry surface braking the baseline vehicle performed best at the higher loads. The vehicles with shifting loads were less efficient as the load increased. The meat trailer was the only vehicle exhibiting directional control difficulty (jackknifing).

Wet surface braking was more efficient (relative to theoretically achievable performance) than dry surface braking. For higher loads, all vehicles except the high density tanker with baffles performed better than the baseline. On the wet surface all vehicles showed a directional control problem, tending to jackknife, requiring corrective action by the driver.

4.3.2 Braking in a Turn Test Results

As for the straight-line braking, during braking in a turn tests, shifting cargoes moved laterally during the turn and forward at brake application but no surge or sloshing affecting the vehicle performance was observed.

For dry surface tests, some degradation in performance was observed with increasing load except for the high density tanker without baffles, which improved with increasing load. The baseline and high density tankers were close in performance. The low density tanker and meat trailer could not negotiate the turn at the nominal speed (40 mph) and their initial speeds had to be reduced to 35 mph and 27 mph, respectively, indicating stability problems at these conditions. No directional control difficulties were encountered for any vehicles.

For wet surface braking in a turn tests, all vehicles were braked more efficiently than for the dry surface. The baseline vehicle performance improved as load increased, the tanker's performance degraded. The baseline vehicle performance was better than those with shifting cargo. The meat trailer initial speed was reduced from the nominal 30 mph to 22 mph in order that it could safely negotiate the turn, indicating less stability than the other vehicles. No directional control difficulties were encountered.

4.3.3 Sinusoidal Steer Test Results

The baseline vehicle performed better than other vehicles during sinusoidal steer tests. For dry surface tests the attainable speed for the baseline vehicle was a little higher than that of the high density tankers and significantly higher than the low density tanker and meat trailer. There was no significant variation with load.

The poorer stability of the vehicles with shifting cargo was further demonstrated by peak roll angles during the maneuver; the high density tankers had roll angles about twice that of the baseline and the low density tanker, and meat trailer roll angles were each about three times that of the basline. No directional control problems were encountered.

Similar results were obtained for wet surface sinusoidal steer tests. On wet surface, attainable speeds were essentially the same as for dry surface tests. Roll angles for the wet surface were higher with the shifting cargo vehicles showing significantly greater increases than the baseline. Fishtailing was observed on all vehicles except the high density trailer with baffles and the meat trailer.

4.3.4 Trapezoidal Steer Test Results

Trapezoidal steer tests were consistent with the sinusoidal steer tests. The attainable speed was higher for the baseline than for the high density tankers and significantly higher than for the low density tanker and the meat trailer. There was no significant variation with load.

Roll angles were higher in the trapezoidal steer tests and increased significantly with load. All vehicles with shifting loads had significantly higher roll angles than the baseline, especially the high density tanker with baffles. No directional control problems were encountered.

5.0 RECOMMENDATIONS

This test program was undertaken to determine, by full-scale testing, how dynamic cargo shifting affects the braking performance and lateral/roll stability of articulated trucks. Reviewing all the data presented in the preceding sections, test results can be summarized as follows:

- The baseline was braked with greater efficiency and shorter stopping distance on the dry surface. For shifting cargo vehicles the driver perceived the cargo movement forward and compensated for it which contributed to this result. On the wet surface some of the shifting cargo vehicles made better use of the available friction and were stopped more efficiently. We can correctly conclude that shifting cargo vehicles do brake differently and require more driver skill.

- In braking in a turn tests, shifting cargo vehicles tested at the same initial speed as the baseline were stopped with about equal or lower efficiency than the baseline and required greater stopping distances. As for straight-line braking, all vehicles were stopped with greater efficiency (used available friction more efficiently) on wet surfaces, but, of course, required greater stopping distance because of the lower friction. The low density tanker and meat trailer could not be driven through turns at speeds as great as the other vehicles, indicating less lateral stability.

- In sinusoidal steer tests the maximum attainable velocity was less than the baseline for all shifting cargo vehicles and significantly so for the low density tanker and the meat trailer. Roll angles (not corrected for suspension spring rates but still indicative of stability) were higher than for the baseline, especially for the low density tanker and meat trailer and more so on the wet surface.

- Trapezoidal steer tests correlated with sinusoidal steer tests, with all shifting cargo vehicles less stable than the baseline, and more driver skill was required to control these vehicles.

The degree of stability problems encountered when transporting partial loads of liquid cargo can be reduced through driver training and instruction, and by recommending that this type of operation be kept to a minimum. The problems with transporting swinging meat loads could be abated by driver training and instruction and a concerted effort on the part of packers and shippers to pack each load as tightly as possible. Because of the importance of driver education we recommend that a more complete evaluation be made of existing driver training practice and, if necessary, that the government prepare and disseminate suitable driver education packages.

A test effort should be undertaken to develop practical devices for restraining the motion of swinging meat cargoes, e.g., tie-down straps, inflatable bladders to take up excess space and tighten the packing, better methods of loading the meat for a tighter pack, and lowering the hanging points to reduce the height of the center of gravity.

The performance of the test vehicles during the turning maneuvers used in the test program indicates that their lateral stability is principally affected by the location of their center of gravity (C.G.). This is primarily determined by the static configuration of truck and load, and the C.G. locations changes when the vehicle is in motion if the load dynamically shifts relative to the trailer. The stability problems of vehicles transporting shifting cargo are influenced by the fact that their static C.G. heights are relatively high. One of the most striking examples of this was in the case of the refrigerated van carrying hanging meat. It had an estimated static C.G. height approximately 25 percent higher than the other test vehicles and had correspondingly more severe lateral instability characteristics. Reducing the vehicle's C.G. would be an appropriate course of action to reduce the lateral stability problems.

It must be remembered that the testing conducted for this program relied on the manual control of the test vehicles by a driver, and that each maneuver was influenced by the subjective performance and evaluations of the driver and the observers. One way to mitigate the inaccuracies inherent in this method of testing in the future would be to exclude driver input as much as possible by conducting further testing using mechanical control inputs such as those provided by steering and braking machines.

For example, during a braking in a turn test, while the meat trailer was executing a left turn, the wheels locked momentarily and the trailer began to jackknife, moving to the right. The meat shifted toward the inside of the turn, tending to stabilize the maneuver. Without doubt, there are other combinations of speed, braking, and steering for which cargo will shift in a destabilizing manner and these conditions should be determined and communicated to the industry. We recommend that a test program of open loop testing be conducted to establish the characteristics of destabilizing maneuvers and more completely determine the nature of problems caused by shifting cargo. During such a program, trailers should be instrumented to document, to the extent possible, the dynamic shift in C.G. location.

This program has made significant progress into the investigation of the effects of cargo shifting on the handling and braking characteristics of articulated vehicles. It is recommended that further testing be performed on a larger cross section of vehicles and a wider variety of loading conditions than has been accomplished thus far, in a continuing effort to reduce the hazards associated with the transportation of shifting cargo.

APPENDIX A

SUMMARY OF SURVEY TO ASSESS THE SEVERITY OF CARGO SHIFTING ON VEHICLE HANDLING

TABLE OF CONTENTS

1.0 INTRODUCTION

This report presents a survey assessing the effect of cargo shifting on the stability of articulated trucks. The types of cargo shift involved are:

- Sloshing of liquid cargo
- Swinging of hanging meat.

The object of the survey was to obtain opinions and information from various trucking companies engaged in the transportation of liquid and hanging meat cargoes. Achieving this objective involved obtaining the companies' opinions, based on their experience, of the magnitude of the safety and stability problems related to shifting cargoes; and gathering data concerning accident involvement, typical equipment, and loading and hauling procedures. The results of the survey will be used as input in full-scale testing. (For instance, the definition of the test vehicles and loading procedures will be finalized, based on this information.) The testing will determine how dynamic cargo shifting affects tractor-trailer handling performance.

2.0 SURVEY OF CARRIERS

To assess the severity of the cargo shift problem, a representative cross section of trucking companies was surveyed. Nine companies were selected, based on combinations of:

- Size of company
- Type of cargo (meat, petroleum, dairy products, chemical or food additives, and viscous fluid)
- Geographic location
- Topographical and climatological environments.

Various types of cargo (e.g., meat and dairy products) are concentrated in a few geographic regions; thus, not all combinations were possible.

The survey consisted of a two-part questionnaire. The first part (Figure 37) was concerned with the overall company size, views on handling and safety problems, driver's training, and experience with FMVSS No. 121 brakes. The second part of the questionnaire (Figure 38) was concerned with the various types of trailer, including size, weight, yearly mileage traveled, accident history, and assessment of handling problems. The results of the survey (summarized in Table 19) are discussed below:

1. Information about the carriers

   - They had from 6 to 1,345 trailers and from 5 to 1,040 tractors. The trailer to tractor ratio ranged from 1.0 to 1.7.
   - The majority of the refrigerated van trailers were manufactured by Great Dane, Fruehauf, American, Tempte, and Trailmobile. The majority of the liquid tank trailers were manufactured by Butler and Heil, Temple, and Fruehauf.
   - The empty weight of the trailers ranged from 14.8 to 17.0 Klb for the refrigerated vans and 7.6 to 20.0 Klb for the tankers.
   - The length of trailers ranged from 40 to 43 feet.
   - The total annual mileage of the carriers ranged from 0.05 to 134.5 million miles.
   - All the carriers either required driver training (to some extent) or hired only experienced drivers.

Company: ______________________ Location: ______________________

1. Total No. of Tractors ____________, Trailers ____________

2. No. of Tank Trailers ____________, Meat Vans ____________

3. Assessment of Handling Problems Common to Both Types of Cargo	
4. Loading Procedures: Packing Density, Hanging Procedure, etc.	
5. Handling and Safety Problems With Other Cargo Types	

6. Company Policy on Driver Training:

   a. Does company conduct training? ____________

   b. Does company require training? ____________

   c. Does training cover handling and safety problem characteristics of various cargo types? ____________

   d. Are all drivers qualified to operate tractor/trailers with any type of cargo? ____________

7. Does Company Operate Units Which Meet FMVSS No. 121 (air brake system)? ____________

   a. Percent of vehicles ____________

   b. What is the experience so far? ____________

8. Miscellaneous: ____________

Figure 37. First part of questionnaire.

Company: ____________________ Location: ____________________

1. Tank Trailer ____________ or Meat Van ____________

2. Make: __________ Model: __________ No. Units: __________

3. Dimensions: ______________ Empty Weight: ______________

4. Yearly Mileage ______________ Mileage Fully Loaded __________

Mileage Partially Loaded __________

Mileage Empty __________

5. Accident Involvement over Last Several Years of Operation	

6. Detailed Information on Accidents:

a. ______________________________

b. ______________________________

c. ______________________________

7. Assessment of Handling Problems Specific to Make and Model	

8. Miscellaneous: ______________________________

Figure 38. Second part of questionnaire.

Table 19. Survey summary.

Hauler Location	Tractor	Meat Van	Tanker	Other	Typ. Empty Wt. (Klb)	Total Year Mileage (million miles): Full	Partly Full	Empty	Training Policy: Conduct	Require	Cover Safety	Qualify All Prod.	FMVSS 121 Brake System: % of Units: Trailer	Tractor	Experience	Accidents in One Year: Accidents Per Year Total	Accidents Per Year Involving Liquid or Hanging Meat Cargo: Total	Per Million Miles
Midwest	50	87	0	0	15.8	3.60	0.02	0.05	Y	Y	Y	Y	25	10	Excellent on trailers	8	1	0.27
South	1040	1345	0	0	16.0	84.70	33.60	16.10	Y	N[2]	Y	Y	-10-[3]		Favorable	685	39	0.29
South-west	450	635	0	0	17.0	31.70	22.20	9.50	Y	Y	Y	Y	25	45	Normal	635	127	2.00
Midwest	301	31	82	349	NA	NA	NA	NA	Y	Y	Y	Y	-10-[3]		No major problems	NA	NA	NA
South	205	228	11	12	14.8	13.70	0.0	2.30	Y	Y	Y	Y	-3-[3]		No problem	NA	2	0.13
Pacific	88	0	88	0	7.6	5.10	0.0	5.10	M	M	L	Y	-2-[3]		Totally un-acceptable	NA	1	0.10
South-west	NA	NA	397	NA	NA	8.00	0.0	8.00	Y	Y	Y	Y	0	0	-	NA	Sev-eral	0.13
South	200	0	300	0	20.0	8.00	7.00 (1)	15.00	N	N[2]	-	Y	5	0	Good	NA	2	0.07
South-west	5	0	6	0	20.0	0.01	0.04	0.01	Y	Y	Y	Y	0	0	-	0	0	0.00

NA = not answered; Y = yes; N = no; M = minimal; L = limited.
(1) Due to weight limit.
(2) Hire only experienced drivers.
(3) Estimated percent of total units.

- The percentage of units with FMVSS 121 brake systems ranged from zero to 45 (on the trailers). The range of experience with the 121 brake systems ranged from unacceptable to excellent (on trailers). Comments about 121 brake systems included:
  - When on the tractor, the front wheel tends to pull to the side.
  - 121 brakes on the tractor and non-121 brakes on the trailer causes harder steering and increases the chances of jackknifing.

2. Accident information

- The percentage of accidents involving vehicles containing shifting cargo out of the total number of accidents ranged from zero to 13. The rate of accidents containing shifting cargo for millions of miles traveled ranged from zero to 2.
- The following comments about the influence of cargo shift on accidents were taken from responses to the questionnaire. Explanatory comments are added in parentheses.
  - Overturns typically do not begin with the cargo shifting but begin because of front tire blowout, running off the road, etc., which causes the vehicle to reach an uncontrollable situation. (Drivers and carriers generally feel that they are capable of transporting potentially shifting cargo under normal circumstances. All admit, however, an unusual steering, braking, or other abrupt input can cause severe problems that are a result of the cargo shift.)
  - Any top-heavy load (such as paper, bananas, etc.) is a potential problem if the driver is not safety minded. (Carriers point out that loads with high c.g. have roll stability problems. While this presents a related handling stability problem, it should not be confused with the more complex problem of cargo shifting.)
  - Accidents have occurred while the vehicle was in a turn or just after turning.
  - One carrier of refrigerated and frozen food products reported approximately 20 to 22 percent of freight movement involved hanging meat and the same percentage of accidents involved hanging meat. (This particular carrier indicated that driver care compensates for the more hazardous condition and thus accident rates are not higher for shifting cargo.)

- Shifting of load depends on amount of cargo loaded in the trailer, and in the case of hanging meat, a loosely packed load adds to the potential problem. (Tighter packing effectively provides a partial restraint for meat loads, thus reducing the severity of the problem.)
- Accidents have occurred when correction in the steering was made after the vehicle had drifted off course.

3. The following comments on handling problems were taken from the responses to the questionnaire:

- When carrying hanging meat, the van's length does not affect handling but its height can.
- Hanging meat can shift more when hung from pipe rail than when hung from I-beams.
- Hazardous material must be loaded with a tolerance for expansion, thus allowing the liquid to slosh. (Fluid surging is particularly noticeable when hauling a liquefied compressed gas cargo).
- The shifting of the cargo can cause the tractor to move forward or backward after coming to a complete stop, or can cause the trailer to tip over after making an accident avoidance maneuver.
- Experienced drivers reduce the chances of an accident when carrying a cargo that can shift.
- Overturn problems occur from any cargo that has a high center of gravity.

The accident data in Table 19 indicates some variation in the accident rate from 0 to 2.0 accidents per million miles traveled. This is probably due primarily to the fact that each company had their own accident data acquisition procedures and no uniform criteria for recording the accident. Some companies were extremely small and did not have enough vehicles or mileage to generate rates of statistical significance. In the accidents involving cargoes of liquid or hanging meat, it is not established whether or not the shifting cargo caused the accident, but only that a potentially shifting cargo was being hauled at the time of the accident.

None of the carriers considered shifting cargoes unsafe. The general feeling was that if due care was exercised in driving a load of shifting cargo, it was within the driver's capability to safely deliver his load. Everyone agreed that special care must be exercised when handling a shifting cargo load.

The general consensus among the carriers interviewed was that meat was more of a handling hazard than liquid, due to cargo shifting. Livestock was reported to be an even more severe problem.

3.0 LOADING PROCEDURES

With liquid cargo, only the level of the fluid in the tank trucks, not the loading procedure, is important relative to vehicle handling stability. However, for hanging meat, the loading procedure can be significant. In order to define a typical loading during testing on the van trailer with hanging meat, several meat packing plants were contacted. The loading procedures are a function of the packing plant, type of route (distance, number of stops, etc.), and customer requests. A commonly used loading procedure consists of loading 40,000 pounds of meat in a 40-foot van in which the front 4 feet is not loaded. The forward end of the van contains space for the refrigeration unit. The average weight of a dressed beef carcass is around 720 pounds, with approximately 55 dressed beef carcasses in a typical load. The carcass is cut into quarters prior to hanging in the truck. The typical loading procedure is to alternate two rows of fores and four rows of hinds with the fores loaded first. The high and low hanging procedure is used for the fores. A row of fores is composed of 6 quarters (using one long 15-inch hook) and 10 quarters hung low (using two long hooks) as illustrated in Figure 39. A row of hinds comprises 8 quarters all hung from the same height using long hooks as illustrated in Figure 40. There are minor deviations in the loading procedure between packing plants. Another loading procedure consists of hanging the meat similarly but loading fores on one side of the van and hinds on the other side. Less common loading procedures include loading fores on one van and hinds on another. The meat van tests will be conducted with a typical meat loading.

The beef sides are ribbed between the 12th and 13th ribs and separated into forequarters and hindquarters as illustrated in Figure 41. The figure also contains the average dimensions of various meat sections. Then, the forequarter represents 52 percent and the hindquarter 48 percent of the beef side. The overall envelope for the forequarters amounts to approximately 42 inches in length, 34 inches in width, and 9-1/2 inches in depth; correspondingly, the overall envelope of the hindquarters is approxmately 55 inches long, 22 inches wide, and 11 inches deep.

The amount of load in a tank trailer is dependent on various factors which include the weight limit of the trailer, number of stops on route, and requirements on expansion room.

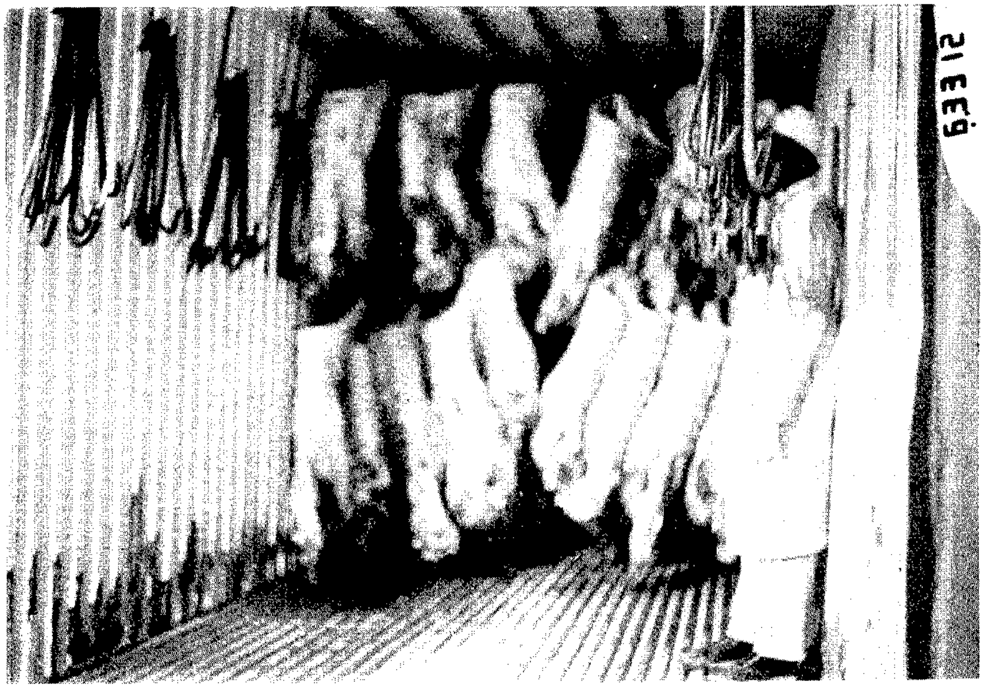


Figure 39. Loading of forequarters.

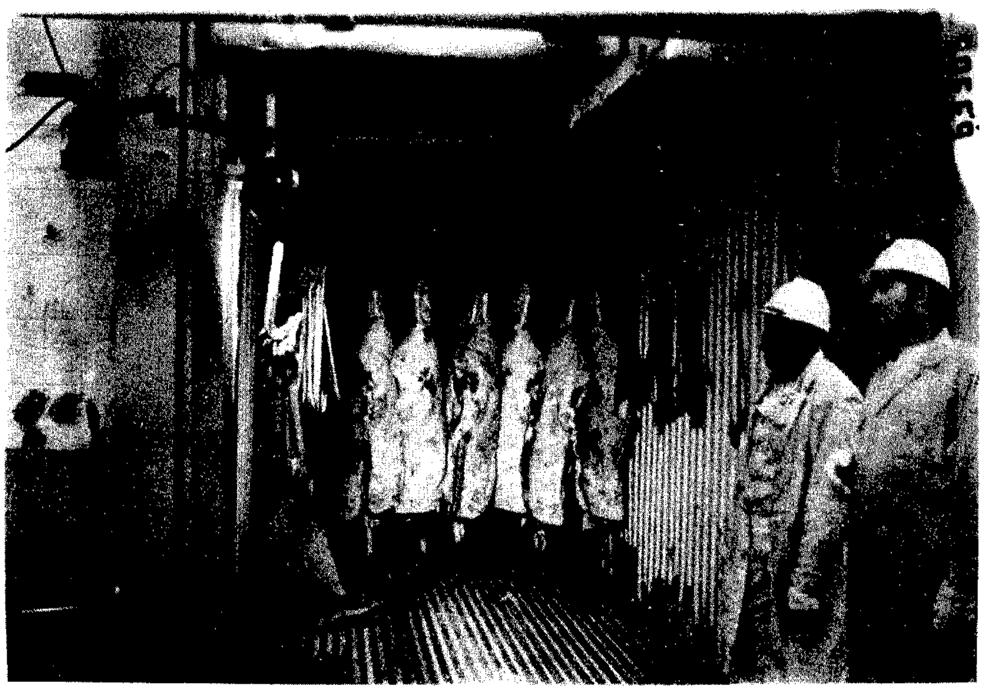


Figure 40. Loading of hindquarters.

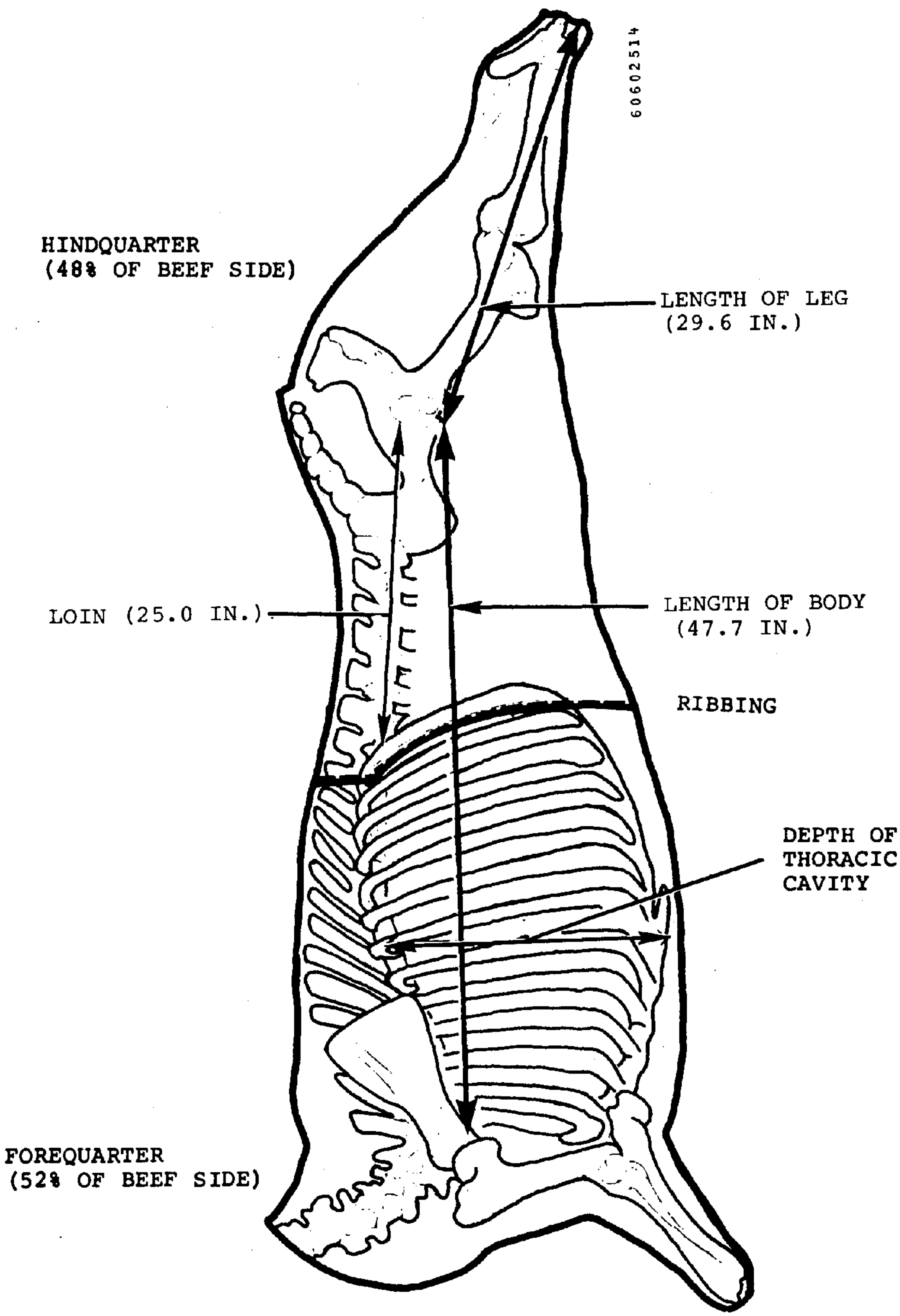


Figure 41. Beef carcass measurements.

4.0 ACCIDENT STATISTICS

To aid in the assessment of the influence of cargo shifting on vehicle handling, some accident data were reviewed. The percentage of tanker accidents reported to the Bureau of Motor Carrier Safety that had a classification of cargo shift was 0.09, 0.07, 0.19, and 0.11 for the years of 1973, 1974, 1975, and 1976, respectively. The primary event statistics for non-collision accidents in the 1974 Accident of Motor Carriers of Property Report listed 1.6 percent under cargo shift. The results of reviewing some accident reports indicate that cargo shifting did not cause the accident by itself, but could have contributed to the cause. Typically, accidents occur when the vehicle is placed in a compromising situation which can be aggravated by cargo shifting. Representative compromising situations include turning too fast, allowing the vehicle to drift off the road, and applying a sudden accident avoidance maneuver. Table 20 briefly summarizes the accidents involving shifting cargo reported by participants in the survey. Table 21 summarizes additional cargo shift accidents. A majority of the carriers surveyed commented that the best accident avoidance technique is the use of experienced drivers who are safety minded and drive in accordance with the load and driving conditions.

Table 20. Summary of accident information from survey accidents reported.

Location	Over Time Period	*Accidents Reported
Midwest	7 yr	Total of 16. 6 involved shifting of cargo; 2 during turning, 2 steering mechanism failure, 2 reckless driver (one when wind caught trailer between hills and moved it, then lost control when turned back).
South	1 yr	Total of 139. 14% of overturns (36) and 69% of other reported accidents (103) had suspended meat; 40% of time load is boxed meat.
Southwest	1 yr	Ten accidents per million miles - 20 to 22% of accidents involved hanging meat.
Midwest	-	Not answered.
South	1 yr	Average of 2 involving meat carcass (one during a turn on a wet road and the load shifted causing overturn, one car crossed center and hit tractor causing it to go off the road).
Pacific	2 yr	One accident (driver fell asleep and vehicle left road, then lost control when steered back causing overturn).
Southwest	-	Several.
South	-	Two or three involving shifting cargo (one while in turn with partly full trailer due to weight limit, one on the freeway exit ramp with an inexperienced driver.
Southwest	-	None.

Table 21. Summary of accident survey.

Source	Cargo	Cause of Accident
Bureau of Motor Carrier Safety	Tankers	Accidents involve cargo shift are 0.09% in 1973, 0.07% in 1974, 0.19% in 1975, and 0.11% in 1976.
1974 Accidents of Motor Carriers of Property	All	Primary event statistics for non-collision accidents was cargo shift was 104 out of total of 6656 accidents or 1.6% of accidents.
Accident Report	Hanging Meat	During slight turn, vehicle ran off road onto shoulder (due to driver inattention) and hit guard-rail causing front tire to blow. The cargo shifted and caused trailer to swerve and overturn (driver was inexperienced) - investigator suggested adding bars to restrain meat.
Accident Report	Liquid	Slowed to make turn and cargo shifted to one side causing overturn.
Accident Report	Hanging Meat	While on freeway ramp, cargo shifted causing overturn.
Accident Report	Cattle	Driver fell asleep and ran off road.
Accident Report	-	After turned onto freeway from on-ramp, cargo shifted and slowly tipped vehicle over.
Accident Report	Liquid	While turning, the half-filled load shifted causing overturn.
Accident Report	Tomatoes	Trailer ran off road onto dirt shoulder. Driver overcorrected when trying to pull vehicle back, causing load to shift and overturn.
Accident Report	Culverts	Load shifted due to failure of a chain and caused overturn.
Accident Report	Cattle	Driving too close to edge and tires fell off edge (4- to 6-inch drop) causing cattle to shift to one side and overturn vehicle.

5.0 TEST VEHICLE SELECTION

The carriers surveyed all indicated that in their opinion there is no significant difference in handling or accident involvement between the various makes and models of tractors and trailers. A trailer of typical size will then be selected.

Some of the respondents to the survey specified the capacity of the trailer, others the dimensions.

Table 22 summarizes the trailer descriptions obtained from the survey.

Table 22. Summary of trailer specifications.

Carrier	Cargo Type	Number of Units	Typical Trailer Height (ft)	Typical Trailer Length (ft)	Typical Trailer Capacity (gallons)
Midwest	meat	87	13 or 12-1/2	40 42	--
South	meat	1,345	13 or 12-1/2	40 43	--
Southwest	meat	635	12-1/2	42	--
Midwest	liquid	82	--	--	4,000 to 8,700
South	meat	228	13	40	--
Pacific	liquid	88	--	--	4,000 to 4,800
Southwest	liquid	397	--	40	--
South	liquid	300	--	40	--
Southwest	liquid	5	--	--	5,800

All refrigerated trailers for meat had seven rails along the roof to suspend the meat. A 40- to 42-foot meat van appears to be an adequate specification for a typical refrigerated meat van.

A typical tank trailer for a dense product (acid, water) has a capacity of 4,000 to 4,800 gallons, and up to about 9,000 gallons for a low density product (petroleum) trailer. Petroleum tankers typically are not single compartment or nonbaffled. High density trailers (acid) will be selected so single compartment tanks, water ballast, and a nonbaffled trailer can be used.

Conversation with a manufacturer of tractors indicated that each tractor is custom manufactured to the customer's requirements. Thus, it is impossible to define an average tractor.

A typical tractor must then be selected. An important consideration is that vehicle properties are required for the computer simulation, and the choice of a vehicle with known properties would be helpful. An effort was made to obtain a tractor used by HSRI on a truck simulation project sponsored by MVMA. Efforts to secure that vehicle were unsuccessful. A tractor with similar characteristics must then be selected. The tractor should have the following characteristics:

- Cab over engine
- Dual-drive axles
- Four leaf spring suspension.

APPENDIX B

SKID RESISTANCE OF PAVED SURFACES USING A FULL-SCALE TIRE

The following method is used to measure the skid resistance of our paved surface:

- The test apparatus consists of an automotive vehicle towing a specially instrumented trailer with full-scale automotive tires. The trailer contains load cells which are placed such that the tractive force (i.e., horizontal force applied to the test tire at the tire-pavement contact patch) can be measured.

- The test apparatus is brought to the desired test speed of 40 ±1 mph. (If required, the track is watered before testing.) The braking system is then actuated to lock the test tire. The resulting frictional force, F, acting between the test tire and the pavement surface and the speed of the test vehicle are measured and recorded with the aid of suitable instrumentation.

- The skid numbers are calculated from the following equation:

$$S/N = 100 \times \frac{F}{W_o - \frac{H}{L} F}$$

where:

F = tractive (frictional) force (horizontal force applied to the test tire at the tire-pavement contact patch), lb.

W_o = static vertical load on the test tire, lb.

H = hitch height, in.

L = trailer wheelbase length (center of axle to center of hitch), in.

A copy of typical data is included. These data were taken at the conclusion of this program.

APPENDIX C

SAMPLES OF COMPUTED DATA FROM

REMOTE SIGNAL CONDITIONING MODULE 1 AND

REMOTE SIGNAL CONDITIONING MODULE 2 INSTRUMENTS

DATA SHEET	DS	TEST TITLE: SKID NUMBER DETERMINATION	DATE: January 6, 1978	Page: 1

TRAILER INFORMATION

HITCH HEIGHT: 9-3/8 in.
WHEEL BASE: 102 in.
TIRE SIZE: 15

RIGHT TIRE S/N: M92477
LEFT TIRE S/N: M92467

FORCE LEVER ARM RATIO: $\frac{d1}{d2} = \frac{6}{12.75} = .471$

TIRE PRESSURES: Right: 24 psi Left: 24 psi

WHEEL WEIGHTS: Right: 1009 lb Left: 1026 lb

CALIBRATION INFORMATION

LOAD CELL	S/N	CAL METHOD	CAL R	R_B	CF	FSEV	100% CAL EQUIV.
Right:	123	SSSR	174K	352.0	.917	3000	1653
Left:	149	SSSR	174K	352.9	.902	3000	1685

FIFTH WHEEL INFORMATION

TACH GEN S/N: 763A-2
WESTON S/N: 1378

PRECAL @ SPIN UP 52.95 mph

TEST DATA

RUN NO.	RUN DIRECTION E/W	TEST SURFACE (LOC.)	PAVEMENT CONDITION WET/DRY	TEST WHEEL R/L/BOTH	RESULT G/B	TEMP. AMB.	TEMP. SUR.	AVERAGE SPEED (mph)	DATA (CHART) %	DATA (CHART) (lb)	X.471= FRICTION FORCE (lb)	$SN = 100 \times \frac{F}{W_o - \frac{H}{L}F}$ SKID NUMBER	
1	E	1	Dry	L	G	60		40	92	1550	730.1	76.1	
2	W	1	Dry	L	G	60		40	105	1769	833.2		
3	E	1	Dry	L	G	60		40	97	1634	769.6	80.6	
4	W	1	Dry	L	G	60		40	100	1685	793.6	83.3	79.9
5	E	1	Dry	R	G	60		40	95	1570	739.5	78.6	
6	W	1	Dry	R	G	60		40	92	1521	716.4	76.0	
7	E	1	Dry	R	G	60		40	102	1686	794.1	84.8	
8	W	1	Dry	R	G	60		40	83	1372	646.2		

TEST DATE 9-17-77 CARGO SHIFT - FREIGHTLINER/MEAT - FULL LOAD PAGE 1
CARGO SHIFT TEST NUMBER 17F-FUL SSD

TIME SEC	AX G	AY G	Y R D/S	HD DEG	VS F/S	VX F/S	VY F/S	X FT	Y FT	F W IN	F W DEG	T-T IN	T-T DEG	ROLL DEG	T RR D/S	TROL DEG	SW TOR FT-LB	RF IN	LF IN	F G	RF LB	LF LB
-1.0	-.01	.00	.1	.0	27.7	27.7	.0	.0	.0	.0	.0	.0	.0	.7	-.0	-.0	-1.3	.2	.3	.02	-292	-606
-1.0	.03	-.00	.0	.0	27.9	27.9	.0	.0	.0	.0	.0	.0	.0	.7	.0	-.0	-1.2	.2	.3	.02	-279	-603
-.9	.01	-.01	.1	.0	27.9	27.9	.0	.0	.0	.0	.0	-.0	-.0	.7	.0	.0	-1.2	.1	.3	.02	-262	-576
-.9	-.02	.03	.2	.0	27.7	27.7	.0	.0	.0	.0	.0	.0	.0	.7	.1	.0	-1.2	.1	.3	-.01	-279	-578
-.6	.04	.00	.0	.0	27.7	27.7	.0	.0	.0	-.0	-.0	.0	.0	.8	.1	.0	-1.1	.2	.3	-.01	-318	-609
-.8	.03	-.00	.1	.0	27.9	27.9	.0	.0	.0	-.0	-.0	.0	.0	.8	-.0	.0	-.9	.2	.3	.04	-306	-550
-.7	-.01	.01	.1	.0	28.0	28.0	.0	.0	.0	-.0	-.1	.0	.0	.8	-.0	.0	-.7	.2	.3	.04	-268	-462
-.7	.03	.01	.1	-.1	28.0	28.0	.0	.0	.0	-.0	-.1	.0	.0	.8	-.0	.0	-.6	.1	.2	-.01	-255	-481
-.6	-.01	.01	.1	-.1	27.7	27.7	.0	.0	.0	.0	.0	.0	.0	.8	-.2	-.0	-.5	.2	.3	-.01	-338	-610
-.6	.01	.00	.0	.0	27.7	27.7	.0	.0	.0	-.0	-.0	-.0	-.0	.8	-.2	-.0	-.5	.2	.4	.03	-367	-714
-.5	.03	-.00	.1	.0	27.9	27.9	.0	.0	.0	.0	.0	-.0	-.0	.8	-.0	-.0	-.6	.2	.4	.00	-374	-731
-.5	.01	.03	.1	-.1	28.0	28.0	.0	.0	.0	-.0	-.1	.0	.0	.8	-.0	-.0	-.6	.2	.4	-.01	-384	-711
-.4	.02	.00	.2	19.1	27.7	27.7	.0	.0	.0	.1	.6	.1	.1	1.1	.2	-.0	-4.3	.0	.3	.00	-7	-630
-.4	.02	.00	.1	.0	27.9	27.9	.0	.0	.0	-.0	-.1	.0	.0	.8	-.1	-.0	.2	.2	.4	.03	-337	-654
-.3	.02	-.00	.1	.1	27.8	27.8	.0	.0	.0	-.0	-.0	-.0	-.0	.8	-.0	-.0	.6	.2	.3	.02	-281	-633
-.3	.02	.00	.1	.0	27.9	27.9	.0	.0	.0	-.0	-.1	.0	.0	.8	-.0	-.0	1.0	.2	.3	-.01	-297	-664
-.2	-.03	.01	.1	.1	28.1	28.1	.0	.0	.0	.0	.0	-.0	-.0	.8	-.1	-.0	1.5	.2	.4	.01	-387	-711
-.2	.03	-.01	.1	.0	28.2	28.2	.0	.0	.0	.0	.0	.0	.0	.8	-.1	-.0	1.8	.2	.4	.02	-407	-746
-.1	.04	-.00	.1	.1	28.0	28.0	.0	.0	.0	.0	.1	.0	.0	.8	.1	-.0	1.9	.2	.4	.02	-354	-719
-.1	-.03	.03	.1	.0	27.9	27.9	.0	.0	.0	.0	.1	.0	.0	.8	.0	-.0	2.6	.2	.3	.01	-321	-651
-.0	.02	.02	.1	.2	27.9	27.9	.0	.0	.0	.0	.3	-.0	-.1	.7	-.1	-.0	3.3	.2	.3	.00	-349	-632
.0	.05	.03	.1	.2	28.1	28.0	.0	1.4	.0	.1	.4	-.0	-.0	.7	-.1	-.0	3.7	.2	.3	.01	-345	-614
.1	-.01	.02	.4	.2	28.2	28.0	.1	2.8	.0	.1	.5	-.0	-.0	.6	.0	-.0	5.0	.2	.3	.02	-338	-606
.1	.00	.04	.4	.1	28.1	28.0	.1	4.2	.0	.1	.6	-.0	-.0	.6	.0	-.0	6.2	.2	.3	.02	-356	-621
.2	-.01	.04	.4	.3	27.9	28.0	.2	5.6	.0	.1	.8	-.1	-.1	.5	-.1	-.0	6.9	.2	.3	.01	-415	-610
.2	.03	.03	.7	.3	27.9	28.0	.2	7.0	.1	.1	1.0	-.1	-.1	.6	-.1	-.0	7.3	.2	.3	.00	-411	-572
.3	.00	.06	1.3	.5	28.0	28.0	.3	8.4	.1	.2	1.3	-.2	-.2	.5	.1	-.0	7.8	.2	.2	-.01	-398	-477
.3	-.01	.08	1.4	.5	28.2	28.0	.4	9.8	.1	.2	1.5	-.2	-.2	.4	.2	-.0	9.0	.2	.2	.01	-407	-425
.4	.01	.06	1.8	.8	28.1	28.0	.4	11.2	.2	.2	1.7	-.3	-.3	.4	.1	-.0	9.3	.2	.2	.04	-416	-363
.4	.00	.06	2.3	.8	28.0	28.0	.5	12.6	.2	.2	2.0	-.4	-.4	.4	.1	-.0	9.9	.2	.2	.02	-407	-272
.5	.02	.09	2.6	1.0	28.0	28.0	.5	14.0	.2	.3	2.3	-.4	-.5	.2	.3	-.0	10.5	.2	.1	-.01	-411	-208
.5	-.01	.10	2.8	1.2	28.0	28.0	.6	15.4	.3	.3	2.6	-.6	-.6	.1	.3	.0	10.1	.3	.1	.01	-474	-197
.6	-.02	.10	3.1	1.5	28.0	28.0	.7	16.8	.4	.3	2.8	-.7	-.8	-.0	.2	.0	10.1	.3	.1	.03	-540	-151
.6	.01	.11	3.7	1.6	27.9	28.0	.8	18.2	.5	.4	3.1	-.9	-.9	-.1	.3	.0	10.5	.3	.0	.05	-534	-22
.7	-.01	.11	4.5	1.9	27.8	28.0	.9	19.6	.5	.4	3.6	-1.0	-1.1	-.1	.3	.1	11.5	.3	-.1	.03	-461	174
.7	-.01	.12	4.9	2.1	27.9	28.0	1.0	21.0	.6	.5	4.1	-1.2	-1.3	-.2	.2	.1	13.2	.2	-.1	.01	-437	262
.8	-.01	.14	5.9	2.4	28.0	28.0	1.0	22.4	.8	.6	4.6	-1.5	-1.5	-.4	.1	.1	15.7	.3	-.2	.02	-483	314
.8	.01	.16	6.5	2.8	28.1	28.0	1.1	23.8	.9	.6	5.0	-1.7	-1.8	-.6	.1	.1	17.3	.3	-.2	.00	-567	346
.9	.03	.17	7.7	3.2	28.1	28.0	1.2	25.2	1.0	.7	5.5	-2.0	-2.1	-.8	.3	.1	17.4	.3	-.2	.02	-621	458
.9	-.06	.19	8.9	3.7	27.8	28.0	1.3	26.6	1.2	.7	5.8	-2.3	-2.4	-1.0	.6	.1	17.4	.4	-.3	.03	-690	634
1.0	-.04	.22	8.8	4.3	27.8	27.9	1.4	28.0	1.4	.7	5.9	-2.6	-2.7	-1.1	.8	.2	16.7	.4	-.4	.03	-773	778
1.0	.02	.19	9.2	4.8	28.0	28.0	1.5	29.3	1.5	.7	6.0	-2.9	-3.0	-1.2	.8	.2	13.5	.5	-.4	.05	-832	850
1.1	-.03	.21	10.4	5.2	28.2	27.9	1.6	30.7	1.8	.7	6.0	-3.2	-3.4	-1.3	.8	.2	8.8	.4	-.5	.05	-824	949
1.1	-.04	.18	10.6	5.7	28.0	27.9	1.6	32.1	2.0	.7	6.1	-3.6	-3.8	-1.3	1.1	.3	6.4	.4	-.5	-.01	-790	996
1.2	-.03	.14	11.0	6.3	27.7	27.8	1.6	33.5	2.2	.7	6.1	-3.9	-4.1	-1.2	1.6	.4	4.9	.4	-.5	-.04	-770	994
1.2	-.04	.13	11.1	6.7	27.6	27.8	1.5	34.8	2.4	.7	6.1	-4.2	-4.4	-1.2	1.9	.5	4.0	.4	-.6	-.01	-749	1057
1.3	-.04	.15	10.8	7.3	27.7	27.7	1.5	36.2	2.7	.7	6.1	-4.5	-4.7	-1.2	1.9	.6	3.0	.4	-.6	.02	-733	1232
1.3	-.06	.15	10.7	7.8	27.8	27.7	1.5	37.6	3.0	.7	5.9	-4.8	-5.1	-1.3	2.1	.7	2.1	.4	-.7	.02	-738	1394
1.4	-.00	.17	10.6	8.3	27.6	27.7	1.5	38.9	3.2	.7	5.5	-5.1	-5.4	-1.2	2.2	.8	.8	.4	-.8	.04	-773	1463
1.4	.02	.15	10.3	8.8	27.2	27.7	1.5	40.3	3.5	.6	5.1	-5.4	-5.7	-1.1	2.1	.9	-.7	.4	-.8	.03	-804	1459
1.5	-.03	.11	10.0	9.2	27.1	27.7	1.4	41.6	3.8	.6	4.6	-5.6	-5.9	-.9	2.0	1.0	-2.1	.4	-.7	-.01	-812	1390

Computed data from RSCM 1 instruments.

TEST DATE 9-17-77 CARGO SHIFT - FREIGHTLINER/MEAT - FULL LOAD PAGE 1
CARGO SHIFT TEST NUMBER 17F-FUL SSD

TIME SEC	PF LB	I AX G	RFD IN	LFD IN	FD G	RFD LB	LFD LB	RRD IN	LRD IN	RD G	RRD LB	LRD LB	RFT IN	LFT IN	FT G	RFT LB	LFT LB	RRT IN	LRT IN	RT G	RRT LB	LRT LB
-1.0	.0	.00	-.0	.0	-.07	93	-83	.0	.0	-.04	-238	-65	.0	-.0	.00	-30	238	-.0	-.0	.02	195	243
-1.0	.1	-.00	-.0	.0	-.01	140	-15	.1	-.0	.00	-219	8	.0	-.0	.00	-32	270	-.0	-.0	.01	202	220
-.9	.1	-.01	-.0	.0	-.01	134	-22	.1	-.0	-.02	-235	9	.0	-.0	.01	-27	274	-.0	-.0	-.02	194	199
-.9	.1	-.01	-.0	.0	.01	172	5	.0	-.0	.01	-171	18	.0	-.0	.02	1	288	-.0	-.0	.01	219	208
-.8	.0	-.01	-.0	-.0	.01	182	78	.0	-.0	.04	-110	76	.0	-.0	.01	8	313	-.0	-.0	-.01	188	206
-.8	-.1	-.01	-.0	-.0	-.00	163	78	.0	-.0	.00	-158	90	-.0	-.0	-.00	30	302	-.0	-.0	-.01	149	206
-.7	-.1	-.00	-.0	.0	.02	181	-25	.0	-.0	-.04	-219	65	-.0	-.0	.01	41	279	-.0	-.0	.01	193	241
-.7	.0	.00	-.0	.0	.00	156	-10	.1	-.0	-.01	-209	7	.0	-.0	.00	-30	238	-.0	-.0	-.04	187	179
-.6	.0	.00	-.0	-.0	-.04	82	88	.1	.0	-.01	-225	-33	.0	-.0	-.00	-66	251	-.0	-.0	-.04	181	202
-.6	-.1	-.00	-.0	-.0	-.02	72	148	.0	.0	.00	-181	-6	.0	-.0	.00	-48	270	-.0	-.0	-.00	219	227
-.5	-.1	-.01	-.0	-.0	-.01	75	140	.1	-.0	-.03	-229	14	.0	-.0	.02	-2	266	-.0	-.0	-.01	251	237
-.5	.0	-.01	-.0	-.0	.03	129	205	.0	-.0	.04	-148	103	.0	-.0	.02	-14	237	-.0	-.0	.01	256	255
-.4	-.1	-.01	-.0	-.1	-.01	91	281	.0	-.0	.04	-139	155	.0	-.0	.00	-13	255	-.0	-.0	-.02	194	199
-.4	-.1	-.00	-.0	-.1	-.01	81	240	.0	-.1	-.00	-184	198	-.0	-.0	-.01	9	263	-.0	-.0	.00	184	199
-.3	-.1	-.00	-.0	-.0	.05	99	184	.0	-.1	-.03	-213	195	.0	-.0	.00	0	219	-.0	-.0	.00	195	213
-.3	.1	-.02	-.0	-.1	.01	61	217	.1	-.0	-.03	-521	17	.0	-.0	.05	-174	339	-.0	-.0	.02	143	227
-.2	.0	.00	-.0	-.1	-.06	21	312	.1	-.0	-.02	-276	85	.0	-.0	-.01	-4	198	-.0	-.0	-.00	193	211
-.2	-.1	.00	-.0	-.1	-.03	49	371	.1	-.0	.02	-292	110	-.0	-.0	-.01	11	181	-.0	-.0	.00	210	232
-.1	-.1	-.01	-.0	-.1	.02	110	380	.1	-.0	-.01	-371	130	.0	-.0	.01	-5	180	-.0	-.0	-.01	251	253
-.1	-.1	-.01	-.0	-.1	.02	136	418	.1	-.0	.02	-311	180	.0	-.0	.02	-19	182	-.0	-.0	.01	290	267
-.0	-.2	-.01	-.0	-.1	-.03	95	439	.1	-.1	.01	-285	211	.0	-.0	-.02	-13	189	-.0	-.0	-.05	232	238
.0	-.1	-.01	-.0	-.1	-.00	65	396	.1	-.1	.01	-282	249	.0	-.0	.00	0	202	-.0	-.0	.02	287	276
.1	.1	-.01	-.0	-.1	.04	54	310	.1	-.1	-.03	-324	216	.0	-.0	.02	-14	169	-.0	-.0	-.00	284	260
.1	.2	-.01	-.0	-.1	-.03	-15	292	.1	-.0	-.04	-362	145	.0	-.0	.00	-13	188	-.0	-.0	-.02	242	228
.2	.1	-.01	-.0	-.1	-.06	-14	335	.1	-.0	.01	-362	175	-.0	-.0	-.01	5	259	-.0	-.0	.01	180	126
.2	.1	-.01	-.0	-.1	-.01	3	372	.1	-.1	.01	-371	219	-.0	-.0	-.01	23	244	-.0	-.0	-.00	180	112
.3	.1	-.02	.0	-.1	.03	22	390	.1	-.1	-.03	-381	207	-.0	-.0	.01	24	211	-.0	-.0	-.01	227	157
.3	.1	-.02	-.0	-.1	.01	45	405	.1	-.0	.01	-301	205	-.0	-.0	.02	29	233	-.0	-.0	.00	247	164
.4	.1	-.02	-.0	-.1	-.01	58	420	.1	-.1	.01	-298	217	-.0	-.0	-.01	37	259	-.0	-.0	-.04	163	132
.4	.1	-.02	-.0	-.1	-.01	29	348	.1	-.1	.02	-317	253	-.0	-.0	-.00	46	302	-.0	-.0	.02	198	180
.5	.1	-.02	-.0	-.1	.06	96	343	.1	-.1	-.02	-337	205	-.0	-.0	.00	18	255	-.0	-.0	-.04	204	151
.5	.1	-.03	-.0	-.1	-.02	16	377	.1	-.0	-.02	-330	105	-.0	-.0	.00	18	272	-.0	-.0	-.02	216	145
.6	.0	-.02	-.0	-.1	-.05	-1	450	.1	-.0	.02	-314	98	-.0	-.0	-.01	25	314	-.0	-.0	-.01	190	176
.6	.0	-.02	-.0	-.1	-.02	23	507	.1	-.0	.00	-371	96	.0	-.0	-.01	-4	299	-.0	-.0	-.01	209	185
.7	.1	-.03	-.0	-.1	.03	67	550	.1	-.0	-.01	-390	112	.0	-.0	.01	-39	346	-.0	-.0	-.01	229	176
.7	.1	-.03	-.0	-.2	.02	58	664	.1	-.0	.04	-323	134	.0	-.1	.01	-57	395	-.0	-.0	-.01	214	140
.8	.1	-.03	-.0	-.2	-.03	10	688	.1	-.0	-.01	-338	112	.0	-.1	-.02	-47	424	-.0	-.0	-.03	146	92
.8	.1	-.02	.0	-.2	-.01	-74	597	.1	-.0	.01	-282	187	.0	-.1	.01	8	448	-.0	-.0	.03	165	137
.9	.0	-.03	.0	-.1	.11	-55	602	.1	-.1	.01	-260	207	.0	-.1	.00	-46	408	-.0	-.0	-.04	111	148
.9	.0	-.04	.0	-.2	-.05	-174	598	.1	-.0	-.05	-337	71	.0	-.1	-.01	-181	435	-.0	-.0	-.03	31	160
1.0	.0	-.03	.0	-.2	-.04	-174	669	.1	-.0	.00	-339	99	.0	-.1	-.01	-312	466	.0	-.0	.00	-127	149
1.0	.0	-.03	.1	-.2	.01	-225	706	.1	-.0	.01	-365	146	.1	-.1	.00	-419	473	.0	-.0	-.02	-200	129
1.1	-.1	-.04	.1	-.2	.04	-278	741	.1	-.0	-.00	-336	189	.1	-.1	.01	-537	535	.0	-.0	-.02	-221	150
1.1	-.1	-.04	.1	-.2	.03	-339	840	.1	-.1	.04	-250	272	.1	-.1	-.01	-619	669	.1	-.0	-.04	-411	113
1.2	-.2	-.05	.1	-.2	.00	-329	894	.1	-.1	.02	-323	325	.1	-.1	-.03	-667	806	.1	-.0	.00	-716	147
1.2	-.1	-.08	.1	-.2	.01	-424	937	.1	-.1	.00	-467	332	.1	-.1	.01	-765	854	.1	-.0	.04	-905	195
1.3	.0	-.09	.1	-.3	.06	-493	1046	.2	-.1	.02	-574	305	.1	-.1	-.01	-1020	790	.1	-.0	-.05	-1017	221
1.3	-.1	-.08	.1	-.3	-.02	-553	1131	.2	-.1	-.02	-750	198	.2	-.1	-.02	-1404	760	.2	-.0	-.06	-1240	203
1.4	-.2	-.05	.1	-.3	-.01	-554	1294	.2	-.1	.01	-876	254	.2	-.1	-.02	-1770	781	.2	-.0	.01	-1531	201
1.4	-.4	-.02	.2	-.4	-.01	-681	1386	.3	-.1	-.03	-1048	303	.3	-.1	-.01	-1992	752	.2	-.0	-.05	-1653	191
1.5	-.2	-.01	.2	-.4	.03	-858	1465	.3	-.1	.02	-1102	425	.3	-.1	.01	-2188	799	.2	-.0	-.02	-1682	328

Computed data from RSCM 2 instruments.