Liquid Cargo Shifting and the Stability of Cargo Tank Trucks

Executive Summary Report
Volume I

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Contract Number: DTFH61-83-C-00160

September 1985

UMTRI The University of Michigan Transportation Research Institute

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.

4. Title and Subtitle LIQUID CARGO SHIFTING AND THE STABILITY OF CARGO TANK TRUCKS Volume I - Executive Summary	5. Report Date September 1985
	6. Performing Organization Code
7. Author(s) R.D. Ervin, M. Barnes, A. Wolfe	8. Performing Organization Report No. UMTRI-85-35/1
9. Performing Organization Name and Address Transportation Research Institute University of Michigan 2901 Baxter Road Ann Arbor, Mich. 48109	10. Work Unit No.
	11. Contract or Grant No. DTFH61-83-C-00160
12. Sponsoring Agency Name and Address Federal Highway Administration Bureau of Motor Carrier Safety Washington, D.C. 20590	13. Type of Report and Period Covered Final 9/30/83-5/31/85
	14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

The literature pertaining to the sloshing of fluids in cargo containers was examined and analyzed for its relevance to the safety of cargo tank trucks. The information which was obtained covered the areas of accident experience, industry hauling practices, the design of transport trucks, the mechanics of fluid slosh including types of sloshing waves, slosh frequencies and forces imposed upon the tank, experimental methods for studying slosh, vehicle response to internal liquid slosh motions, and approaches toward mitigating slosh. In addition to literature review, the results of an inquiry into worldwide regulatory restraints on cargo tank truck design and operation are reported. Also, the risk of suffering rollover during operation of slosh-loaded cargo tank trucks was analyzed and the results reported for the example case of bulk gasoline transportation. Considerations pertinent to potential new U.S. regulations covering the fluid slosh potential of cargo tank trucks are also discussed.

17. Key Words	18. Distribution Statement
sloshing liquids, surge, tank trucks, waves, forces, stability, safety, risk prediction	No restrictions. This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	9	

EXECUTIVE SUMMARY

INTRODUCTION

This document constitutes the Executive Summary Report on Contract No. DTFH61-83-C-00160 entitled "Liquid Cargo Shifting and the Stability of Cargo Tank Trucks." The study was conducted by the staff of The University of Michigan Transportation Research Institute (UMTRI).

The objective of this study was to determine, through review of the literature and analysis of information and current practices, efficacious means for mitigating the effects of slosh on the safety of cargo tank truck operations. As conceived, this effort was to examine the findings of the research community and the experiences of the practicing industries in order to explain the nature of the slosh phenomenon occurring in bulk tankers and the steps which have been taken to prevent or attenuate slosh disturbances. The phenomena of interest include a broad class of underdamped fluid motions which occur in non-full vessels in response to accelerations of the vessel. In tank trucks, for example, the principal vessel accelerations which excite slosh motions of the fluid are developed during cornering and braking. The slosh "problem" arises when the fluid response to these accelerations imposes such large forces upon the tank that vehicle motions are seriously disturbed, or even destabilized. Additionally, sloshing fluids become a problem when the force reactions on the tank tend to overstress or fatigue the vessel itself.

Slosh is of concern in a vehicle safety context to the extent that the disturbance or destabilization of vehicle motions may lead to loss-of-control accidents. Since a great variety of liquid commodities are transported in bulk by tank truck or tank trailer, the number of vehicles which could potentially suffer from a problematic slosh condition is large, in an absolute sense. Further, a substantial portion of bulk liquid transportation involves hazardous commodities for which special safety concerns arise. Especially insofar as vehicle rollover may be induced as a result of fluid slosh, the potential for a spill, fire, or noxious release following the rupture of a cargo tank in a rollover is of central concern.

The state of knowledge on the slosh subject as it pertains to tank trucks was addressed in this study from the viewpoint of accident experience, vehicle design, the mechanics of the fluid motions, the stability and control implications for vehicles, and the steps which have been taken or proposed for mitigating the effects of slosh. The resources employed for conducting this portion of the study included computerized literature searches and the review of numerous papers and reports which were uncovered. In addition, information on regulations which have been promulgated around the world to mitigate the slosh problem was sought by direct mail inquiry.

CONCLUSIONS

Conclusions which can be drawn from the investigation are as follows:

1) Accident data do not clearly implicate the role of liquid slosh as a factor in tanker accidents, except at the level of individual incidents. The lack of a clear implication does not constitute a finding that slosh is unimportant, however, since the accident documentation process is currently incapable of either detecting or usefully coding the fact that slosh may have played a role in the causation of a given tanker accident.

2) There are a wide variety of industries which transport bulk liquids in a manner which allows a significant degree of fluid slosh. Principal among these are transport operations in which multiple pickups or deliveries are made in a single trip and those which employ a tanker to carry a full-weight (but not full-volume) load of a liquid which is substantially more dense than the liquid for which the tank vessel was sized.

3) Tanks which are employed for transporting bulk liquids over the road are designed in a variety of configurations--some of which provide effective constraints against longitudinal slosh, but essentially none of which incorporate features for controlling lateral slosh. A substantial number of the applications in which slosh loading is practiced involve the use of cleanbore tanks which include no interior bulkheads or baffles for achieving any degree of slosh mitigation. In other types of service, the common use of

tanks having multiple compartments appears to have effectively mitigated the occurrence of slosh problems.

4) Although a great deal is known about the mechanics of sloshing liquids in transportation tanks of various kinds, the fluid mechanics may be exceedingly complex, and the slosh motions difficult to generalize upon, when the tank contains baffles or other flow restrictions and when wave amplitudes become severe. Both analysis and experiment have shown that slosh motions of the liquid in road tankers tend to (a) translate the fluid mass center in the horizontal plane such that the simple static load distribution is affected and (b) impose horizontal reaction forces against the tank. For simple, unbaffled tanks, the natural frequencies of these dynamic slosh motions are easily approximated.

5) A substantial body of information is available for estimating the magnitude of the slosh-related disturbances which can be expected for various tank configurations, when a steady oscillatory stimulus is assumed. For the more common cases involving transient excitation, the response of a sloshing liquid cannot be easily estimated without either experiments or high level computations. In this regard, both scale model laboratory experiments and complex numerical computations have been shown to provide successful means of evaluating the slosh behavior occurring with specific tank configurations. Viscosity of the liquid has been shown in such studies to be virtually inconsequential as a determinant of slosh behavior.

6) Sloshing liquids produce notable disturbances to road tankers in three types of maneuvering conditions, namely, (a) braking maneuvers in tankers lacking transverse baffles or compartmentation, (b) steady cornering and maneuvers involving steering reversals in all typical tankers, and (c) combined braking/steering maneuvers with cleanbore vessels. The disturbances occurring during pure braking are seen as distracting and uncomfortable for the driver, but otherwise of little importance to vehicle performance. The cornering disturbances are clearly of substance as a threat to maintaining roll stability—dynamic lateral slosh has been seen to reduce the roll stability of a tanker by as much as 50 percent. Under combined steer/brake maneuvers, the strong longitudinal slosh occurring in cleanbore semitrailer tankers places most of the payload weight on the tractor and thereby provides

a major loss in the roll stability of the combination. In a separate case, tankers constructed as full trailers are hypothesized to have an especially high sensitivity to sloshing liquids because their inherently lightly damped yaw behavior may resonate with the slosh action. A resonant interaction of this type may precipitate an anomalous yaw and roll oscillation of the trailer and, perhaps, premature rollover in a steering maneuver.

7) The threat of vehicle disturbances arising from sloshing liquids can be mitigated or avoided altogether through either the reduction of slosh-loading practices or the use of more slosh-resistant tanker designs. Slosh-loading practices are clearly derived from the particular needs of each involved industry; the decision to accept slosh loading is ultimately rooted in the economics of the operation. Tankers become more resistant to the deleterious effects of slosh when they incorporate (a) compartments such that partial load conditions can be handled with an array of filled and empty compartments or, at minimum, a reduction in the size of the effective sloshing mass is obtained due to separation of the slosh-loaded liquid into smaller volumes, (b) baffles to impede sloshing flow, and (c) tractor and trailer suspensions which maximize roll stability of the overall vehicle combination.

8) Regulations promulgated by the U.S. and other countries indicate that (a) many jurisdictions meaningfully constrain the length of individual compartments, especially in the case of non-pressurized tankers carrying hazardous liquids, (b) no jurisdictions require longitudinal baffles which would mitigate the influence of sloshing liquids on roll stability, and (c) certain jurisdictions, most notably the European community, directly constrain the slosh-loading practices of industries hauling flammable liquids by limiting the maximum ullage volume which may be attained. It is apparent, however, that a number of regulatory bodies around the world are currently concerned with the improvement of constraints placed upon the design and operation of tankers carrying hazardous liquids.

9) The absolute level of the safety risk posed by the operation of tankers in a slosh-loaded condition is generally unclear, although it is rather clear that the primary hazard category is rollover. For gasoline transportation, supporting data have enabled an analysis which predicts that a fully effective slosh countermeasure would only reduce tanker rollovers by

four percent. This example is not thought to be representative of other industries, however, whose products are much more frequently transported in a slosh-loaded state. The "switch-loading" of products having greatly dissimilar density values in the same, cleanbore, tanker is viewed as the most hazardous type of practice, from the viewpoint of potential slosh disturbances.

10) Problems posed by the prospective regulation of tankers to require baffles and/or compartmentation include (a) cleanability of tanks used to transport edibles or dissimilar liquids for which cross-product contamination is of concern, (b) the need to provide for access to all portions of the tank to effect repair of the vessel or its plumbing, (c) the need to develop expertise in design and manufacturing needed to produce reliable tanks having longitudinal baffles, and (d) the economic implications associated with (1) increased tank weight (and thus reduced payload weight), (2) increased cost of a more complex tank, and (3) increased costs associated with maintenance and cleaning.

Overall, the study establishes that while slosh may constitute a serious threat to vehicle safety in certain road tanker applications, various practicalities involving the design and use of tank trucks seems to render mechanical countermeasures unattractive for general implementation. Operational practices can, in many cases, help to avoid or mitigate the slosh problem but are unlikely to be adopted voluntarily because they will reduce the flexibility of trucking services or impose economic penalties. Moreover, like so many issues concerning transportation safety, judgments will ultimately be required in order to trade off the potential safety benefits against the costs which countermeasures impose.

The recommendations which have been formulated on the basis of these conclusions are presented below.

RECOMMENDATIONS

1) Since the primary safety hazard due to sloshing liquids is that due to rollover, and since rollover is primarily a single-vehicle accident which

does not threaten the citizenry unless spillage of hazardous material is involved, we recommend that the focus of any DOT initiatives to mitigate the problem of sloshing loads be directed at the transportation of hazardous liquids. Although gasoline transportation is known to dwarf the transportation volume of all other hazardous commodities, pursuit of regulations controlling slosh in gasoline tankers would appear to warrant a very careful cost/benefit analysis, since the projected risk of rollover due to slosh is seen as a small fraction of the total rollover experience. Notwithstanding the small "fractional" risk, it may be that the absolute probability that a gasoline tanker will roll over as the result of an aggravating slosh factor is greater than for any other single commodity.

2) To enable the conduct of analyses which can support a cost/benefit determination on slosh countermeasures, it is recommended that DOT carry out a limited study to monitor the liquid loading practices of carriers involved in shipping the various hazardous commodities of interest. The results of such studies would provide measures of the extent of partial load transportation occurring, together with identification of the compartmentation of the tanks being used. Subsequent analysis can establish estimates of the extent to which the slosh condition of the load has compromised the roll stability of the involved vehicles.

3) It is anticipated that the worst slosh-load problems of all will involve so-called "switch-loading" of liquids of differing densities in the same tank vessel, resulting in a partial filling for dense liquids. It is recommended that DOT prioritize any further study initiatives to focus on those operations which are switch-loading hazardous liquids, particularly if the denser of the liquid products being carried in a given tanker constitutes a hazardous substance. Should a field monitoring effort confirm that such practices are commonly occurring, corrective measures might include (a) mandatory compartmentation to ensure controlling denser loads, (b) longitudinal baffles or other countermeasures to the lateral slosh occurring in an underfilled vessel, or (c) banning the practice of underfilling through some operating constraint.

4) We recommend consideration of a blanket regulation for hazardous liquids similar to that imposed by the ADR (European Agreement Concerning the

Transportation of Dangerous Goods by Road) requiring that tanks be filled to within a specified small percentage of their capacity unless they have been, for all practical purposes, emptied. The European requirement specifies 20 percent as the maximum ullage fraction. The stability data suggest that 20 percent constitutes a liberal allowance, although admittedly much more beneficial than no constraint at all. Such a blanket regulation for the carriage of hazardous liquids would simply confirm the good practices already employed by various sectors of the industry, while otherwise rendering illegal the slosh-loading practices which others have decided to adopt. Conduct of the monitor study recommended in item 2, above, would permit estimation of the burden which such a regulation would impose upon the industry in the U.S.

5) It is recommended that the U.S. DOT consider a regulation on basic roll stability for all tankers used to transport hazardous commodities. Such a requirement would render the regulated vehicles more capable of resisting the destabilizing influence of sloshing loads, as well as other stimuli which threaten rollover. The regulation could take the form of the simple geometric constraints on track width and height of center of gravity which are currently imposed in various parts of the world. Alternatively, recognizing that suspension selections also constitute a strong determinant of the roll stability level, the U.S. could adopt a roll stability performance standard employing a whole vehicle experiment such as the tilt-table test. In such a test, the complete vehicle combination is tipped sideways on a rotating platform, or table. The platform angle at which the (tethered) rollover occurs directly determines the stability performance of the vehicle.

Roll stability standards employing a tilt-table compliance test have been used to regulate buses in the United Kingdom for many years and have been recommended in various countries for application to tankers carrying flammable liquids. The compliance levels for a roll stability standard in the U.S. could be set at either of two basic ranges of performance, namely,

a) levels which simply reflect good design practice, allowing tolerance for measurement error and manufacturing variations, for conventional vehicles used in interstate transportation today, or

b) substantially elevated levels of performance which would apply to vehicles which are allowed a modest increase in gross weight allowance. Such a concept was proposed in 1982 by an initiative of the tank industry and is worthy of careful consideration. The concept recognizes that substantial improvements in stability are possible, but they involve a significant change in vehicle design. Although the tanks would be substantially more expensive, the productivity gains due to the larger payload would vastly outweigh the equipment costs. Such a notion deserves study as a possible means to dramatically upgrade the safety of hazardous material transportation, recognizing that the government's authority to regulate truck weights can also be used as a tool to implement a change which serves public safety.

6) It is recommended that the stability degradations resulting from slosh loading in full trailers be studied at the earliest opportunity to determine if such practices should be expressly forbidden. Such a study would address both truck/full trailer combinations and tractor/semitrailer/full trailer (doubles) combinations. It is expected that the lightly damped motions of the sloshing liquid and the trailer's yaw response will be sufficiently close in natural frequency, in many common cases, that large stability degradations will occur. Should this hypothesis be confirmed, it seems reasonable that the practice of loading full trailer tankers in a slosh condition should be banned. The primary industry affected by such a constraint would be the transporters of petroleum fuels on the West Coast. While the current study has focused on the slosh issue, it is worthy to note that a good deal of evidence exists suggesting that the truck/full trailer configuration is especially low in dynamic stability and may be judged as inherently unsuitable (regardless of slosh considerations) for transporting hazardous commodities.