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REDUCING THE RISK OF SPILLAGE IN THE TRANSPORTATION OF CHEMICAL WASTES BY TRUCK

By:

Robert D. Ervin
Arvind Mathew

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16. Abstract

The spillage of liquids in bulk quantities during transportation is examined from the viewpoint of the risk reduction which will result from improved vehicle roll stability. Roll stability limits were first computed for conventional vehicles used currently by the Rohm and Haas Company to transport chemical waste products. The vehicles in question included tractor-semitrailer combinations having both van- and tank-type trailer configurations. The stability level of individual vehicles was related to a national rate of rollover risk, expressed in rollovers per million miles of travel. The risk projections were based upon an evaluation of accident and exposure information generated through a detailed survey program undertaken previously.

Improvements in suspension selection, height of the payload center of gravity, and tractor axle width were also examined by means of the stability analysis. When used in combination, such improvements were seen to reduce the rollover risk by as much as 35% relative to Rohm and Haas' current equipment. The problem of fluid slosh occurring when a bulk tanker is underfilled was also considered by reference to existing literature.

17. Key Words
safety, rollover, tractor-semitrailers, fluid spillage, fluid slosh, stability, chemical wastes

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1.0 INTRODUCTION

This report deals with a limited set of computations showing the roll stability levels of tractor-semitrailers used in the transportation of chemical wastes and the likely rollover accident rate that may derive from the operation of such vehicles on U.S. roads. The vehicles were selected to represent van-semitrailer and tank-semitrailer combinations such as are operated by the Rohm & Haas Corporation. The stability levels computed for these vehicles cover both a baseline configuration of each vehicle type and various changes in configuration that are being considered in the interest of improving safety performance. The safety performance of differing vehicles was addressed in this study only in the context of the risk of vehicle rollover. The study was confined to the rollover issue in recognition of the fact that the spillage of bulk quantities of liquid cargo in truck accidents involves rollover in approximately 95% of recorded cases. [1]

The report presents a definition of the vehicles studied, the variations which were made in examining each, and the results of a computerized analysis of static roll stability. A companion examination of truck accident data was employed to develop a generalized curve relating the static roll stability of a tractor-semitrailer to the expected rate of rollover accidents, expressed in rollovers per million miles of vehicular travel. This curve, which was first developed a few years ago [1] in UMTRI investigations using the accident file of the Bureau of Motor Carrier Safety of the U.S. Department of Transportation, was revised in the course of the current effort with the aid of a new data set produced through new survey techniques by UMTRI's Center for National Truck Statistics.

The results of the study are expressed in terms of the rollover risk that is associated with each vehicle configuration that was examined. It is expected that such results would contribute to cost/benefit considerations by the sponsor. Decisions could then be made on the selection of vehicles which would yield a cost-effective minimum of rollover incidents and spills of chemical wastes in highway transportation.

2.0 VEHICLE CONFIGURATIONS STUDIED

Two basic vehicle types were considered in the analysis. A five-axle tractor/van-semitrailer combination was evaluated with a payload arrangement that involved a full load of 55-gallon drums. The drums were considered to be evenly distributed within the trailer and stacked only one high on the floor of the trailer. The full set of parameters used to define the static roll properties of this vehicle are presented in Table 1. The specific values represented in the table were obtained largely from prior measurements conducted by UMTRI using components and vehicle layouts comparable to those employed by Rohm & Haas. Engineering drawings of the the Rohm & Haas semitrailer plus specifications for chassis components provided the basis for matching existing component data with the specific vehicle in question.

The second vehicle of interest was a five-axle tractor/tank-semitrailer combination. One set of tank dimensions, as they represented the height of the center of gravity of the tank and liquid payload, were found to correspond to both a 5,000-gallon compartmented tanker and a 5,300-gallon cleanbore tanker that were operated by Rohm and Haas. Since both of these tank vehicles also incorporated the same suspensions, tires, and weight distribution, and were used in conjunction with the same tractor unit, one set of parameters was employed in simulating both units. The corresponding parameter list is shown in Table 1. As noted in the table, the tank vehicle was analyzed for the case in which the overall width was 102 inches as well as the more common case of 96-inch overall width.

It was observed that the both the tractors and semitrailers employed by Rohm & Haas incorporated components and dimensions which were very typical of the more popular equipment seen in broad service in the U.S.

Table 1. Parameter Values Used in Computing the Static Roll Stability of the Baseline Van and Tank Semitrailer Combinations.

Variable description	Variable name	Tractor and van trailer	Tractor and tank trailer
Weight of the front axle (lb)	WU1	1200.00	1200.00
Weight of the tractor's tandem axles (lb)	WU2	5000.00	5000.00
Weight of the trailer's tandem axles (lb)	WU3	3572.00	3000.00
Load carried by the front axle (lb)	WAXL1	12131.00	12136.00
Load carried by the tractor's tandem axles (lb)	WAXL2	33896.00	33946.00
Load carried by the trailer's tandem axles (lb)	WAXL3	33973.00	33917.00
Half track width of the front axle (in)	T1	40.00	40.00
Half track width of the tractor's tandem axles (in)	T2	29.50	29.50
Half track width of the trailer's tandem axles (in)	T3	32.50	29.50
Dual tire spacing on the front axle (in)	A1	0.00	0.00
Dual tire spacing on the inner tires on the tractor's tandem axles (in)	A2	13.00	13.00
Dual tire spacing on the inner tires on the trailer's tandem axles (in)	A3	13.00	13.00
Half spring spacing on the front axle (in)	S1	16.00	16.00
Half spring spacing on the tractor's tandem axles (in)	S2	19.00	19.00
Half spring spacing on the trailer's tandem axles (in)	S3	22.12	19.00
C.g. height of the tractor's cab (in)	ZS1	38.79	38.79
C.g. height of the rear of the tractor (in)	ZS2	38.00	38.00
C.g. height of the trailer (in)	ZS3	69.50	86.50
Rolling radius of tires on the front axle (in)	R1	19.00	19.00
Rolling radius of tires on the tractor's tandem (in)	R2	19.00	19.00
Rolling radius of tires on the trailer's tandem (in)	R3	20.00	20.00
Height of the roll center of the front axle (in)	HR1	18.25	18.25
Height of the roll center of the tractor's tandem (in)	HR2	27.00	27.00
Height of the roll center of the trailer's tandem (in)	HR3	28.25	29.00
Height of the fifth wheel center (in)	Z5	48.00	48.00
Tractor frame torsional axis height (in)	ZFR	38.00	38.00
Vertical spring rate of a tire on the front axle (lb/in)	KT11	5000.00	5000.00
Vertical spring rate of dual tires on the tractor's tandem (lb/in)	KT21	10000.00	10000.00
Vertical spring rate of dual tires on the trailer's tandem (lb/in)	KT31	10000.00	10000.00
Auxiliary roll stiffness of the front axle (in.lb/rad)	KRS1	8700.00	8700.00
Auxiliary roll stiffness of the tractor's tandem (in.lb/rad)	KRS2	30000.00	30000.00
Auxiliary roll stiffness of the trailer's tandem (in.lb/rad)	KRS3	36000.00	120000.00
Tractor frame torsional stiffness (in.lb/rad)	MFR	9603.00	9603.00
Coulomb friction present in tractor frame (lb)	COULFR	3036.00	3036.00
Trailer structural and fifth wheel compliance (in.lb/rad)	M5	1000000.00	1000000.00
Moment that causes separation of the fifth wheel plates (in.lb)	MOMSEP	531486.40	532489.00
Separation of the fifth wheel (in)	LASH	0.00	0.00
Vertical load carried by the fifth wheel assembly (lb)	W5	29527.00	29582.70
Weight of the tractor's rear sprung mass (lb)	WS2	1000.00	1000.00
Lateral stiffness of a tire on the front axle (lb/in)	KYT1	5000.00	5000.00
Lateral stiffness of dual tires on the tractor's tandem (lb/in)	KYT2	10000.00	10000.00
Lateral stiffness of dual tires on the trailer's tandem (lb/in)	KYT3	10000.00	10000.00
Overturning stiffness of a tire on the front axle (lb/in)	KOVT1	352.20	352.20
Overturning stiffness of dual tires on the tractor's tandem (lb/in)	KOVT2	704.40	704.40
Overturning stiffness of dual tires on the trailer's tandem (lb/in)	KOVT3	704.40	704.40
Roll increment (deg)	DELPH	0.10	0.10
Printout increment (deg)	XPRINT	0.50	0.50

Table 1. (Continued)

	Tractor and van trailer		Tractor and tank trailer	
	Force (lb)	Deflection (in)	Force (lb)	Deflection (in)
Spring table for the front axle	-19075.00	-20.00	-19075.00	-20.00
	-787.50	-0.75	-787.50	-0.75
	-75.00	0.00	-75.00	0.00
	825.00	1.00	825.00	1.00
	1775.00	2.00	1775.00	2.00
	2200.00	2.50	2200.00	2.50
	3230.00	3.50	3230.00	3.50
	4250.00	4.50	4250.00	4.50
	20253.57	20.00	20253.57	20.00
Spring table for tractor's tandem	-23225.00	-10.00	-22002.60	-10.00
	-10725.00	-5.00	-10160.60	-5.00
	-100.00	-0.75	-94.80	-0.75
	-100.00	0.00	-94.80	0.00
	2800.00	0.50	2652.60	0.50
	11100.00	1.50	10515.80	1.50
	16200.00	2.00	15347.40	2.00
	58377.00	6.50	55304.60	6.50
	72471.00	8.00	68656.80	8.00
Spring table for trailer's tandem	-5487.70	0.37	-83350.00	-2.00
	-1758.88	0.69	18600.00	-0.75
	-267.36	0.93	21200.00	-0.25
	180.10	2.43	22275.00	0.00
	4207.22	3.01	23325.00	0.25
	10173.32	3.65	25550.00	0.75
	13752.98	4.00	26775.00	1.00
	20614.00	4.59	86812.50	2.50
	27027.55	5.02		
	37766.54	5.60		

3.0 CONFIGURATION VARIATIONS

Since the purpose of this study was to examine means for improving roll stability in Rohm & Haas vehicles, a number of computations of the rollover threshold were made for cases in which parameters were varied away from the baseline designs. Parameters were varied singly and in combination in order to show alternative schemes for improvement. A few partial load cases were also examined to show the influence of common under-fill conditions on the static roll stability level. In none of these cases was the extent of partial loading such as to permit liquid sloshing.

The variations that were studied are defined below:

for the van semitrailer,

- **a forward bias of 75% payload weight** -- meant to represent the case in which the rear quarter of the trailer is not loaded. This case involves a reduction in payload weight which, of itself, tends to improve roll stability. At the same time, the rear-empty case causes a greater fraction of the load to bear on the tractor suspensions, thus somewhat reducing vehicle stability. The trade-off between these two effects is evident in the total analyzed stability level.
- **stiff trailer suspension** -- an alternative trailer suspension is selected. The alternative is chosen to represent the highest level of vertical stiffness which is seen in trailer service in the U.S., given available data.
- **stiff tractor rear suspension** -- an alternative tractor rear suspension is selected. The alternative is chosen to represent the highest level of vertical stiffness which is seen in the rear tandem position on tractors in the U.S., given available data.
- **stiff tractor and trailer suspensions** -- both of the stiffened suspensions from above are combined in the analyzed vehicle combination.
- **trailer's center of gravity height is lowered by 12 inches** -- the height of the trailer sprung mass (van body and payload mass) is lowered by 12 inches relative to the baseline location. Such a height reduction could be achieved, in practice, through a major reconfiguring of the trailer design, such as in a drop-frame trailer. Configurations of this type are known to be impractical for normal dock entry with fork lifts but may have limited application where product can be loaded through specialized means.
- **wide tractor suspension** -- the overall width across the tires on the tractor tandem is increased from 96 inches to 102 inches. Although such widened tractor drive axles are not now available on the market, it is anticipated that such hardware will be available at some point in the future. Thus, this variation provides an indication of a possible stability enhancement that may prevail in the future.

for the tank semitrailer,

- **a 90% payload level** -- the liquid payload in the tanker is reduced to a uniform level representing 90% of the baseline payload volume. At this level, the payload does not slosh perceptibly, but the center of gravity reduces considerably to yield a stability improvement.
- **trailer's fourth compartment empty** -- the fluid is completely removed from the rearmost compartment of the 4-compartment, 5,000-gallon tanker. This loading case is analogous to the rear-unloaded case with the van semitrailer in which a somewhat lighter payload weight prevails, but the load is borne more fully by the tractor suspensions.
- **trailer's third compartment empty** -- same as the above case, except that only the third of four tank compartments is empty.
- **stiff trailer suspension** -- the stiffest available trailer suspension is installed in place of the baseline trailer suspension.
- **stiff tractor rear suspension** -- the stiffest available tractor drive axle suspension is installed in place of the baseline suspension at the tractor drive axle positions.
- **stiff tractor and trailer suspensions** -- both of the stiffer suspensions are installed at the same time.
- **trailer's center of gravity height is lowered by 12 inches** -- the height of the trailer sprung mass (tank and payload mass) is lowered by 12 inches relative to the baseline location. Such a height reduction could be achieved, in practice, through a major reconfiguring of the trailer design, such as with a drop-section tank. Although such designs are relatively expensive, they are thought to be achievable within conventional practices of tank manufacturers.
- **wide tractor suspension** -- the overall width across the tires on the tractor tandem is increased from 96 inches to 102 inches, as discussed above.

4.0 ANALYSIS OF STATIC ROLLOVER THRESHOLD

The static roll stability of each vehicle in each of the represented configurations was determined using an analysis program called the UMTRI Static Roll Model. This method describes the vehicle in terms of masses, spring properties, and geometry so as to determine the level of steady lateral acceleration beyond which rollover will occur. The result of this analysis is a "static rollover threshold" value, expressed in g's of lateral acceleration. The analysis determines the rolling of the tank and payload mass due to suspension deflection, the rolling of each axle mass due to tire deflection, and the net lateral movement of the masses which results from this roll activity and which finally influences the static rollover threshold.

The static roll model determines the roll stability limit by incrementing the sprung mass roll angle up to the point at which the so-called "critical wheel liftoff" occurs. Beyond this point, even though the steering axle tires are typically still on the ground, an unstable roll motion ensues. Commonly, the critical point coincides with the liftoff of the tractor's drive axle tires.

This static roll model is documented in Reference [2].

5.0 ANALYSIS OF REFERENCE CURVE FOR ROLLOVER ACCIDENT RATE

A previous examination of accident data was refined in the course of this study to provide a refined illustration of the influence of rollover threshold on the likelihood of rollover accident involvement. The following steps were taken to produce a refined predictive method:

- A new data file produced by the UMTRI's Center for National Truck Statistics was employed to relate cases in which rollover occurred with the gross vehicle weight of the involved truck. The accident cases of interest were those involving 5-axle van-semitrailers. All of the accidents in this file involved a fatality.
- For each rollover case, an estimate of the rollover threshold of the involved vehicle was computed using (a) the gross weight information, (b) a protocol for estimating the height of the payload center of gravity (c.g.), and (c) values for suspension, tire, and geometric parameters which correspond to typical hardware used in the U.S. trucking fleet.
- Two protocols for estimating the height of the payload center of gravity were developed. In one, the payload c.g. height was assumed fixed at an elevation of 80 inches and the payload weight was incremented upward to match the gross weight condition reported for each vehicle. In the second protocol, the payload density was assumed fixed and an assumed stack of freight was gradually built up from the floor of the trailer as payload weight went up. Although a preliminary display of the data for both protocols is shown, the "constant density" protocol was selected as the more representative case for presentation of the study findings.
- Recognizing that for each rollover event that produces a fatality there are many more rollovers with no fatality, it was necessary to obtain a conversion from the available (all-fatal) data to the numbers representing all rollovers. (Note that since the issue in the potential spillage of chemical wastes is simply that of rollover, per se, in which the trailer strikes the ground, it is the "all-rollover" statistic that is most relevant to the objectives of this study). The conversion value was derived from data obtained through the National Accident Sampling System which is developed by the U.S. Department of Transportation, indicating that 33 rollovers occur with tractor-semitrailers for each fatal rollover.
- In order to obtain an accident rate, measured in rollovers per million vehicle-miles of travel, the exposure data from the National Truck Trip Inventory Survey was employed in the analysis. These data represent the first authoritative measure of the mileages actually accumulated by heavy-duty vehicles in this country. Mileages were obtained for 5-axle tractor/van-semitrailer combinations at each of the increments of gross vehicle weight for which rollover accidents were determined.

- These multiple sets of information were combined such that, in each gross weight category, the number of rollovers, number of vehicle-miles of travel, and the computed value for rollover threshold (see Table 2) could be employed in one plotted relationship. Using both of the candidate protocols for estimating the height of the payload center of gravity, the results of this analysis are shown in Figure 1. The figure shows solid data points and a somewhat steeper curve corresponding to the "constant c.g. height" protocol. The "constant density" protocol is marked by the open square data points and the fitted curve which goes further to the left on the figure. In both cases, although the data show a substantial amount of scatter, they still provide good definition of a curve which matches our general understanding of the nature of these phenomena. [3]

In the results projecting rollover risks for Rohm & Haas vehicles, presented in the next section, only the constant density curve is employed. This curve shows that when rollover threshold is at 0.75 g's, as with empty units, tractor-semitrailers experience approximately 0.25 rollovers per million vehicle miles, or one rollover every 4 million miles in that condition. Conversely, a unit carrying a full load of freight that results in a rollover threshold down in the vicinity of 0.24 g's should expect 1.5 rollovers per million miles, or one every 667,000 miles.

Although these data represent a national sample from all kinds of trucking operations, and even though the data have been processed with some simplifications regarding placement of payload center of gravity, we believe that they illustrate a basically factual relationship that will apply, at least qualitatively, to Rohm & Haas operations, as well. Further, they show the same nominal multiplication in rollover risk, going from empty to loaded, that was seen through the independent set of accident data reported eight years ago in Reference [1]. As for the absolute level of risk indicated on the vertical axis, it should be recognized that large variations in this scale have been observed from one type of trucking operation to the next. Thus, while fully loaded trucks in general use in this country may suffer as many as 1 rollover every 667,000 miles of travel, it may well be that Rohm & Haas could expect a much lower absolute level of risk due to a carefully selected driver pool, better training and followup on driver performance, better vehicle maintenance, improved route selection, etc.

Table 2. Numerical Data Produced from Accident and Exposure Data Files, Together with Static Rollover Thresholds Corresponding to Selected Increment in Gross Vehicle Weight.

Weight Groups	Annual rollovers of specific weight groups as a percentage of all rollover accidents of 5 axle van trailers	Annual exposure of specific weight groups as a percentage of total travel of 5 axle van trailers	Ratio of % rollover accidents to % annual exposure of 5 axle van trailers	Total number of rollover accidents per million miles of travel for the specific weight class of 5 axle van trailers	Rollover threshold with a constant density payload	Rollover threshold with the payload at a c.g. height of 80"
35-40,000 lb	2.30	4.65	0.49	0.251	0.643	0.551
40-45,000 lb	3.30	5.36	0.62	0.317	0.597	0.511
45-50,000 lb	5.50	7.65	0.72	0.367	0.551	0.484
50-55,000 lb	6.30	3.95	1.59	0.819	0.502	0.461
55-60,000 lb	6.80	7.26	0.94	0.481	0.457	0.446
60-65,000 lb	8.00	7.09	1.13	0.583	0.414	0.431
65-70,000 lb	18.30	9.10	2.01	1.036	0.373	0.416
70-72,500 lb	11.60	8.71	1.33	0.688	0.344	0.407
72.5-75,000 lb	13.00	10.09	1.29	0.662	0.325	0.401
75-76,000 lb	3.00	2.47	1.21	0.621	0.313	0.397
76-77,000 lb	2.50	3.33	0.75	0.381	0.307	0.395
77-78,000 lb	3.00	1.68	1.79	0.912	0.300	0.393
78-79,000 lb	2.00	1.24	1.61	0.811	0.292	0.390
79-80,000 lb	3.40	0.56	6.07	3.147	0.285	0.388
> 80,000 lb	0.70	1.42	0.49	0.262	0.282	0.387

Weight Groups	Annual rollovers of specific weight groups as a percentage of all rollover accidents of 5 axle van trailers	Annual exposure of specific weight groups as a percentage of total travel of 5 axle van trailers	Ratio of % rollover accidents to % annual exposure of 5 axle van trailers	Total number of rollover accidents per million miles of travel for the specific weight class of 5 axle van trailers	Rollover threshold with a constant density payload	Rollover threshold with the payload at a c.g. height of 80"
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45-50,000 lb	5.50	7.65	0.72	0.367	0.551	0.484
50-55,000 lb	6.30	3.95	1.59	0.819	0.502	0.461
55-60,000 lb	6.80	7.26	0.94	0.481	0.457	0.446
60-65,000 lb	8.00	7.09	1.13	0.583	0.414	0.431
65-70,000 lb	18.30	9.10	2.01	1.036	0.373	0.416
70-72,500 lb	11.60	8.71	1.33	0.688	0.344	0.407
72.5-75,000 lb	13.00	10.09	1.29	0.662	0.325	0.401
75-77,500 lb	5.90	6.32	0.93	0.478	0.307	0.396
77.5-80,000 lb	7.90	2.97	2.66	1.374	0.291	0.391
> 80,000 lb	0.70	1.42	0.49	0.262	0.282	0.387

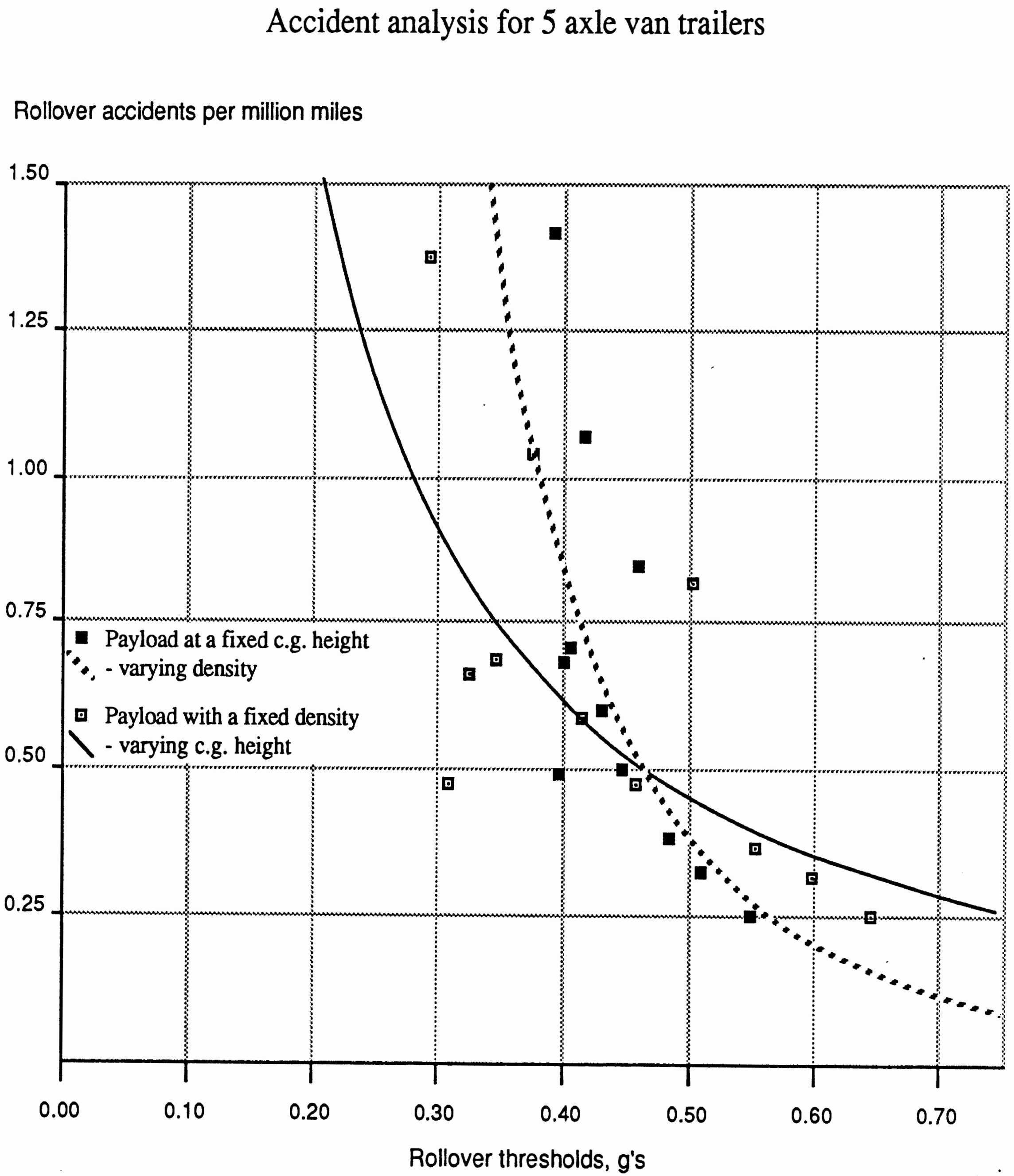


Figure 1. Rollover rate vs. rollover threshold for two different c.g. placement protocols.

6.0 ROLLOVER ACCIDENT RISKS FOR BASELINE VEHICLES AND SELECTED VARIATIONS

Values for the rollover threshold and predicted rollover accident rates corresponding to each of the vehicle cases of interest have been prepared in both tabular and graphical formats. Three sets of results will be presented, covering (a) the tractor and van semitrailer and both (b) 96-inch wide and (c) 102-inch wide versions of the tank semitrailer. For each basic configuration, a set of variations are presented as discussed earlier.

Figures 2, 3, and 4 show the computed results corresponding to each of the respective vehicle configurations. On each figure, the data points representing the Rohm & Haas baseline and variation vehicles are shown with comparison to the point representing the MC-306 gasoline tanker used commonly in the United States. This latter vehicle, having a rollover threshold of 0.32 g's, may be looked upon as something of a reference (although not an ideal, in any sense of the word) for transportation of hazardous liquids in bulk. Each figure also presents a tabular reporting of the coordinates of each point on the graph. The numbers entered adjacent to each data point on the graph correspond to the itemized variations listed in the table.

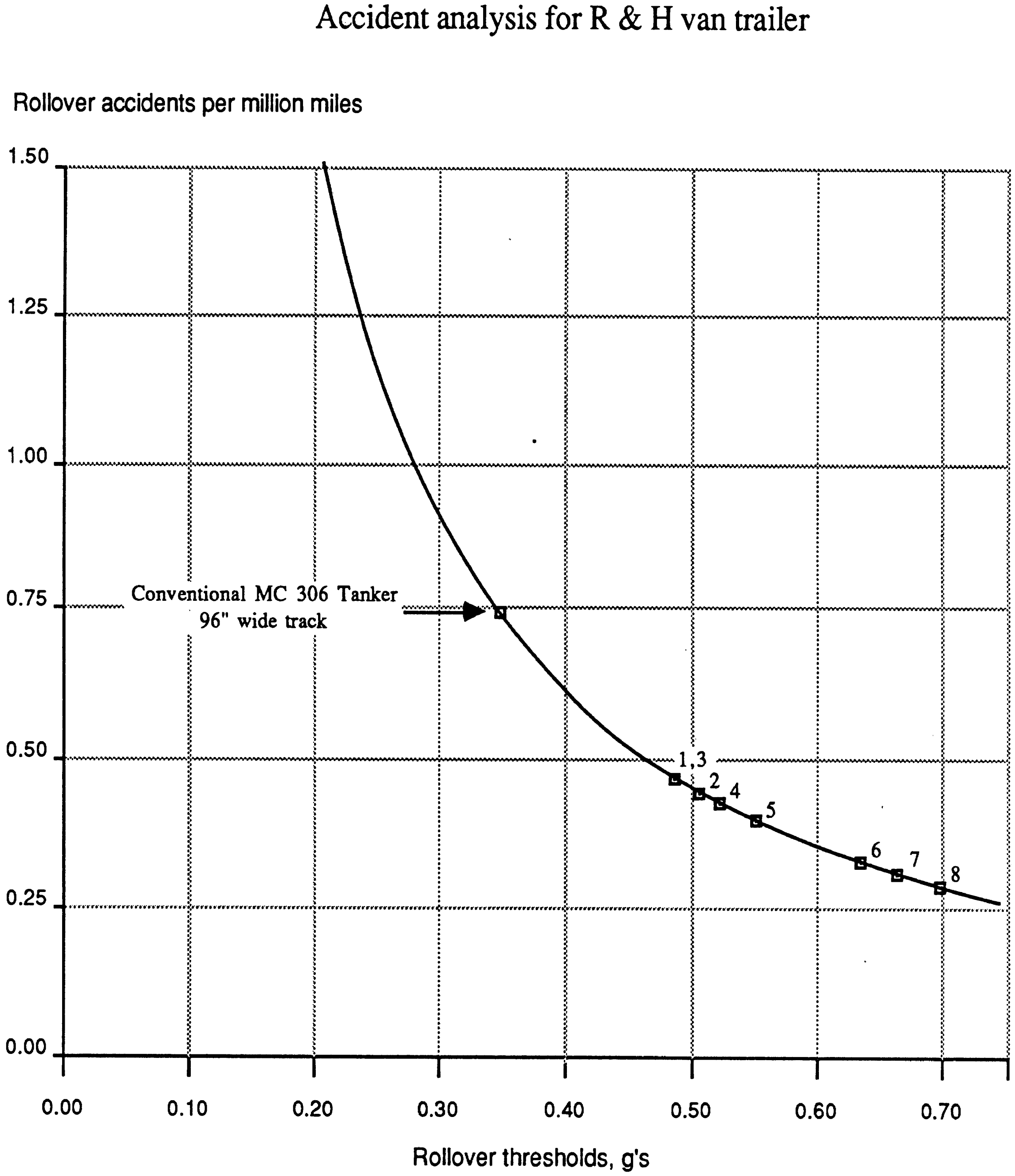
Looking at Figure 2, we note, for example, that the variations, 1 through 8 for the tractor and van semitrailer cover a range of rollover thresholds from 0.490 to 0.693 g's. The corresponding values for the predicted rate of rollover occurrence range from 0.466 to 0.292 rollovers per million vehicle miles of travel. The following observations can be made:

- The baseline case, No. 1, shows a rollover threshold level which is decidedly above the 0.32-g value for the MC-306 reference tanker. As a result, we predict a much lower occurrence of rollovers with this vehicle than occurs in the operation of the reference tanker combinations (assuming that the 55-gallon drums are constrained within the Rohm & Haas van trailer so as to prevent lateral shifting motions.)

- In Case 2, a small improvement in roll stability derives from the rear-empty loading condition, indicating that the stability benefit deriving from payload reduction is greater than the destabilizing effect of placing a larger fraction of the total trailer load onto the tractor suspensions.

- Stiffening the trailer suspension, by itself, in Case 3, causes a very small decline in rollover threshold. This result is due to an anomaly in trailer roll moment development after the trailer axles lift off the ground, but before the tractor wheels have begun to lift off.

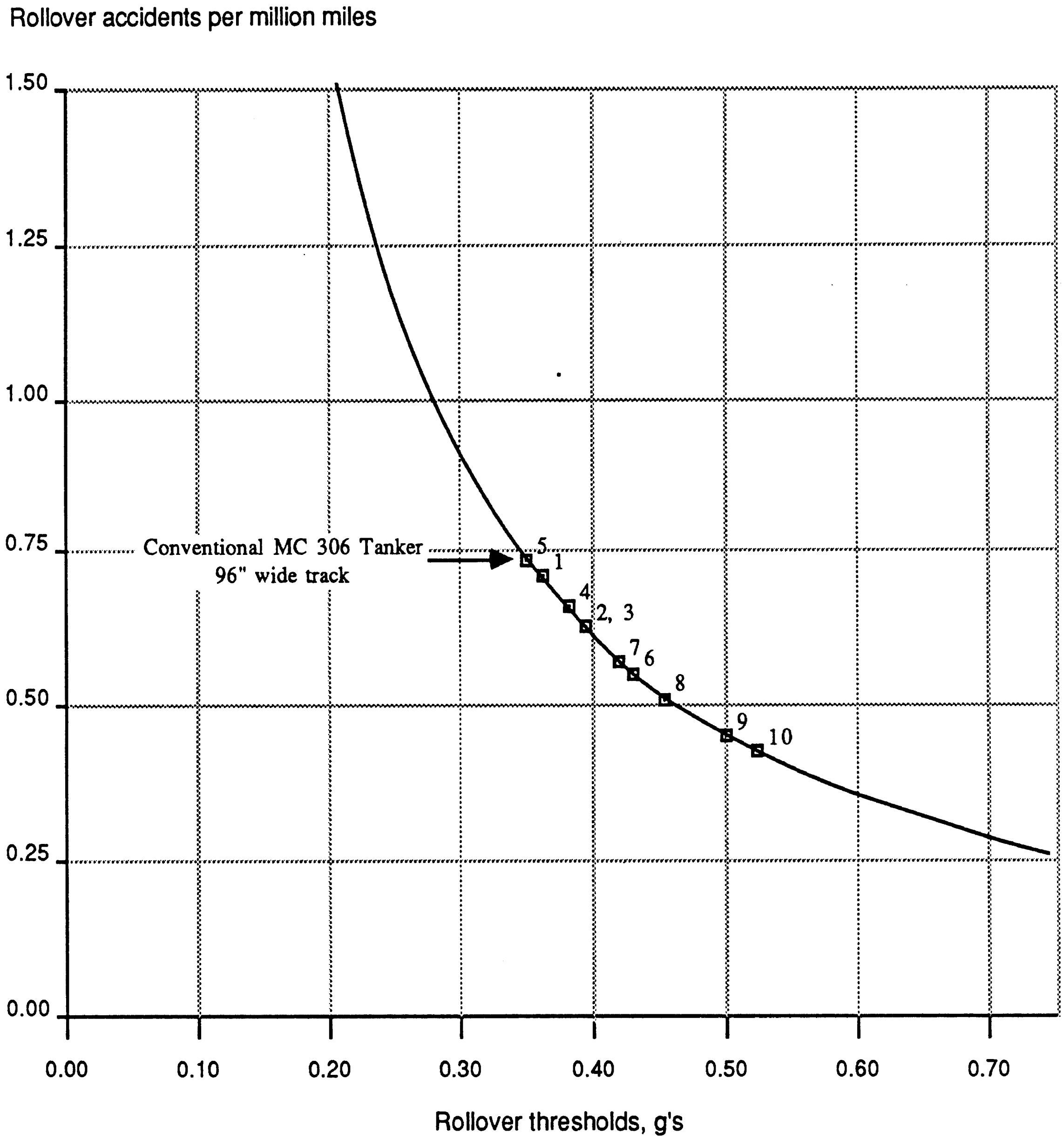
- The stiffened tractor rear suspension in Case 4 yields a distinct improvement in vehicle rollover threshold since the baseline tractor rear suspension constitutes a relatively "soft," and thus critical, element in determining net roll stability.



Variation	Rollover threshold (g's)	Predicted rollover accidents per million miles
1. Baseline tractor and van trailer	0.490	0.466
2. Baseline vehicle with forward bias of 75% payload weight	0.502	0.451
3. Baseline vehicle with stiff trailer suspension	0.489	0.467
4. Baseline vehicle with stiff tractor suspension	0.517	0.433
5. Baseline vehicle with stiff tractor and trailer suspensions	0.542	0.406
6. Baseline vehicle with trailer's total c.g. height lowered by 12"	0.630	0.332
7. Baseline vehicle with variations 3, 4, and 6	0.661	0.311
8. Baseline vehicle with wide tractor suspensions and variation 7	0.693	0.292

Figure 2. Rollover rate vs. rollover threshold for a tractor and van semitrailer.

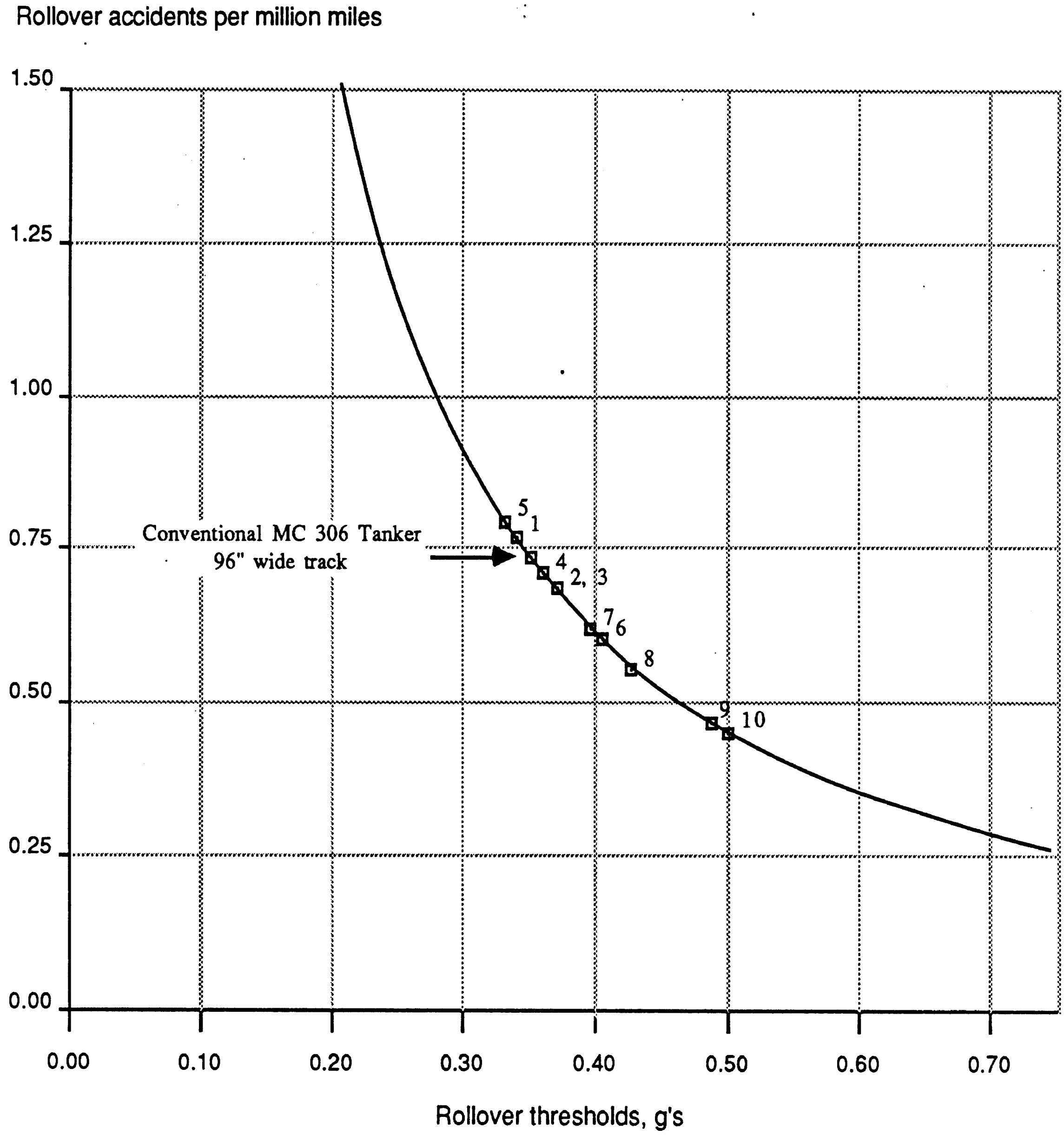
Accident analysis for R & H tank trailer with 102" trailer axles



Variation	Rollover threshold (g's)	Predicted rollover accidents per million miles
1. Baseline tractor and tank trailer	0.361	0.703
2. Baseline vehicle with 90% payload: c.g. height reduced	0.394	0.625
3. Baseline vehicle with trailer's fourth compartment empty	0.392	0.629
4. Baseline vehicle with trailer's third compartment empty	0.382	0.652
5. Baseline vehicle with stiff trailer suspension	0.352	0.728
6. Baseline vehicle with stiff tractor suspension	0.425	0.564
7. Baseline vehicle with stiff tractor and trailer suspensions	0.417	0.579
8. Baseline vehicle with composite trailer c.g. height lowered by 12"	0.448	0.526
9. Baseline vehicle with variations 5, 6, and 8	0.497	0.457
10.Baseline vehicle with variations 5, 6, 8, and 102" wide tractor axles	0.519	0.431

Figure 3. Rollover rate vs. rollover threshold for a tractor and 102-inch-wide tank semitrailer.

Accident analysis for R & H tank trailer with 96" trailer axles



Variation	Rollover threshold (g's)	Predicted rollover accidents per million miles
1. Baseline tractor and tank trailer	0.336	0.775
2. Baseline vehicle with 90% payload: c.g. height reduced	0.370	0.680
3. Baseline vehicle with trailer's fourth compartment empty	0.368	0.685
4. Baseline vehicle with trailer's third compartment empty	0.358	0.711
5. Baseline vehicle with stiff trailer suspension	0.326	0.807
6. Baseline vehicle with stiff tractor suspension	0.404	0.604
7. Baseline vehicle with stiff tractor and trailer suspensions	0.400	0.612
8. Baseline vehicle with composite trailer c.g. height lowered by 12"	0.416	0.581
9. Baseline vehicle with variations 5, 6, and 8	0.474	0.487
10.Baseline vehicle with variations 5, 6, 8, and 102" wide tractor axles	0.498	0.456

Figure 4. Rollover rate vs. rollover threshold for a tractor and 96-inch-wide semitrailer.

- When both the tractor and trailer suspensions are stiffened in Case 5, the result is a somewhat higher stability level than existed with the stiffer tractor suspension, alone. This result reflects the fact that the stiffened tractor suspension rendered the tractor rear axles even more stiffly sprung than the baseline trailer axles. Accordingly, an increase in trailer suspension could only result in a further improvement in rollover threshold for the whole vehicle combination (a full explanation of such sensitivities can be found in Reference [4]).

- Lowering the center of gravity of the trailer by 12 inches, as in Case 6, constitutes a very powerful mechanism for improving the roll stability of the unit, raising the rollover threshold by more than 0.01 g per inch of c.g. height reduction.

- When Cases 3, 4, and 6 are combined, providing stiffer tractor and trailer suspensions as well as the reduced-height value for the trailer center of gravity, the rollover threshold is increased by an additional increment.

- Case 8 establishes that a further improvement in rollover threshold, to a value of 0.693 g's, is obtained when the combined variations of Case 7 are augmented with a widened tractor suspension.

In Figure 3, we see that the tractor and 102-inch-wide tank trailer exhibits a baseline rollover threshold that is closer to that of the MC-306 tanker (assumed to be 96 inches in width across the trailer tires). The substantially lower level of roll stability of this vehicle, relative to that of the van semitrailer considered above, is due primarily to the differences in height of trailer center of gravity. Namely, the c.g. height for the van trailer sprung mass was 69.5 inches in contrast to a value of 86.5 inches for the tank trailer. The individual cases having variations away from the baseline show the following:

- Case 2 represents a generalized condition of modest under-filling of the tank, yielding a reduction of 10% in the payload weight and an approximate 5% reduction in the height of the trailer center of gravity. The result is a modest improvement in rollover threshold. This result, in which the fluid is considered to be essentially in a non-sloshing condition, is to be distinguished from the less filled conditions in which lateral movement of the fluid in the under-filled container can substantially degrade stability, especially in dynamic maneuvers.

- Case 3 represents the "rear-empty" state corresponding to the multi-compartmented tank having fluid in compartments 1,2, and 3, while compartment 4 is emptied. We see that an approximate 10% improvement in roll stability is accrued.

- Case 4 represents the same type of condition as in Case 3, except that the emptied compartment is No. 3, counting from front to back in the trailer. A somewhat smaller improvement over the baseline stability level is observed, reflecting the smaller volume of compartment 3 compared to compartment 4. Examination of these two compartment filling cases was intended to underscore the general point that the preferable context in which to transport an under-filled load is by means of emptied compartments instead of slosh-loading the vessel and thus risking reductions in dynamic stability.

- Cases 5, 6, and 7 represent the substitutions of stiffer suspension hardware at the trailer suspension, tractor rear suspension, and both suspensions, respectively, as with the van trailer, above. The characteristic reduction and improvement in rollover threshold, respectively, that accompany stiffening of trailer and tractor rear suspensions only, result from the same mechanics as noted in the case of the van trailer. With this vehicle, however, the stiffening of the tractor rear suspension alone renders a nearly matched set of tractor and trailer stiffnesses. Thus, when the trailer is stiffened in combination with the tractor (Case 7), a small reduction in rollover thresold is observed as the system becomes slightly non-ideal relative to Case 6.

- Case 8, reflecting a 12-inch reduction in the height of the trailer center of gravity, yields a major increase in the rollover threshold, again illustrating the powerful influence of this most basic parameter of the system.

- Cases 9 and 10 represent further combinations of improvements which afford even greater net increases in rollover threshold. Clearly, the means for achieving the greatest reduction in risk of rollover involve careful constraint upon a combination of parameters including suspension stiffnesses, payload height, and track width.

Computations presented in Figure 4 are essentially identical to those in Figure 3 except that the narrower trailer axle layout yields an approximate 0.02-g reduction in rollover threshold at each of the various conditions examined. This 96-inch vehicle width was included as a separate set of computations in reflection of the fact that a great deal of trailering equipment having this width dimension is in common service.

7.0 CONSIDERATION OF SLOSHING LIQUID LOADS

The reader is referred to Reference [5] for an in-depth discussion of the mechanics of sloshing liquids in bulk tankers. That document indicates that lateral movement of liquid within an under-filled vessel will degrade the roll stability of the vehicle beyond the values determined in a static analysis. Further, such reductions in stability are primarily of concern under dynamic maneuvering conditions, especially when the driver applies rapid steer inputs—such as when attempting to avoid an obstacle in the roadway.

The worst-case sloshing conditions occur when tanks are filled in the range of 40 to 70% of the tank volume. In typical road tankers, such fluid loads can cause the effective lateral acceleration levels in a rapid steering maneuver to approximately double, thus inducing a rollover in a maneuver whose peak acceleration input reached only half of the value of the static rollover threshold. Rapid steering maneuvers producing such a "resonant" response from the underfilled liquid load involve steering wheel inputs having a good deal of frequency content in the vicinity of 0.5 Hz.

One obvious approach toward avoiding stability degradations due to slosh is to simply avoid the underfilled condition. For example, the European economic community has adopted a regulation dealing with this issue under its "European Agreement Concerning the International Carriage of Dangerous Goods by Road." Article 211.173 of this agreement states "When tanks intended for carriage of liquids are not divided by partitions or surge-plates into sections not more than 7,500 liters in capacity, they shall be filled to not less than 80% of their capacity unless they are practically empty." This requirement would apply to cleanbore vessels such as Rohm & Haas employs, plus the compartmented vessels having sections of approximately 2,000 gallons or greater. In fact, the size of the compartment has virtually no bearing on the potential for lateral slosh and the degradation in roll stability. The European agreement takes the conservative approach in stipulating that full conditions below 80% are not permitted. (The "practically empty" provision is intended to acknowledge that an emptied tank is still likely to contain a few gallons in the sump at the base of the vessel.)

When a multi-compartmented tank is used, it is also recognized that slosh-filling of one compartment, while others are full, may not markedly deteriorate the stability of the overall unit. Shown in Figure 5, for example, is a generalized set of results which show the variation in a dynamic rollover threshold measure due to partial filling of a compartmented tanker. The horizontal axis represents the percentage of the total tank volume which is filled in a given loading state. The curves represent lines of constant "slosh fraction." The slosh fraction is defined as the ratio of the fluid volume which is in compartments that are loaded between 25% and 75% of their respective fluid capacities. We see that the worst condition prevails, for example, when the vehicle is loaded to approximately 45% of its total capacity (along the horizontal axis) and all of the fluid is "free to slosh" (that is, all of the fluid is situated in compartments which are between 25% and 75% full). Alternatively, one could observe that it might be advisable to always assure a rollover threshold that is at least as high as that for the fully loaded unit—by requiring that the portion of the fluid

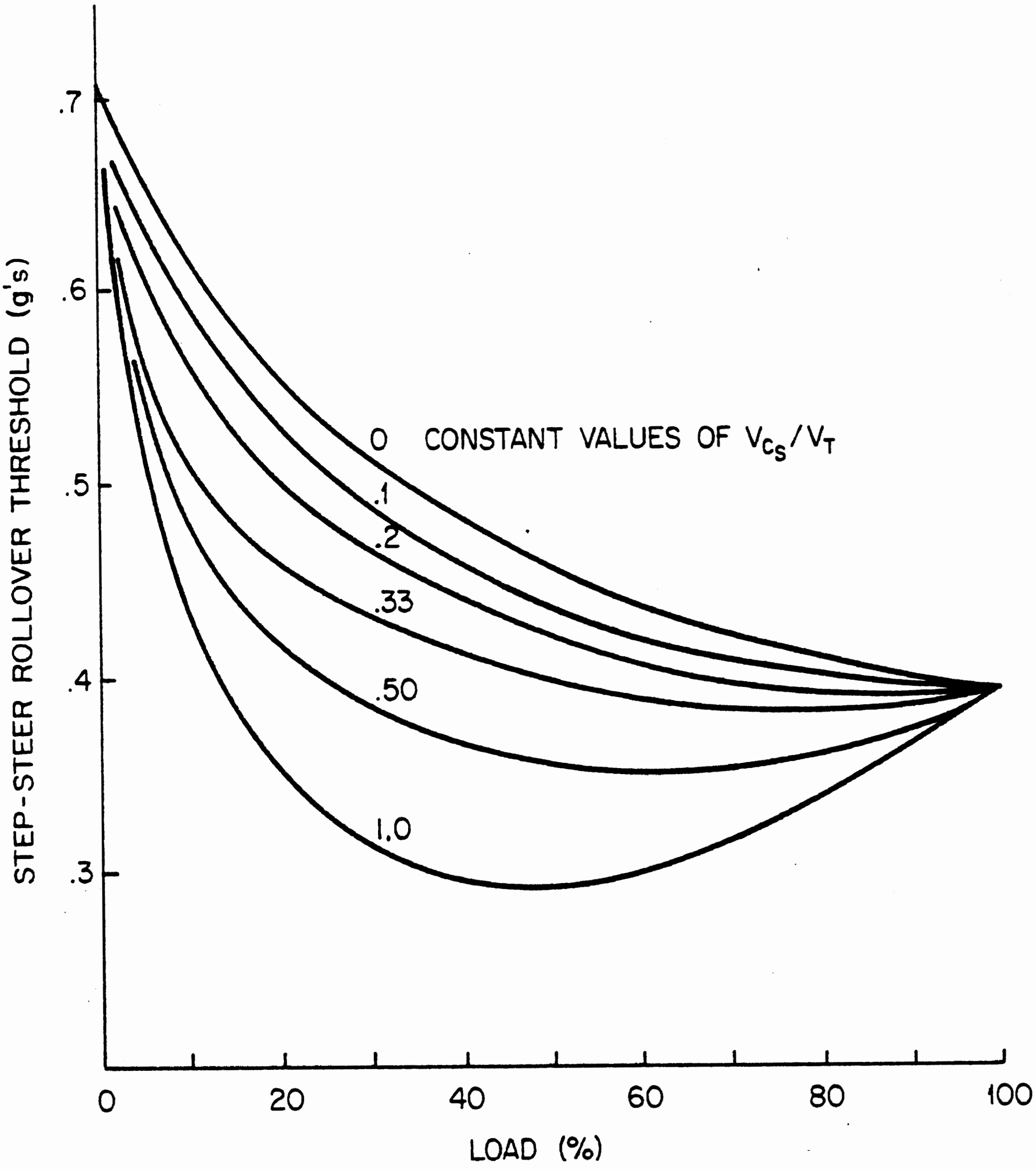


Figure 5. Dynamic rollover threshold as a function of load percentage and fractional slosh volume.

volume which is free to slosh is no more than approximately 0.20 times the total fluid volume (note that the ".2" line does not drop below the level of the rollover threshold at 100% load).

The conceptual alternative to constraining the value of percent-fill is the use of longitudinal baffles. As shown in Figure 6, tanks with an elliptic cross-section are shown outfitted in (A) a cleanbore configuration and (B,C, & D) with differing arrangements of longitudinal baffles. The figure illustrates the extent to which the imposed side force on the tanker resonates at differing frequencies of excitation. If one recognizes that real drivers can provide steering excitation up to approximately 0.5 Hz, it is apparent that:

> 1) the cleanbore vessel is highly resonant in the vicinity of the 0.5 Hz ergonomic limit,
>
> 2) the vertical baffles installed in Cases C and D simply act to shift the resonant peak up to higher frequency levels—where excitation through driver steer input is not encountered,
>
> 3) the horizontal baffle arrangement in Case B is seen to be very effective, although it should be noted that Reference [5] indicates this baffle design to be highly sensitive to the fill level of the tank. That is, the baffle declines in effectiveness very rapidly when the quiescent fluid level is substantially higher or lower than the location of the horizontal elements.

Although the reductions in fluid slosh such as shown in this figure have been recognized for many years, longitudinal baffles are not found in common service anywhere in the world. The primary reason seems to be that tanks are difficult to clean when baffles are installed. Accordingly, any party choosing to employ longitudinal baffles as a countermeasure to the slosh problem will likely need to install multiple access hatches to allow access for cleaning equipment within each of the baffle-separated sections of the tank.

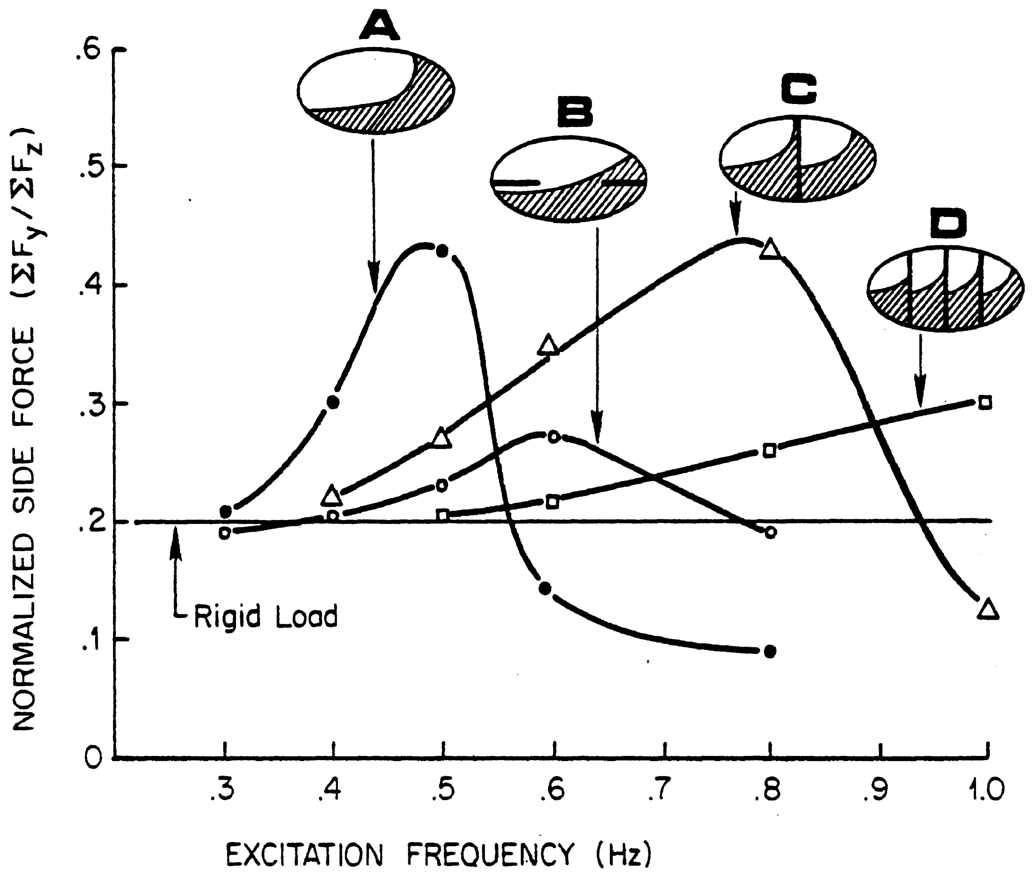


Figure 6. The influence of differing baffle concepts on the normalized side force levels due to fluid sloshing in a 50%-filled elliptic tank.

8.0 CONCLUSIONS

Static rollover threshold values were computed for current vehicles used by Rohm & Haas to transport chemical waste products. The performance levels were noted to be above that of MC-306-type tankers which are in common use for transporting gasoline and other petroleum products in bulk.

The rollover risk attributed to Rohm & Haas vehicles was seen to range from .47 to .70 rollovers per million miles of vehicle travel, assuming that such vehicles would be used in a manner which represents the average of all truck operations across the U.S. Actual rollover risks encountered in the Rohm & Haas fleet may be substantially different from these levels due to atypical drivers, vehicle maintenance, and route selection.

Variations in suspension selection, trailer configuration as it determines the height of the payload center of gravity, and tractor axle width were seen to markedly alter the stability level of the respective van and tank vehicles that were studied. All of the examined variations, with the exception of widened tractor axles, were thought to be achievable within current technology and available components. Combining these "currently achievable" features in one tractor-semitrailer configuration, the rollover risk was seen to reduce by approximately 35% relative to Rohm & Haas' current equipment.

The problem of fluid slosh occurring when a bulk tanker is underfilled was considered by reference to existing literature. Countermeasures to the slosh problem include adoption of a practice whereby the extent of underfilling is constrained and the possible construction of tank vessels with longitudinal baffle plates installed. The practice of constraining the extent of underfilling is seen as a tractable approach, especially when multi-compartmented tanks are employed. The use of longitudinal baffles to prevent sloshing action at any fill condition is seen as feasible but difficult. The difficulty arises primarily in the need to gain access of all baffle-confined spaces in the tank in order to accomplish the cleaning task. The difficulty is sufficiently great that virtually no usage of longitudinal baffles is practiced anywhere in the world.

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