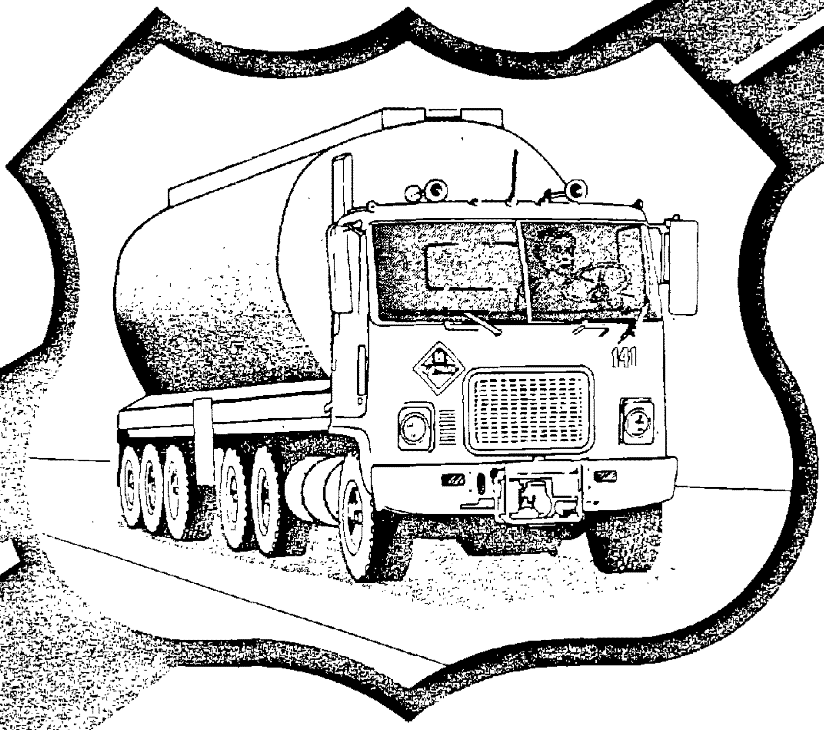
Report No. FHWA/RD-80/142

COMPUTER SIMULATION OF THE EFFECT OF CARGO SHIFTING ON ARTICULATED VEHICLES PERFORMING BRAKING AND CORNERING MANEUVERS

Vol. 1. Executive Summary

May 1981

Final Report



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Prepared for

FEDERAL HIGHWAY ADMINISTRATION

Offices of Research & Development

Structures and Applied Mechanics Division

Washington, D.C. 20590

FOREWORD

This report is a summary of the work done under a contract for simulating the effect of cargo shifting on vehicle handling. It was done in conjunction with an experimental test program on the same subject, for which a final report has been published:

Report FHWA-RD-78-76, "Effect of Cargo Shifting on Vehicle Handling," by C. Culley, R. L. Anderson, and L. E. Wesson (NTIS No. PB 298 110/AS).

The articulated vehicle simulation used in this work is part of a larger simulation program, developed for FHWA under Contract DOT-FH-11-8519, "Modeling the Interaction of Heavy Vehicles with Protective Barriers." A subroutine for liquid sloshing was developed and integrated with the vehicle part of the above program. The simulation is operational at the contractor's facility, Johns Hopkins University Applied Physics Laboratory.

This report is distributed by memorandum to individual researchers. The computer program can be made available to potential users. Such users are requested to provide feedback information to the FHWA contract manager on problems with the program and changes made to it.

Other reports issued under this contract are:

Volume 2, Technical Report, FHWA/RD-80/143
Volume 3, Technical Supplement, FHWA/RD-80/144
Volume 4, User's Manual, FHWA/RD-80/145

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

NOTICE

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16. Abstract

The effects of sloshing liquid cargo on the limit performance of articulated trucks have been investigated. The limit performances of four vehicle configurations in cornering and braking maneuvers were simulated using an augmented version of the vehicle simulation program, TDVS (Three Dimensional Vehicle Simulation). The vehicle configurations consisted of tractor with unbaffled, baffled, and compartmentalized tank trailers and a baseline van. Simulated maneuvers were lane change, cornering, straight-line braking, and braking-in-a-turn. Both vehicle configurations and maneuvers were modeled to correspond with the full-scale experiments, "Effect of Cargo Shifting on Vehicle Handling", (DOT-FH-11-9195), conducted by Dynamic Sciences, Inc.

This report covers the validation of the augmented TDVS program, and the development and implementation of a methodology for conducting limit of performance simulations. Results are discussed and summarized in the context of the simulation program and in light of experimental data. Finally, recommendations are presented for vehicle dynamics analysis methodology and for future studies.

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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)		
	ounces	28	grams	g
	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

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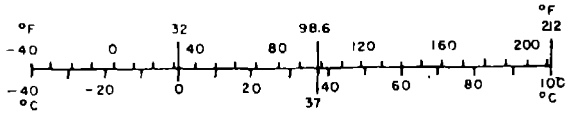
*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.

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



Abstract

The effects of sloshing liquid cargo on the limit performance of articulated trucks have been investigated. The limit performances of four vehicle configurations in cornering and braking maneuvers were simulated using an augmented version of the vehicle simulation program, TDVS (Three Dimensional Vehicle Simulation). The vehicle configurations consisted of tractor with unbaffled, baffled, and compartmentalized tank trailers and a baseline van. Simulated maneuvers were lane change, cornering, straight-line braking, and braking-in-a-turn. Both vehicle configurations and maneuvers were modeled to correspond with the full-scale experimental analysis "Effect of Cargo Shifting on Vehicle Handling", (DOT-FH-11-9195) as conducted by Dynamic Sciences, Inc.

This report covers the validation of the augmented TDVS program, and the development and implementation of a methodology for conducting limit of performance simulations. Results are discussed and summarized in the context of the simulation program and in light of experimental data. Finally, recommendations are presented for vehicle dynamics analysis methodology and for future studies.

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1.0 Summary

This research program investigated the effects of sloshing liquid cargo on the limit performance of articulated trucks (Reference 1). The investigation encompassed two objectives: the development and verification of a slosh dynamics model and the application of this model in predicting a limit performance threshold. The experimental data for verification, the vehicle parametric data, and the limit performance methodologies were derived from the companion experimental study, "Effect of Cargo Shifting on Vehicle Handling" (Reference 2), conducted by Dynamic Sciences, Inc. (DSI).

The research program was grouped into the following tasks:

1. Development of a slosh dynamics model.
2. Selection of an articulated truck simulation for use in conjunction with the slosh model.
3. Integration of the articulated truck simulation and slosh dynamics model.
4. Verification of the correctness of (3).
5. Collection of simulation parametric data.
6. Simulation of the experimental limit performance.
7. Repetition of (6), while adjusting maneuver parameters until the limit of stability was attained.

The slosh dynamics model was developed for the articulated truck simulation under subcontract (Reference 3). The slosh dynamics of fluid in up to a six-compartmented tank trailer or tank truck can be simulated. These compartments may be of arbitrary elliptical cross-section and location. Fore/aft and lateral damping ratios may be specified for each compartment to simulate baffling. Fluid depth and density may also be specified for each compartment.

TDVS (Three Dimensional Vehicle Simulation) was selected as the base articulated truck simulation. This IITRI (Illinois Institute of Technology Research Institute) developed model (Reference 4) was preferred for its economical vehicle parameterization and analytical virtue. Parameterization data for this simulation study were obtained from DSI (when possible) and prior studies with similar vehicles. The data described four vehicle configurations:

- Tractor with 40-foot (12-meter) van semitrailer.
- Tractor with unbaffled tank semitrailer.
- Tractor with baffled tank semitrailer.
- Tractor with compartmentalized tank semitrailer.

The implementation of the slosh dynamics model was verified by analytical and numerical checks. The simulation of full-scale experiments also served as verification; however, the verification process was seriously compromised by the lack of experimental fluid slosh data.

An approximation of the experimental methodology was required for the simulation of the experimental limit performance. Duplication of the full-scale maneuver path required use of the TDVS path-following algorithm. Unfortunately, this algorithm became numerically unstable when simulation on low friction surfaces was attempted, rendering maneuvers on wet surfaces impossible. Other modeling simplifications were responsible for wildly optimistic braking performances. Thus, in both cases, the simulation of the experimental limit performance proved somewhat meaningless.

The balance of the simulations predicted vehicle limit performance above and below the stable experimental limit. In general, the simulation seemed more sensitive to rollover. In its present form, the slosh dynamics augmented TDVS simulation is considered a qualitative, not quantitative, analysis tool.

The research program is reported upon in the following documents:

- The Executive Summary listing the highlights of the program (Volume 1).
- The Technical Report detailing the slosh dynamics model, research methodology, and results (Volume 2).
- The Technical Supplement containing data considered too voluminous for inclusion in the Technical Report (Volume 3).
- The User's Manual for TDVS as augmented to include slosh dynamics (Volume 4).

A parallel effort to investigate the effects of hanging meat carcasses was originally included in this cargo shifting research program. However, this work was suspended due to simulation difficulties and lack of funds. This effort is not documented in this report. The status of the research, when suspended, was as follows:

1. Hanging carcass model developed
2. Model integrated into TDVS
3. Dynamic Science full scale test data reduced for simulation comparison
4. Input data deck prepared.

The hanging load version of the simulation was programmed but never successfully executed. Initial indications were that the cost per run for the hanging load version would be at least ten times the cost per run of the liquid load version.

2.0 Slosh Dynamics Model

The modified Three Dimensional Vehicle Simulation program (hereafter referred to as TDVS/SLOSH) simulates the effects of sloshing liquid cargo in tank trucks and trailers. The tanks can be compartmented as desired with the compartment having any arbitrary location on the vehicle. The tank can be of any elliptical cross-section. Depth and density of liquid can be specified for individual compartments, as can damping ratios in the fore/aft and lateral directions to simulate baffles.

The formulation of the problem followed the direction of Weir (Reference 5). The required preliminary derivation of geometrical quantities for the mathematical description of the elliptical cross-section tank included cross sectional area, inertias and fluid centroid. The equations of motion for sloshing fluid were derived using Lagrange's equation. This required the fluid volume element to be described in terms of both kinetic and potential energies. The expression for the kinetic energy of a fluid volume element was obtained in terms of a fluid element velocity. (The analysis in this study differed slightly from Reference 5 in this area.) This velocity is the gradient of the velocity potential function. The potential energy of a sloshing fluid element can be expressed in terms of the partial derivative with respect to time of the velocity potential function via the Bernoulli equation. The kinetic energy of a fluid volume element was then integrated over the unperturbed free surface of the liquid.

Modal equations were formed for the sloshing motions using Lagrange's function. These equations of motion represent the mode shapes and undamped natural frequencies for the unforced fluid motions in the nonaccelerated tank. Using a classical vibration analogy, the equations of motion were modified to represent damped fluid motions by adding viscous damping terms. These damping terms, expressed as longitudinal and lateral damping ratios, are used to simulate baffling.

The modal equations of motion of the sloshing liquid were developed into forced vibration equations by considering the fluid motion in the accelerated tank. This required the fluid motions to be reformulated in position coordinates prior to consideration of the vehicle accelerations which induce the sloshing motions.

The last step involved development of expressions for forces and moments applied to the center of gravity of the sprung mass. This was done by obtaining an expression for the pressure throughout the fluid in terms of the partial derivative with respect to time of the velocity potential. This pressure, which acts normal to the tank surface, must be integrated over the unperturbed wetted tank surface (with the appropriate moment arms where applicable) and resolved into center-line axis force and moment components. These components are then applied to TDVS as external forces.

The assumptions made in this analysis were:

- The fluid is incompressible and inviscid.
- The fluid is initially irrotational and remains irrotational.
- Sloshing wave amplitudes are small.
- The fluid velocity potential function is independent of depth for the unaccelerated tank.

3.0 Slosh Dynamics Model Verification

Verification considered correctness of the slosh dynamics model and its implementation within the framework of TDVS. Fluid response was taken to be the primary indicator of the former and vehicle response of the latter. Experimental data were used to verify the correctness of the simulated response. Unfortunately, appropriate data were not always available. Analytical and numerical checks served as additional verification.

The lack of experimental wave data was most notable. This significantly degraded the slosh model transient response verification. The successful verification of the earlier Weir (5) slosh model against experimental data was taken as a measure of confidence in view of the modeling similarities. However, important dissimilarities exist which should be addressed; viz., the effects of elliptical tank cross-section, arbitrary fluid depth, and the viscous damping approximation to baffling. The known steady-state slosh response was verified in constant lateral (cornering) and longitudinal (braking) acceleration regimes.

The implementation of the slosh model was verified by an "equivalent load" vehicle configuration - a TDVS configuration possessing the inertial and mass properties equivalent to a tractor with half-full tank semitrailer. The fluid in the corresponding TDVS/SLOSH model was "frozen" into the static position by zeroing slosh acceleration terms. Equivalent response from both models verified correct force and moment resolution in the slosh dynamics modifications to TDVS. The calculation of an equivalent ballast cargo also served to check the correctness of initialization computations (e.g., fluid inertias, tank wetted areas) required by the slosh dynamics model.

Numerical stability of the TDVS/SLOSH model was verified in a series of runs with varied timestep. A timestep of 0.01 second was chosen as a compromise between computational accuracy and economy.

4.0 Methodology

The simulation methodology for limit performance analysis was dictated by the experimental methodology utilized by DSI in "Effect of Cargo Shifting on Vehicle Handling" study. Methodological considerations included:

- Vehicle configurations
- Maneuver types and dimensions
- Maneuver implementation
- Limit performance criteria
- Vehicle response parameters

The vehicle configurations consisted of a tractor in conjunction with one of four semitrailers:

- 40-foot (12-meter) van
- 8000 gallon (30,200 liter), 5-compartment, 34-foot (10-meter) elliptical tank
- 4700 gallon (17,800 liter), single-compartment, 40-foot (12-meter) baffled cylindrical tank
- 3850 gallon (14,600 liter), single-compartment, 44-foot (13-meter) unbaffled cylindrical tank

The experimental tractor/tank trailer vehicles are shown in Figures 1-3. The 40-foot (12-meter) van was simulated with two ballast cargo configurations of nominally twenty thousand and forty thousand pounds (9100 and 18,200 kg). The cylindrical tank trailers were simulated in the half, three-quarter, and seven-eighth full load configurations. The elliptical tank trailer was simulated with all compartments three-quarters full. The simulated liquid cargo was water in all cases.

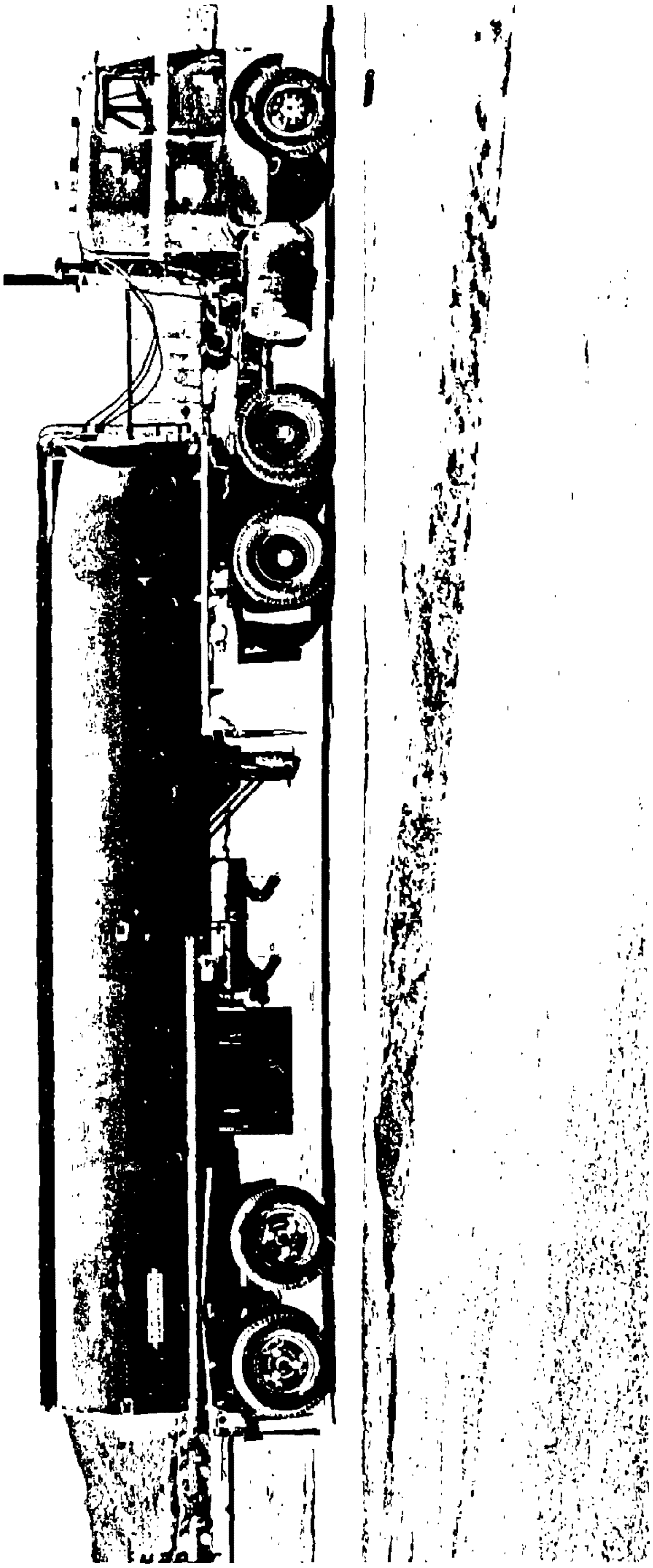


Fig. 1 Tractor with elliptical tank trailer.

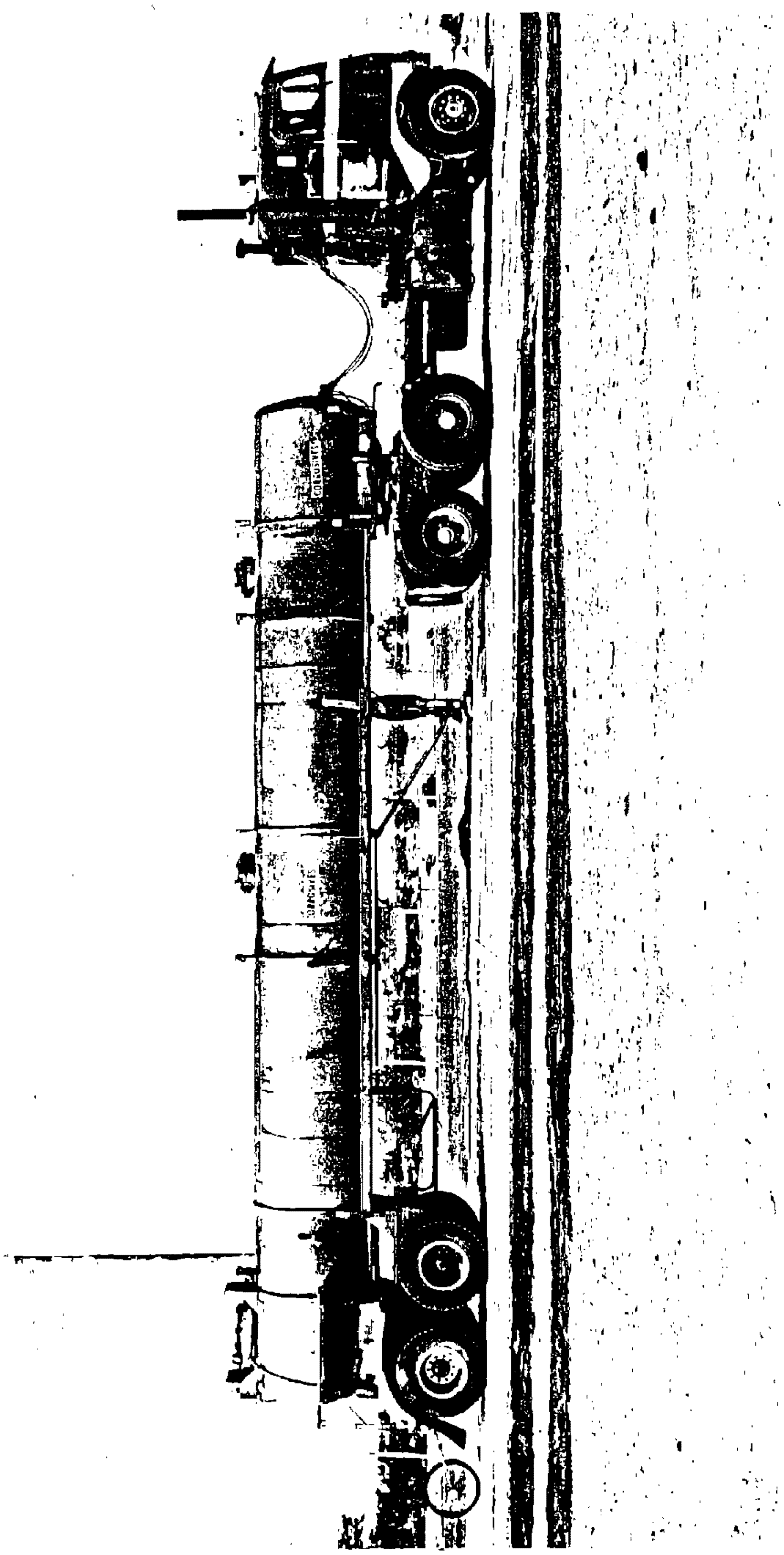


Fig. 2 Tractor with baffled tank trailer.

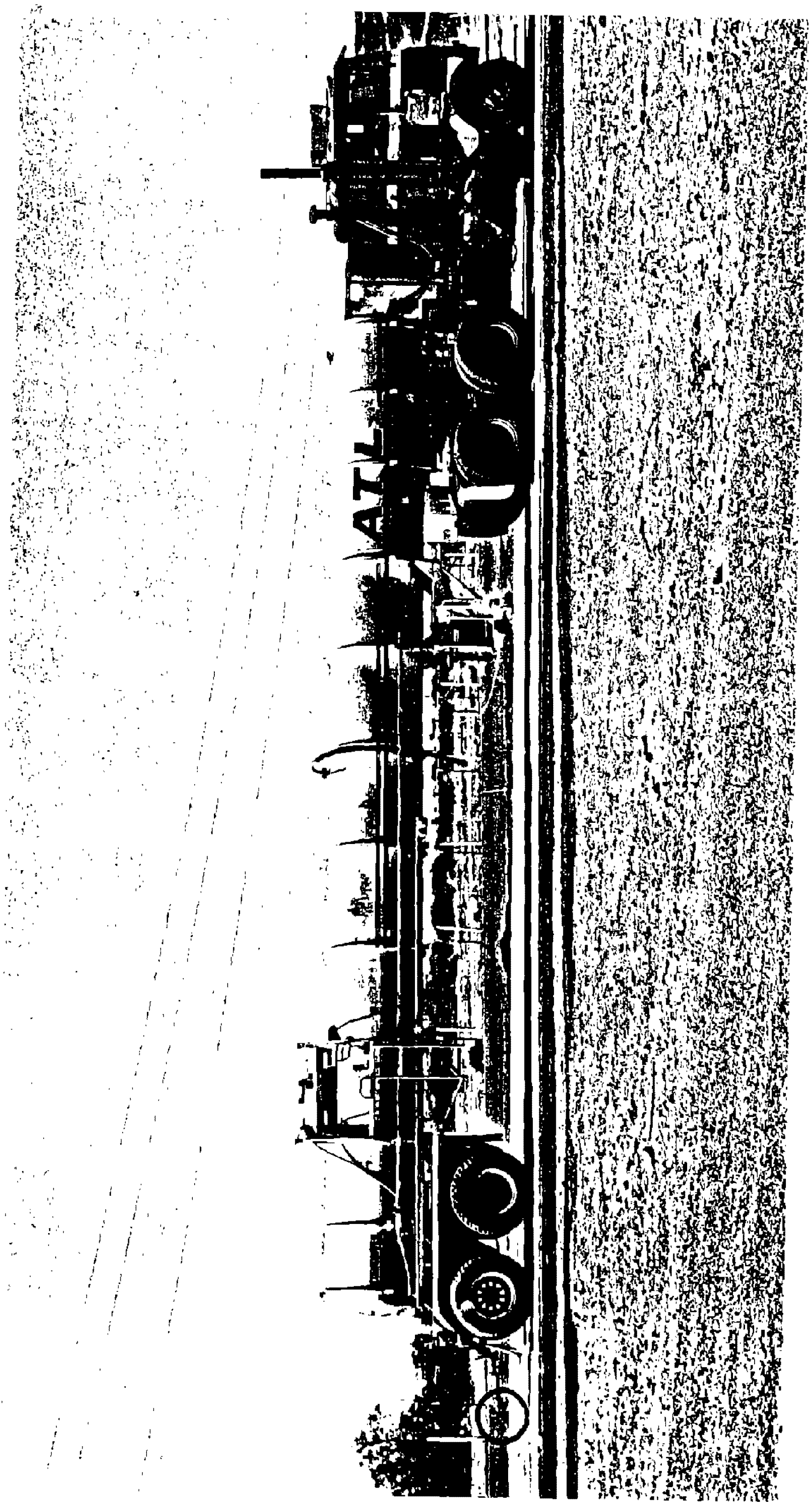


Fig. 3 Tractor with unbaffled tank trailer.

Four maneuvers testing braking and cornering performance were simulated:

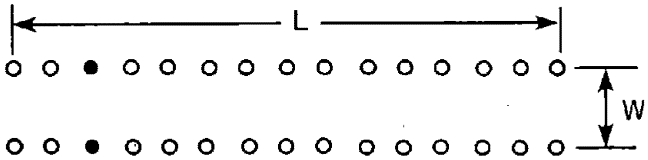
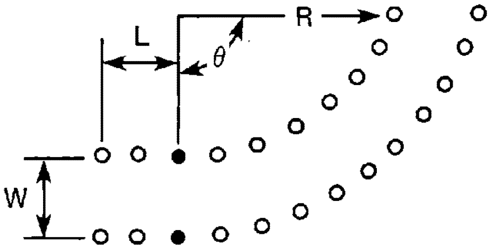
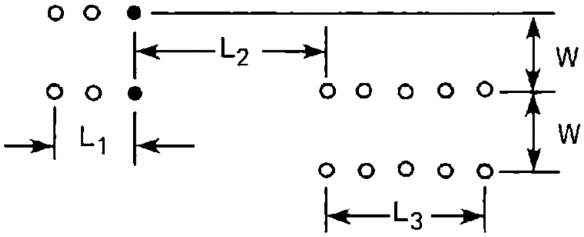
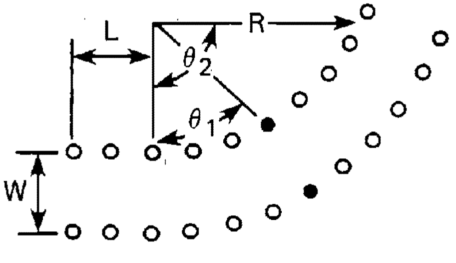
- Straight-line braking
- Lane change
- Cornering
- Braking-in-a-turn

Maneuvers were simulated for both wet and dry surfaces. The diagrammatic maneuver definitions used by DSI are illustrated in Figure 4. The matrix of simulated vehicle configurations/ maneuvers is presented in Table 1.

Three methods are available in TDVS for maneuver implementation: steer and brake input specification, acceleration specification, or path specification. The inability of the first two methods to yield reasonable path fidelity prompted the selection of the latter. Braking was simulated by imposing a longitudinal acceleration profile. Wet roadway surfaces were simulated by degrading tire/roadway friction coefficient. Parameters for path specifications, braking profiles, and roadway friction coefficient were taken from DSI experimental data.

The experimental limit performance was defined by the run with the shortest braking distance for successful braking runs and greatest entry speed for successful cornering runs. Successful experimental runs were defined as those negotiating the course without striking any pylons. The simulation limit performance was defined by maximum entry speed in a stable cornering run and maximum deceleration in a stable braking run. Stable simulation runs were defined as maneuvers with normal terminations, as opposed to instability terminations. The TDVS path-following algorithm contains such terminations for three instability modes:

- Maximum steer rate violation
- Maximum steer angle violation
- Loss of control

Maneuver	Course
Straight-line braking	 L = 1000′ W = 12′
Cornering	 W = 12′ R = 420′ θ = 135° L = 50′
Lane change	 L_1 = 50′ L_2 = 65′ L_3 = 100′ W = 12′
Braking in a turn	 W = 12′ R = 420′ θ_1 = 50° θ_2 = 135° L = 50′

● Test indicator point　　o Traffic cone

Fig. 4 Test maneuver specifications.

Table 1

Experimental limit run data selected for simulation comparison.

CONFIGURATION				MANEUVER FILE NUMBER					
TRAILER	LOAD	CODE	TAPE NO.	SBD	SSD	TSD	BTD	SSW	BTW
VAN	20K	20KB	DS-A261	39	17	53	44		111
VAN	40K	40KB	DS-A261		127				
ELLIPTICAL	3/4 FULL	3QET	DS-A210	17	20	25	31	39	43
BAFFLED	1/2 FULL	1HBT	DS-A262	11	17	32			
BAFFLED	3/4 FULL	3QBT	DS-A262	91	76	126	111	137	142
BAFFLED	7/8 FULL	7EBT	DS-A262	150	159	164			
UNBAFFLED	1/2 FULL	1HCT	DS-A263	24	29	35			
UNBAFFLED	3/4 FULL	3QCT	DS-A263	106	115	121	126	98	86
UNBAFFLED	7/8 FULL	7ECT	DS-A263	148	154	162			

MANEUVER CODE

SBD	DRY STRAIGHTLINE BRAKING
SSD/SSW	DRY/WET LANE CHANGE
TSD	DRY CORNERING
BTD/BTW	DRY/WET BRAKING IN A TURN

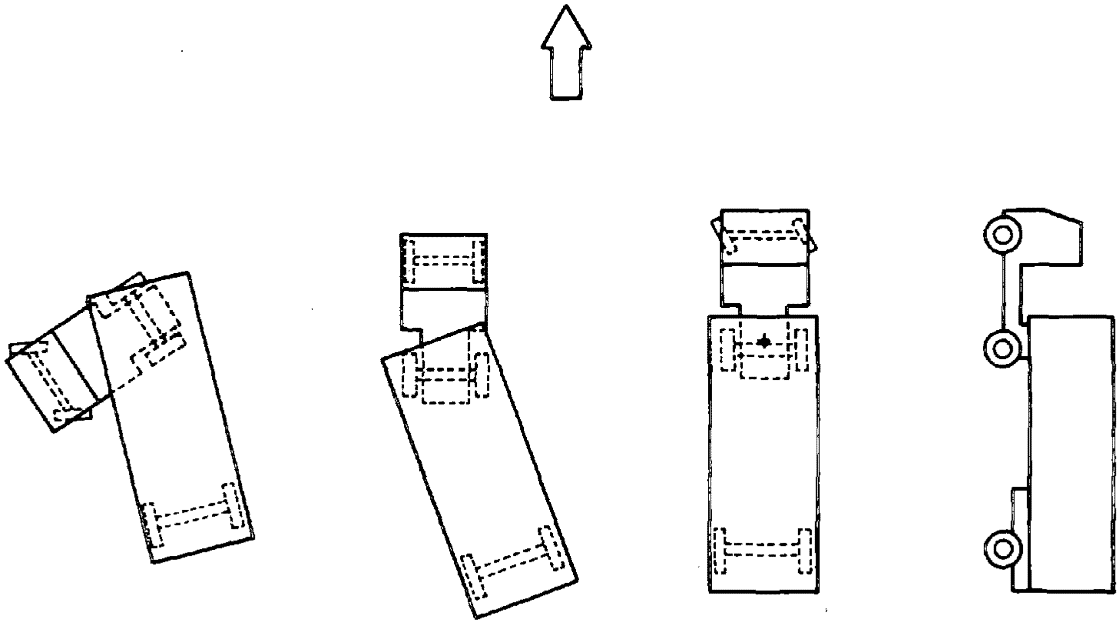
The first two modes occur when the path-following algorithm requires a steer rate or angle to achieve the desired path which violates the respective limit set in the simulation. For all limit performance simulations, the maximum steer rate and angle were set to a generous 900 deg/s and 43 deg, respectively. The latter instability mode occurs when the path-following algorithm generates complex roots.

These simulation instability modes may or may not correspond to physical instabilities. Examples of physical instability modes are rollover, jackknifing, trailer swing, and plow (Figure 5). The existence of such modes within a simulation is determined by analyzing the data. Both the simulation instability mode ("Message") and physical instability mode ("Mode") generated by exceeding the limit performance are listed in the summary tables (Tables 2-5).

Six parameters were available to compare experimental and simulated vehicle response:

- Steer angle
- Speed
- Tractor lateral acceleration
- Tractor longitudinal acceleration
- Articulation angle
- Tractor roll angle

Two of these parameters were used for simulation limit performance criteria: maximum speed for cornering maneuvers and maximum deceleration for braking maneuvers. Average deceleration values were computed for the experimental braking distances to provide a basis of performance comparison.

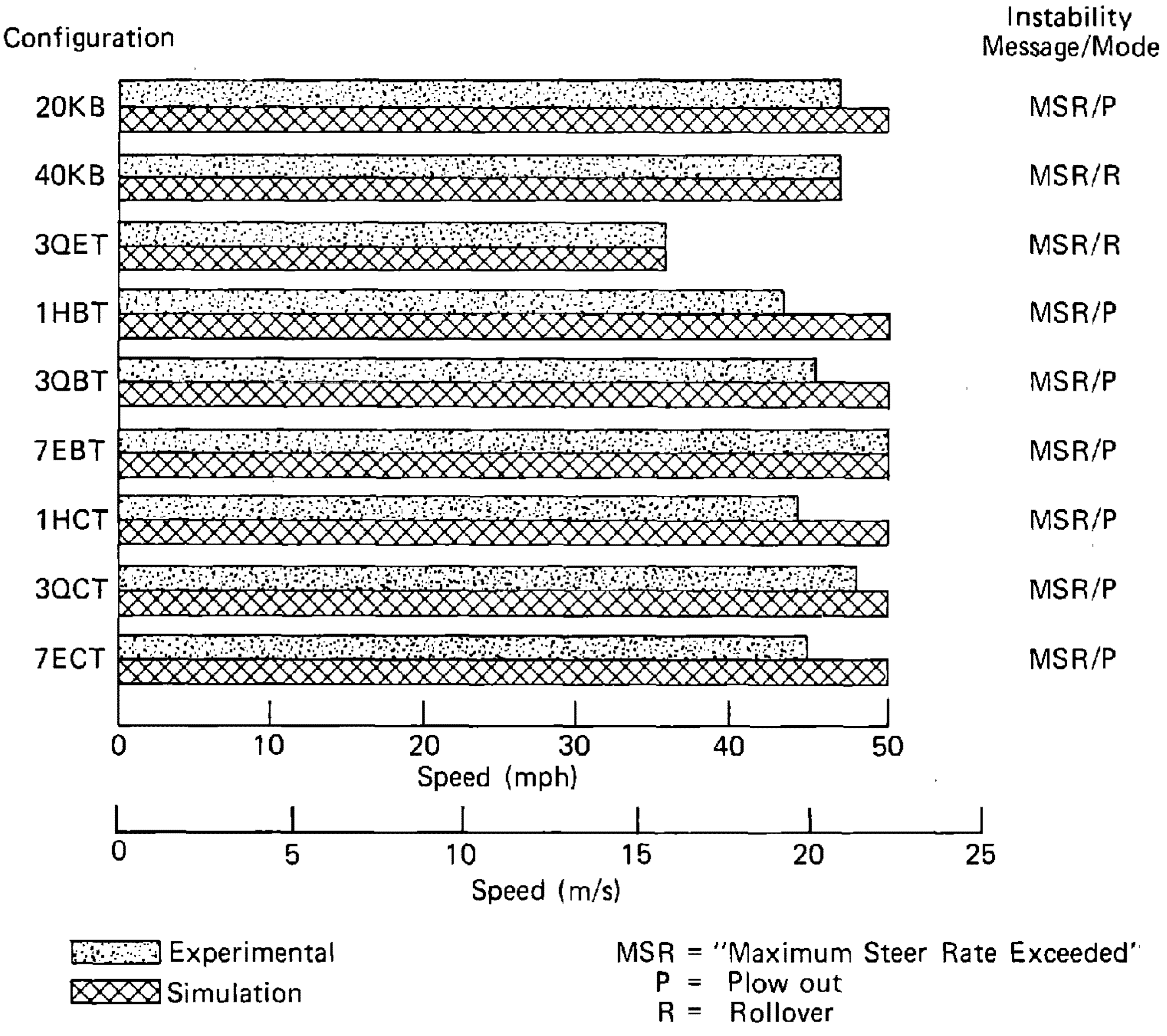


Jackknifing   Trailer swing   Plow out   Rollover

Fig. 5 **Physical instability modes for articulated truck.**

Table 2

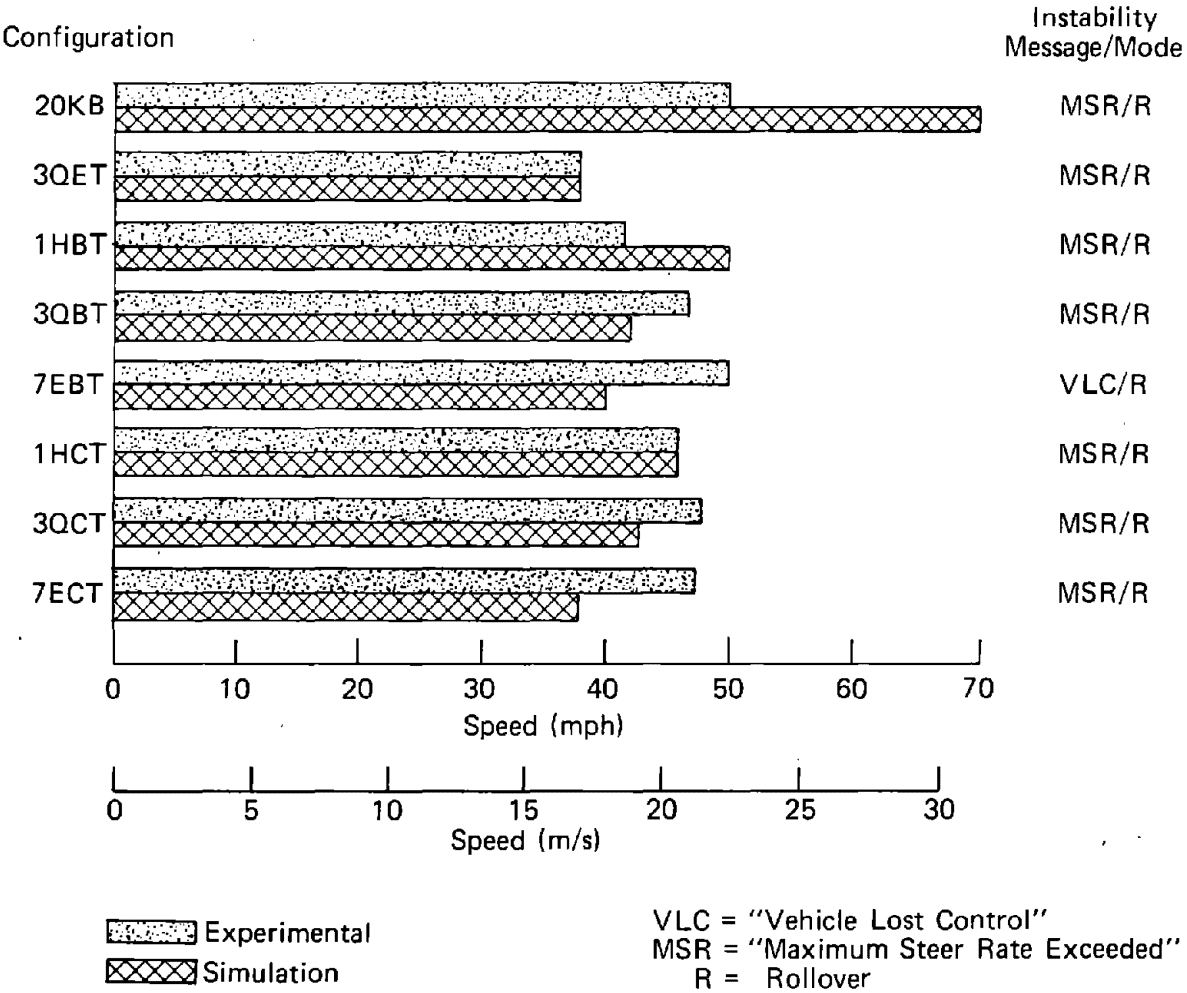
*SSD: Lane Change Maneuver Limit Performance Summary.



*Sinusoidal Steer, Dry Surface

Table 3

*TSD: Cornering Maneuver Limit Performance Summary.



VLC = "Vehicle Lost Control"
MSR = "Maximum Steer Rate Exceeded"
R = Rollover

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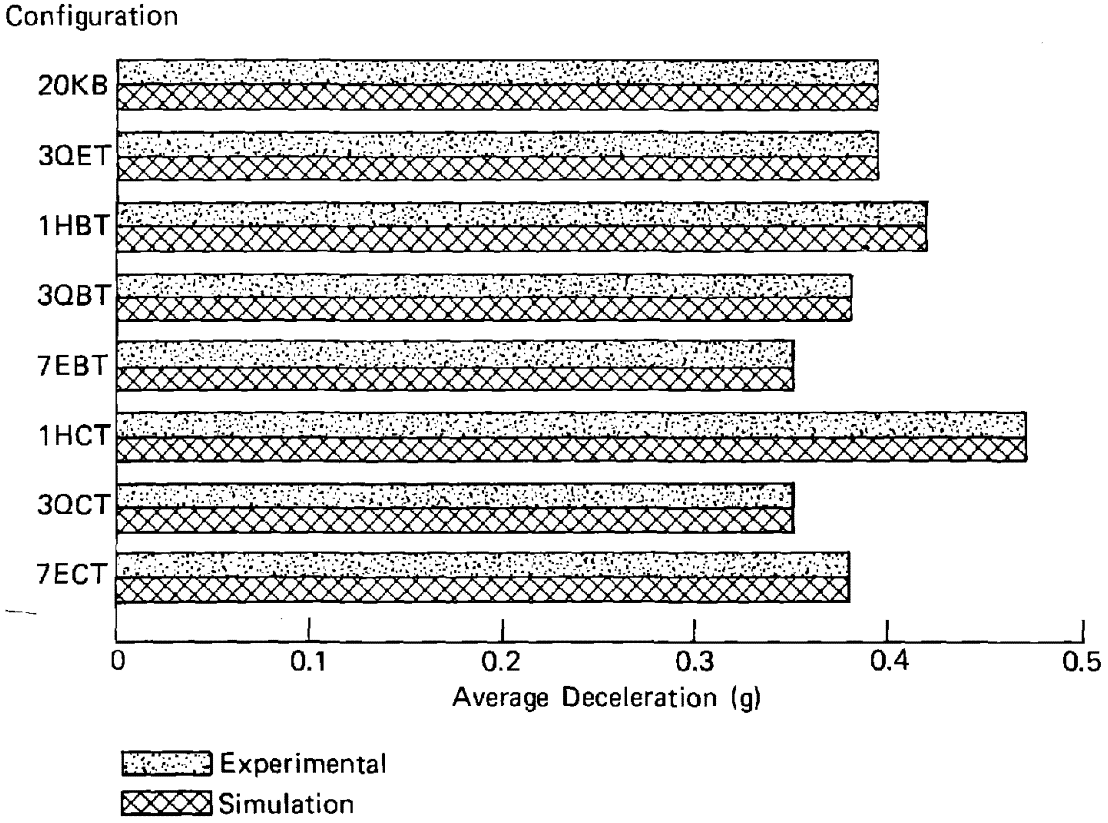
*Trapezoidal Steer, Dry Surface

Table 4

*SBD: Straight-Line Braking Limit Performance Summary.



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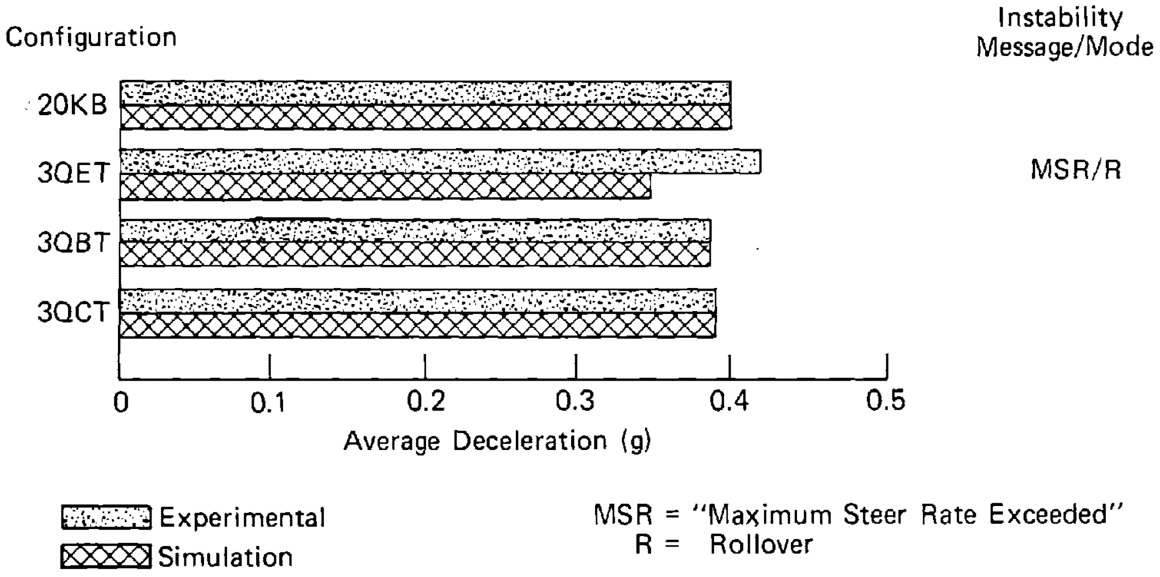
*Straight Line Braking, Dry Surface

Table 5

*BTD: Braking in a Turn Limit Performance Summary.



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*Braking-In-A-Turn, Dry Surface

5.0 Results and Discussion

The original intent was to simulate the experimental limit performance and then extend it. However, this was not always possible. The simulation limit performances are compared with the experimental limit performances by maneuver in Tables 2-5 and briefly discussed below.

5.1 Wet Braking and Cornering Maneuvers

No limit performance summaries are presented for wet braking and cornering maneuvers. The implementations of these maneuvers were not possible at tire/road friction coefficients corresponding to wet roads. The difficulties lie in the path-following algorithm which produces an instability termination for maneuvers on low friction roads.

5.2 Dry Lane Change Maneuver

For all configurations, simulated limit lane change maneuvers were at higher speeds than their experimental counterparts (Table 2). In fact, all but two configurations achieved the same limit speed of 50 mph (22 m/s); greater speeds were stymied by insufficient steer rate. The resultant vehicle behavior was to "plow" off course. The exceptional configurations, 40K ballast and three-quarter full elliptical tank, both suffered rollovers for speeds greater than the experimental limit.

5.3 Dry Cornering Maneuver

With only two exceptions, the 20K ballast and half-full baffled tank configurations, the simulation-predicted limit performance was at or below the experimental limit speed (Table 3).

The relative difference was significantly greater for the ballast cargo configurations; all others are within 20 percent. The physical instability mode was rollover in all cases. Quite unlike the experimental results, instability occurrence increases with load in the simulation study.

5.4 Dry Straight-Line Braking Maneuver

The simulation limit performance in straight-line braking was identical to the experimental limit (Table 4) for all configurations and for good reason; greater deceleration rates were not attempted. It was found that unrealistically high deceleration rates could be achieved by all vehicle configurations. This behavior stems from the lack of an adequate braking model in TDVS.

5.5 Dry Braking-In-A-Turn Maneuver

With the exception of the three-quarter full elliptical tank configuration, the straight-line braking comments apply here. The elliptical tank configuration experiences rollover at a deceleration level considerably less than the experimental limit. This is not surprising; the entry speed for this maneuver (35 mph or 16 m/s) is precariously close to the limit cornering speed (38 mph or 17 m/s).

In summary, the simulation study predicts grossly pessimistic limits for maneuvers in the wet and equally optimistic limits for dry braking. The balance of the limit performance simulations identify the instability threshold in the neighborhood of the experimental limit. In these cases, however, the simulation study does not reliably predict performance trends. In general, the simulation seems overly sensitive to rollover.

6.0 Conclusions

Conclusions were drawn with regard to the limit performance simulation results, the simulation methodology, and the TDVS/SLOSH program.

With regard to the limit performance simulation results:

1. On the influence of load configuration on instability.
    - i. In steady-state dry surface cornering, an articulated truck with fluid cargo is less stable than with ballast cargo of equivalent weight and static c.g. height (such may not hold for transient maneuvers, e.g., lane change).
    - ii. In steady-state dry surface cornering, the unbaffled tank configuration is less stable than the baffled tank for all load configurations (i.e., 1/2, 3/4, and 7/8).
    - iii. In steady-state dry surface cornering, stability decreases as load increases for both baffled and unbaffled tank configurations.
    - iv. The three-quarter full elliptical tank configuration is significantly less stable than all other configurations for both steady-state and transient dry surface cornering.
2. On the influence of maneuver on instability.
    - i. The instability mode for limit steady-state dry cornering is rollover.
    - ii. The instability mode for limit transient dry cornering (lane change) is plow out (this may result from the path-following algorithm used).

With regard to simulation methodology:

1. On requirements of experimental test data.
    - i. Experimental test data must initiate from steady state.
    - ii. Experimental test data must be indexed to both time and vehicle position.
2. On requirements of limit performance simulation studies.
    - i. For limit performance studies, a sophisticated simulation tire model is required.
    - ii. For limit performance studies, extensive vehicle parameterization data are required.
3. On requirements to simulate closed-loop maneuvers with a path-following algorithm.
    - i. The algorithm should stably handle arbitrary trajectories.
    - ii. The algorithm should restrain the vehicle within a "tolerance band" about the specified trajectory (i.e., the algorithm should not be unreasonably strict).
    - iii. Braking should be specified independently of the algorithm.

With regard to the TDVS/SLOSH simulation program:

1. The inadequacy of TDVS for limit performance studies.
    - i. The tire model does not include the longitudinal slip degree-of-freedom required for accurate braking simulation.
    - ii. The suspension limits are incorrectly implemented.
    - iii. The path-following algorithm used becomes unstable for limit maneuvers on low friction surfaces.

2. The inadequacy of the slosh dynamics model for limit performance studies.
    - i. The wave height constraint is incorrectly implemented with respect to fluid depth.
    - ii. The correctness of the pseudo-baffling viscous damping has not been verified.
    - iii. The linearizing assumptions of the slosh model are probably not valid for limit maneuvers.

7.0 Recommendations

Recommendations are presented for enhancements to the TDVS/SLOSH simulation program, simulation study requirements of experimental data, and future research.

For enhancements to the TDVS/SLOSH simulation program:

i. The code should be rewritten in a more clear and concise manner.
ii. The tire model should include the longitudinal slip degree-of-freedom.
iii. The suspension limit code should be corrected to model stop impact.
iv. The slosh constraint code should be corrected.
v. A more sophisticated integration routine should be implemented to improve performance prediction.
vi. The initialization procedure should be altered to allow kinematic and vehicle initiation conditions.

For simulation study requirements of experimental data:

i. For limit performance studies, the test vehicle should be extensively parameterized (tires should be parameterized in situ, i.e., for the test track surface utilized).
ii. Experimental test data should initiate from steady-state.
iii. Experimental test data should be indexed to both time and vehicle position.
iv. Experimental test data should include error bound estimates (one technique might require several gyro packages per sprung mass; quoting an instrument manufacturer's austere performance specification is inadequate).

For future research:

i. The slosh model should be more extensively verified (parameter studies, e.g. effects of tank ellipticity on stability, could then be carried out with confidence).

ii. Alternate path-following algorithms should be researched.

iii. Probabilistic and frequency analysis techniques should be investigated for experimental/simulation data correlation.

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