Liquid Cargo Shifting and the Stability of Cargo Tank Trucks

Final Technical Report
Volume II

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Contract Number: DTFH61-83-C-00160

September 1985

UMTRI The University of Michigan Transportation Research Institute

NOTICE

Technical Report Documentation Page

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

4. Title and Subtitle	5. Report Date
LIQUID CARGO SHIFTING AND THE STABILITY OF CARGO TANK TRUCKS Volume II - Final Technical Report	September 1985
	6. Performing Organization Code
7. Author(s) R.D. Ervin, M. Barnes, A. Wolfe	8. Performing Organization Report No. UMTRI-85-35/ 2
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	149	

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ACKNOWLEDGEMENTS

The study of this subject was greatly aided through the cooperation of certain persons and organizations. In particular, Mr. Larry Botkin of the Liquid and Bulk Tank Division of the Fruehauf Corporation provided assistance in defining the typical tank constructions in use in the U.S. Mr. Lennart Strandberg of the National Road and Traffic Research Institute in Sweden has kindly given permission for broad use of figures from his most substantive research on slosh in road tankers. A large number of trucking fleets operating in Michigan and adjacent States provided gracious assistance in outlining the practices of various industries in the hauling of liquid products in bulk. Also, the efforts of Mrs. Ann Grimm, of the UMTRI Library, are acknowledged, recognizing that much of the literature which she procured in this study was obtained from non-automotive realms of technology. Finally, the cooperation of standards associations, ministries of transport, and other industry and road safety organizations in the following countries is gratefully acknowledged:

Australia
United Kingdom
Sweden
Israel
France
Japan
Switzerland
Federal Republic of Germany
South Africa
New Zealand
Austria
Canada
Indonesia
Finland
Norway
Netherlands

1.0 INTRODUCTION

This document constitutes the final report on Contract Number 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 is addressed in this report 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. In addition, information on regulations which have been promulgated around the world to mitigate the slosh problem was sought by direct mail inquiry. The technical information on sloshing liquids is discussed in section 2.0 and the regulatory matter is presented in section 3.0.

The literature gleaned from other transportation fields has shown that, in certain cases, the slosh problem has reached intolerable proportions, such that operation without suitable countermeasures is simply ludicrous. Primary among these cases are ocean-going tanker ships and liquid-fueled rockets. In the case of tank trucks and truck combinations, the strong potential for seriously destabilized vehicle behavior due to sloshing liquid loads appears to be muted, in a probability sense, by the infrequent (and often uneconomical) operation of such vehicles in the underfilled condition for which slosh is of concern. In section 4.0, the risk probability issue is addressed for an example case of gasoline tankers. Section 4.0 also presents discussions on the attractiveness of slosh countermeasures which can be identified.

In section 5.0, conclusions and recommendations are provided. 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 seem 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.

2.0 THE STATE OF KNOWLEDGE PERTAINING TO THE SLOSH PROBLEM

The sloshing of liquids in underfilled vessels has been a recognized phenomenon in the motor transport field for many years. The clear identification of the role of fluid slosh as a causal factor in traffic accidents, however, has not been accomplished. A number of accident analysts have suggested that sloshing liquids may have contributed to certain classes of accidents, but the accident record has not been sufficiently informative to permit solid substantiation of this link in most cases. In section 2.1, the evidence which does appear to correlate fluid slosh to tanker accidents will be reviewed. Given that an argument can be made linking slosh to accidents, the state of knowledge on the occurrence of slosh loading in practice and the influence of slosh on vehicle dynamic properties merits evaluation. In the subsequent sections of this chapter of the report, various aspects of this state of knowledge will be examined.

2.1 An Overview of Accident Studies Addressing the Role of Fluid Slosh

One of the few known accident cases in which fluid slosh was directly cited as causing a rollover event was reported by the National Transportation Safety Board in 1971 [1]. The report concluded that the rollover of a tanker loaded to 75 percent of fluid capacity with liquid sugar was due to "grossly excessive speed in a turn and to the resultant dynamic surge of the liquid cargo." The conclusion regarding the involvement of "surge" was based upon a calculation showing that a similar vehicle with a rigid load could have sustained a speed of 64 mi/h (103/km/h) on the same 11-degree curve without rollover. This conclusion can be called into question, however, with the aid of more recent advancements in the means of estimating truck rollover limits [2]. That is, more comprehensive analysis of the stability matter indicates that a corresponding rigidly loaded vehicle would have actually been on the verge of rolling over at approximately 50 mi/h (81 km/h), which was the nominal speed value estimated for the accident-involved vehicle. Thus, it appears that this particular vehicle would have rolled over with even a rigid load--such that the partial load of a liquid product was incidental rather than causal.

In a 1978 study addressing the problem of cargo shifting [3], nine individual accident reports collected in the 1974 file of Accidents of Motor Carriers of Property were cited as illustrating the involvement of load shifting. Payloads, including liquids, hanging meat, poorly restrained solid products, and livestock were seen as "contributory, but not causal by themselves" in a variety of accident scenarios.

In certain studies which have addressed tanker accidents rather broadly, data have revealed a strong correlation between apparent slosh-loading conditions and accidents. In an extensive study of tanker accidents in California, for example [4], 30 out of 117 tankers involved in accidents were found to be filled to 85 percent, or less, of the tank capacity at the time of the accident.

It is important to note that the raw data from these accident reports do not distinguish whether the "underfilled" status of the 30 tankers actually involved sloshing fluid within individual compartments or simply a reduced payload volume due to emptied compartments (such that no sloshing occurred).

Comparing the types of accidents involving these potentially "slosh-loaded" vehicles with the remainder of the vehicles in the accident sample, examination of the raw data tabulation used in the California study shows that rollover occurred in 22 of the 30 accidents involving underfilled tankers (73 percent), compared to only 47 of the 87 accidents involving other vehicles (54 percent). The data also showed that 13 of the 22 rollovers (59 percent) with underfilled tankers occurred "on turns," while only 11 of the 47 rollovers involving other tankers (23 percent) occurred on turns. (Presumably the majority of rollovers occurring, generally, derive from a variety of conditions which are not necessarily likely to excite slosh motions, such as running over uneven terrain at the roadside. It may be, then, that slosh-loaded vehicles become peculiarly involved in rollovers when a distinctly lateral stimulus is provided, such as during cornering.) While these results strongly suggest that the slosh-load condition has contributed to accident causation, the incomplete information on the compartment fill status makes definitive findings unavailable.

Indepth investigations of 42 tanker accidents by the Traffic Authority of New South Wales, Australia, led to the citation of "liquid load movement" as a contributing factor in 4 incidents [5]. Insofar as no detailed analyses of vehicle motion dynamics were attempted in these investigations, however, the potential role of the liquid movement factor was not clearly demonstrated. In fact, "liquid load movement" was generally identified as a contributing factor in combination with "high center of gravity," thereby implicating a low overall level of roll stability.

Moreover, the accident record provides a substantial amount of evidence which appears to implicate slosh as an accident factor, while generally failing to clearly establish its role in individual cases through indepth reconstruction analysis.

2.2 Inquiry into American Industry Liquid Hauling Practices

In order to gain an understanding of the potential for hazardous sloshing of liquids being transported in tank trucks and trailers, telephone contacts were made with a number of persons involved with the hauling of liquid commodities of various types. Information was sought on the size and structure of the cargo tanks used, particularly in relation to compartments and baffles, and on the extent of travel with the tank in a partially loaded condition.

The findings from this inquiry are presented below in relation to various types of hazardous and non-hazardous liquid commodities.

2.2.1 Gasoline and Fuel Oil. Contacts with a number of gasoline and fuel oil distributors in Michigan indicated considerable variation in the sizes and configurations of gasoline tankers. Single semitrailers varied from 5,700 to 15,300 gallons in capacity. The numbers of compartments ranged from two to five, with four the most common number.

The various semitrailer and doubles-configured tankers are used primarily to deliver the various types of gasoline, diesel fuel, and home-heating oil from pipeline terminals, oil refineries, and other storage facilities to gasoline service stations and heating-oil distributors. Typically, all compartments are loaded full, with the oil products being delivered at one location, and the tanker then returning empty. However, it is fairly common for one or more compartments to be only partially filled with a particular petroleum product, and it is not uncommon to make two deliveries on a single trip, which may lead to some partially loaded compartments while traveling between the two delivery points. Thus, for a significant portion of their travel miles, these tankers may have at least one compartment only partially loaded, with a resultant potential slosh effect on vehicle stability and control.

For the delivery of heating oil to residential customers, respondents reported using single-unit tank trucks ranging from 2,000 to 3,000 gallons. These trucks contained from three to five compartments. Usually these tankers leave the storage facility fully loaded, but typically they make from 8 to 10 home deliveries. So, as the vehicle travels between delivery points, some of the compartments are necessarily in a partially loaded condition. However, respondents said that the use of many relatively small compartments prevents much disturbance due to liquid sloshing.

2.2.2 Crude Oil. For hauling crude oil from wellheads to refineries and pipelines, three northern Michigan respondents reported using large semitrailers ranging from 13,500 to 16,500 gallons. These tankers contain just two compartments, but they do have extensive baffling. One company reported purchasing 55 13,800-gallon semitrailers which have a 3,450-gallon front compartment containing 2 baffles and a 10,350-gallon rear compartment containing 7 baffles. That company cut out 4-inch holes in the top and sides of the baffles in addition to the 18-inch center hole and the 12-inch bottom hole, so that the trailer could be pumped out if it rolled on its side. These tankers usually travel either empty or full (allowing for about five percent ullage), but sometimes they will make two or three pick ups and thus travel partially loaded between pick-up points. One respondent mentioned that the tankers feel noticeably "squirrelly" in the partially loaded condition.

2.2.3 Industrial and Salvage Oils. For the transport of industrial and salvage oils, such as motor and hydraulic oils, 2 respondents reported using single-unit tank trucks between 1,500 and 3,500 gallons in capacity and containing 3 or 4 compartments. Both reported substantial travel in a partially loaded condition between delivery or pick-up points, but they said their drivers found no slosh problems as long as they drove carefully.

2.2.4 Liquified Petroleum Gas. For the delivery of propane from storage facilities to industrial users or residential distributors, large semitrailers in the 9,600- to 14,500-gallon range are used. These are single-compartment tanks with three or four baffles. These tankers usually travel either empty or full, since they usually deliver a full load to a single location. Propane tankers are customarily loaded only 85 percent full due to necessary allowances for expansions.

For residential distribution, specialized single-unit tank trucks are used, ranging from 2,400 to 3,000 gallons. These tankers usually leave full (allowing for 15 percent ullage), but they may service 10 or more delivery points on 1 trip, such that they are traveling partially loaded much of the time. While these tankers all incorporate single compartments, some contain baffles and some do not. One respondent whose tankers are baffled said one can sometimes feel the slosh on corners at high speed and that it used to be worse with an unbaffled tank. (Since the baffles in question are only of the transverse variety, this comment is mysterious unless, perhaps, braking-in-a-turn maneuvers were actually the setting for the complaint.) Another respondent said that he found no slosh problem in these small tankers, even without baffles.

2.2.5 Industrial Chemicals. For the transport of the wide variety of industrial chemicals, solvents, acids, alkalies, phosphates, etc., respondents reported using semitrailer tankers ranging from 5,000 to 8,500 gallons in capacity. The great majority of these vehicles incorporate from two to six compartments. The transported chemicals may vary in density from 5.7 lbs to 16 lbs per gallon, such that the tanks are typically underfilled when carrying heavier liquids, although in such a case, shippers state that they attempt to use compartmentation advantageously when it is available. The necessity of carrying out a thorough cleaning of the tank between transport of different chemical products tends to discourage the use of interior baffles.

Usually these products are transported over fairly long distances from the manufacturer or storage facility to one industrial user, or to two or more industrial users in the same general area. So, unless the product is too dense to permit completely filling the tank, there is little travel in a partially loaded condition. One respondent reported that, if two or more deliveries were to be made, they would attempt to load the tanker in such a way that the back compartment(s) could be unloaded first.

2.2.6 Cryogenic Liquids. A number of gases are customarily transported in bulk in insulated cargo tanks which keep them in liquified form below minus 130F. These included such gases as oxygen, hydrogen, nitrogen, helium, and argon. Generally, each type of gas has its own specialized type of semitrailer tanker, ranging from 4,700 to 13,000 gallons in capacity. These tankers are always single compartments, usually containing 2 or 3 transverse baffles which contain a 16-inch hole in the center and half-moon openings at the top and bottom. One tanker manufacturer reported experimenting with blocking the center hole, but he felt that this increased the slosh effect slightly with a partial load.

Liquified cryogenic gases are usually transported in bulk in full tanks over long distances to one or more local deliveries in the same area, so there is rarely much travel in a partially loaded condition. Local distribution is usually in gas cylinders rather than in bulk.

2.2.7 Milk and Other Edible Liquids. In Michigan, most bulk milk is transported by the Michigan Milk Producers Association (MMPA) or the Independent Milk Producers Association (IMPA). Farm pick ups are carried out largely by independent milk haulers who are licensed by the Michigan Department of Agriculture and who are under contract to the MMPA or to the IMPA or to the few individual dairies which have their own pick-up operations. Dairy farms have their own refrigerated tanks in which milk is temporarily stored, so pick ups are usually scheduled only once every two or three days. The average farm will provide 300 to 500 gallons on one pick up, but large farms may provide up to 1,000 gallons.

For collecting milk directly from dairy farms, respondents reported using single-unit tank trucks varying in size from 1,500 gallons to 4,500 gallons and tank semitrailers varying in size from 5,000 gallons to 13,000 gallons. All tanks are configured with cleanbore, single-compartment construction without baffles, such that the tank can be cleaned according to rigid State regulations.

Most of the miles are covered with the tanker either in an empty condition on the way to the first pick-up point, or in a full condition returning to the dairy or milk distribution center from the last pick-up point. However, the "full" condition is not always completely full due to variations in milk availability at particular farms, and due to the practical inability of structuring each route so as to achieve a full load. Also, for a substantial portion of their miles, the tankers are in a partially loaded state as they move among the 5 to 20 farms on a typical milk pick-up route. Usually, one truck picks up milk from a group of farms in one general area, which tends to minimize the percentage of the route which is covered with the tank in a partially loaded condition, but this percentage varies considerably, depending on the length and structure of particular pick-up routes.

Because of the absence of internal baffles and the relatively high number of miles covered in a slosh-loaded condition, milk pick-up tankers are particularly vulnerable to the slosh effects of partial loads in cornering or in emergency stops. Respondents mentioned that drivers need to be careful, especially when turning. One veteran respondent recalled at least three tip-over accidents with partially loaded milk tankers.

For the distribution of milk from pumpover stations to dairies, respondents reported using 5,000-, 6,000-, and 6,500-gallon semitrailers or 6,600-gallon semitrailers combined with 5,600-gallon "pup" trailers. These twin trailers can carry 104,000 lbs (23 mg) of milk, well over the federal recommended maximum of 80,000 lbs (18 mg) total weight, but legal in Michigan. These tankers also incorporate single-compartment construction without baffles for ease in cleaning. They usually leave with a full load for a single destination and return empty. However, one respondent mentioned having to load the twin trailers to a less-than-full condition for trips using the Mackinac Bridge because of weight restrictions on the Bridge.

Occasionally, milk tankers are used to transport other edible liquids, especially on returning from a milk delivery. Such alternative commodities include syrup, chocolate, wine, and potable water. Since some of these products are denser than milk (up to 12 lbs per gallon compared to 8.6 lbs per gallon for milk), it is not always possible to fully load the tanks when carrying these alternative liquids.

Respondents felt that there was not much of a slosh problem in the longer haul operations of milk tankers because the operating conditions rarely involved a partial load of fluid.

2.2.8 Liquid Fertilizer. There are two rather different aspects to hauling liquid fertilizer; namely, local and over the road. The manager of a company which sprays lawns with fertilizer and weed killer reported using 2 kinds of single-unit tank trucks--a 1,200-gallon truck with one cross baffle and a 1,000-gallon truck with 5 separate fiberglass compartments each holding 200 gallons. He said that these tankers are rarely completely full. They carry what is expected to be needed to service 15 or 20 customers per day and, of course, they become progressively emptied as the trucks move from customer to customer throughout a 2-county region.

A local distributor of liquid fertilizer to farmers uses a 1,000-gallon tank trailer pulled by a pickup truck. He usually takes a full load to one farmer. Two larger distributors reported using semitrailer tankers varying from 3,000 gallons to 5,500 gallons with single, unbaffled compartments. Because of the relatively high densities of these fertilizers (10.2 to 13.0 lbs per gallon), the tankers are constrained by load laws to carry only a partial load, when the denser fertilizers are involved. Also, the tankers are often employed in deliveries to two or more farmers such that partial loads are inevitable along the route. One of these respondents reported that drivers definitely feel the slosh under partial load conditions and that drivers are warned to be especially careful under wet conditions.

A dispatcher for an interstate shipper of liquid fertilizer said his company had 5 5,500-gallon semitrailers with 2 "half baffles" in the single compartment, 1 5,500-gallon single-unit tanker without compartments or baffles, and 1 7,500-gallon old oil semitrailer without compartments or baffles. Because of the relatively high density (16.7 lbs per gallon) of the 28 percent solution fertilizer, these tankers are usually only loaded to 4,800 gallons, yielding a 13-percent ullage volume for the 5,500-gallon tankers. However, for the unbaffled 7,500-gallon tanker, the 4,800-gallon load yields a 36-percent ullage volume and thus a distinct potential for sloshing wave action.

These tankers almost always travel empty or filled to the 4,800-gallon level for delivery to a single retail distributor. The dispatcher mentioned that the slosh definitely could be felt in a previously owned tanker without baffles and that he had felt the slosh quite a bit when he once drove a 2,000-gallon load in a baffled 5,500-gallon tanker. However, he said his company used experienced drivers, and he didn't feel slosh was a significant safety problem.

2.2.9 Water Used in Fire Fighting. In transporting water, most fire-fighting equipment conforms to the National Fire Protection Association's National Fire Codes, whose provisions on tank construction are discussed in section 3.

Four local fire departments were contacted in determining tank configuration and filling practices. Water tanks varying in capacity from 300 gallons to 3,000 gallons were reported for single-unit fire trucks. Most of these tanks have a rectangular rather than a rounded shape, typically employing a "T-" type cross section with the lower part of the tank between the wheels and the upper part of the tank spreading out above the wheels of the truck. All of these tanks were reported to be baffled in accordance with the NFPA Code. There was also one small semitrailer with a 2,500-gallon oval tank containing 4 transverse baffles in its 12-ft length. A 3,000-gallon, single-unit tanker was described as having 2 separate compartments plus baffles within each. One department mentioned having a single-unit commercial tank truck with a 2,100-gallon elliptical tank which it found marginally stable for fire service because the chassis had not been configured for carrying the denser water load. This vehicle had apparently been converted from gasoline service--a conversion that the NFPA recommends against.

As for partial loading, fire-fighting tankers ordinarily leave the station full. If all of the water is not used at a particular fire, the tank will normally be refilled at a nearby hydrant or stream before returning to the station. When this is not feasible, especially in rural areas, fire-fighting tankers may travel a substantial portion of their miles on the return trip in a partially loaded condition. None of the fire chiefs who were contacted considered the slosh problem to be a serious concern, although one admitted that the liquid sloshing motions can certainly be felt when the tank is half full and that it was necessary for drivers to be especially careful in such a situation. Fortunately, these tank trucks are usually in less of a hurry on their return trips than on their outgoing trips.

2.2.10 Sewage. Four local septic tank waste haulers reported using single-unit tank trucks ranging from 1,500 gallons to 3,600 gallons in capacity. All of these had single compartments with two or three baffles. These tankers are almost never filled at a single pick up, so a substantial part of their travel is in a partially loaded condition.

The respondents all said that the baffles seem to prevent any real slosh problem. One said he could feel the difference when a baffle broke, and another one said one can feel the forward surge in a fast stop. One respondent said he thought that some trucks in the business developed clutch problems relating to the liquid surging and sloshing.

2.2.11 Discussion. This exploration of liquid-hauling practices in various industries is insufficient to provide definitive information on any particular industry. However, it is sufficient to suggest that there exists a potential safety problem from sloshing liquids in many industries. Many respondents tended to discount the importance of the problem, however, suggesting that careful drivers could take the slosh potential into account.

The potential for a liquid slosh effect on safety seems particularly large in industries which make considerable use of uncompartmentalized and unbaffled cargo tanks traveling in a partially loaded condition. The prime example of this is the use of tank trucks for farm milk pick up. Other industries of particular concern include those which employ a single tanker configuration to transport commodities having a wide range of densities.

Examples of such operations include the transport of liquid edibles, industrial chemicals, and liquid fertilizers.

The normal incidence of slosh loading would, of course, be compounded if any new regulations were imposed to limit the weight allowance on existing vehicles. The special loading constraint applying to Michigan's Mackinac Bridge, for example, has the effect of forcing partial load operations with all of the larger capacity tankers which are designed to operate in a filled condition elsewhere in the State.

Analogous weight restrictions also affect liquid-hauling operations in States subject to spring freezing and thawing cycles. In Michigan, some State roads have their weight limits reduced 35 percent for protection of the road structure during designated periods of February through May each year. County roads and bridges which are not of all-weather construction may be limited even more. The restriction period can range from 5 to 12 weeks. This problem was mentioned particularly by respondents involved with picking up crude oil from rural wellheads, but these restrictions can increase the incidence of slosh loading for many other industries as well.

2.3 The Design Characteristics of Bulk Transport Tanks and Tank Vehicle Chassis

A great variety of liquid products are carried in bulk quantities by tank truck to distribution or consumption points. When persons responsible for the transportation function select tank vehicles for these hauling tasks, they begin with an identification of the properties of the liquid which is to be carried. The properties of primary interest are:

1) Hazardous material classification (such that certain regulations regarding the tank container may apply)

2) Fluid density

3) Pressure of containment during transportation

4) Temperature during transportation

5) Viscosity

6) Corrosiveness (such that particular tank materials are required)

In addition to the properties of the liquid itself, there are ancillary issues influencing tank design such as the means of loading and unloading, the need to carry multiple commodities in separate compartments, the need to carry differing commodities having significantly differing densities, and the need to clean the tank between loads, for the sake of either sanitary protection of foodstuffs or the avoidance of chemical contamination with dissimilar commodities.

Beginning with the road-use laws which apply in the jurisdiction in which the vehicle is to be operated, the total weight and axle loading of the tank truck or trailer is determined. Assuming a gross weight for the tractor, the tank vessel is then designed with a certain target weight in mind. The volume of the vessel is determined by finding the sum of the tank and fluid weight, plus the chassis, which yields the target weight. If various commodities are to be carried in the tank, the fluid having the lightest density generally determines the design volume of the tank such that the maximum load allowances can be achieved over the whole range of intended products. Considering this fluid, the tank is then designed to be somewhat oversized, allowing for an ullage, or vacant, space at the top of the tank to accommodate expansion of the liquid load. Of course, when liquids of higher density are carried in the subject tank, the effective ullage volume may be much larger than the design value which was provided as the minimum to accommodate the lightest density liquid. As will be shown, the larger ullage volumes associated with alternative, high-density liquids provides the opportunity for sloshing motions in the fluid load.

Shown in figure 1 are three basic types of tank construction which are employed commonly in the transportation of bulk liquids. Tank type (a) is a smooth-skin, low-pressure vessel having internal baffles or bulkheads situated along its centerline. The baffles provide for stiffening of the tank barrel while also impeding the longitudinal sloshing flow of liquid in the partially filled condition. The bulkheads provide stiffening as well as compartment sealing for the sake of hauling dissimilar products in one trip. The vessel

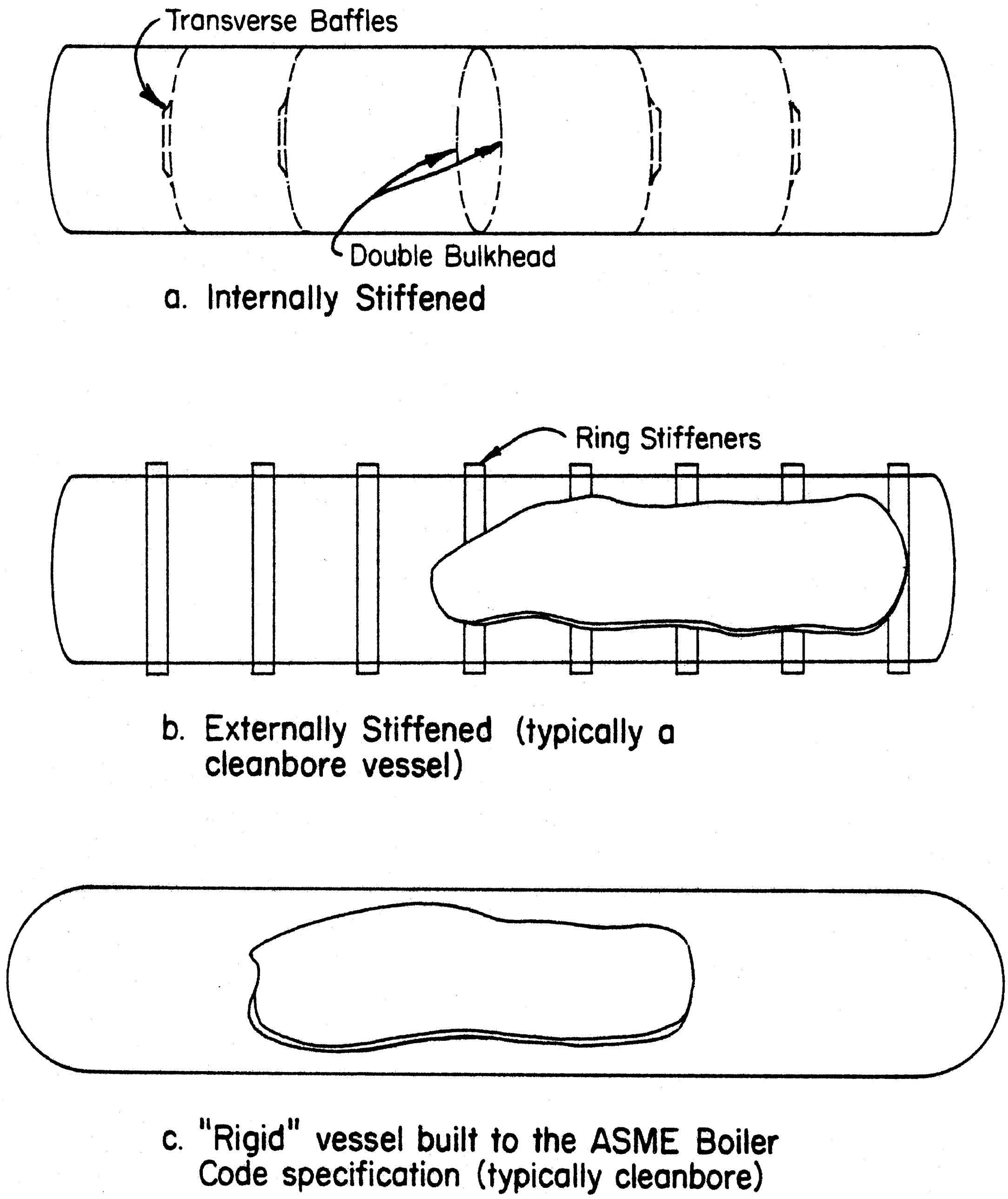


Figure 1. Types of tank construction.

characterized by type (a) is commonly employed in the transportation of various petroleum products and is constructed under the MC-306 specification of the Code of Federal Regulations.

Tank type (b) is typically a circular vessel with "ring stiffeners," in lieu of internal baffles or bulkheads, for the achievement of stiffness along the barrel. Such designs are commonly selected for transportation of the broad variety of commercial chemicals. Such tanks may also be found, occasionally, with internal baffles for mitigating the longitudinal slosh with partial loads. Baffles are not common in this type of service, however, since it is quite difficult to clean baffle-equipped tanks to the high degree of purity needed to prevent contamination with differing products.

Tank type (c) is a circular vessel constructed to the requirements of the boiler code of the American Society of Mechanical Engineers. The tank employs a heavy gauge steel shell which needs no other reinforcement elements for stiffening. Such tanks are used in the transportation of liquified petroleum gases and other pressurized loads. Because these vessels are universally of the cleanbore variety, with no internal baffles, partial liquid loads are free to slosh without impedance.

Shown in Table 1 is a listing of liquid commodities typically transported by tank trailer, together with the corresponding tank volumes and construction types which are employed. For each nominal class of liquid product, specific example fluids are identified with the corresponding density value which ultimately determines tank volume. As can be seen, certain commodities are known to be commonly transported in tanks which are sized to also accommodate lighter density products, such that apparently "oversized" tank vessels are found matched to these products (see, for example, the industrial chemicals group). The table indicates example dimensions for the tank cross section and the type of vessel which is commonly found in each category of service.

It should be noted that the "cryogenic (liquified) gases" group of commodities involves liquified air products which must be maintained at very low temperatures. Such liquids are transported in cylindrical tank vessels which have either no, or perhaps one or two, transverse baffles. An inner

Table 1. Examples of transport tank configurations used in transporting various common liquids

Commodities			Transport Tank		
General	Example	Density, lb/gal	Capacity gal	Typ. Pattern	Construction
Petroleum Fuels	Gasoline Diesel	6.2 7.1	9,000	Elliptical 95"x67.5"	4-Compartment Intern. Baffles
Other Petro. Products	Crude Oil & Industrial Oils	7.0 to 8.0	8,100	Elliptical 86.5x60.25"	Single Bore Intern. Baffles
	Asphalt	7.0 to 8.6	6,750	Circular 62.4" Dia.	Single Bore Ring Stiffen.
Industrial Chemicals	Alcohols Ammonium Nitrate Vinyls	6.4 to 6.8 7.5 6.2 to 7.8	7,125	Circular 69.25" Dia.	Single Bore Ring Stiffen.
	Glycols Acids	8.3 to 9.3 9.5 to 15.3	6,500	Circular 65.25" Dia.	Single Bore Ring Stiffen.
Industrial & Oil Field Wastes	Misc. Mixtures	9.0	5,300	Circular 59" Dia.	Internal Baffles
Dairy Pickup	Milk	8.5	6,000	Circular 62.75" Dia.	Single Bore Ring Stiffen.
Cryogenic (Liquified) Gases	Hydrogen	0.58	13,250	Circular 92" Dia.	Single Bore, Vacuum-Insulating Jacket, Intern. Baffles
	Helium	1.04	11,000	Circular 92" Dia.	
	Nitrogen	6.71	8,300	Circular 80" Dia.	
	Oxygen Argon	9.52 11.60	6,000	Circular 65" Dia.	
Other Liquified Gases	Butane Propane Anhydrous Ammonia	4.86 5.14	9,000	Circular 88" Dia.	Pressure Vessel Single Bore No Baffles

vessel which contains the product is encased within a sealed outer vessel and the annular space between the two vessels is evacuated of air and filled with an insulating material to minimize heat transfer.

An insulated jacket is frequently found on many other kinds of tanks also. Various commodities must be maintained at a relatively cool temperature in order to protect the quality of the liquid, such as in the case of milk. Other products, such as asphalt for example, are transported hot for the sake of reduced viscosity and readiness for the end-use application. Such vessels typically incorporate a blanket-type insulating material around the fluid vessel itself, with a thin outer skin sheeting over the insulation.

A typical transverse baffle seen in many kinds of cargo tank construction is shown in figure 2. The baffle constitutes a slightly dished plate having a large center hole providing the primary path for the dynamic flow of sloshing liquid. The center hole is sized so that a person may climb through, thereby assuring access to all portions of the vessel for inspection or repairs. The semicircular hole at the bottom of the baffle provides for efficient drainage flow when the tank is being emptied. The small holes sometimes found at the 0, 90, and 270 degree positions on the baffle provide for easier "pumping off" of liquid from a tank which has been rolled onto its side or top in an accident.

In appendix A to this report, example tank layout sketches are presented as illustrations of dimensions and configuration details which are thought to be rather typical of semitrailer tankers used in the U.S.

2.4 The Mechanics of Sloshing Liquid Loads

A large number of research endeavors have been undertaken, over the years, to study the mechanics of fluids which are caused to slosh inside various vessels. In this section of the report, the findings and methods of analysis and experiment developed in these studies will be summarized as they aid in describing the slosh phenomena which occur with road tankers. First, the general nature of the slosh problems which have occurred in differing

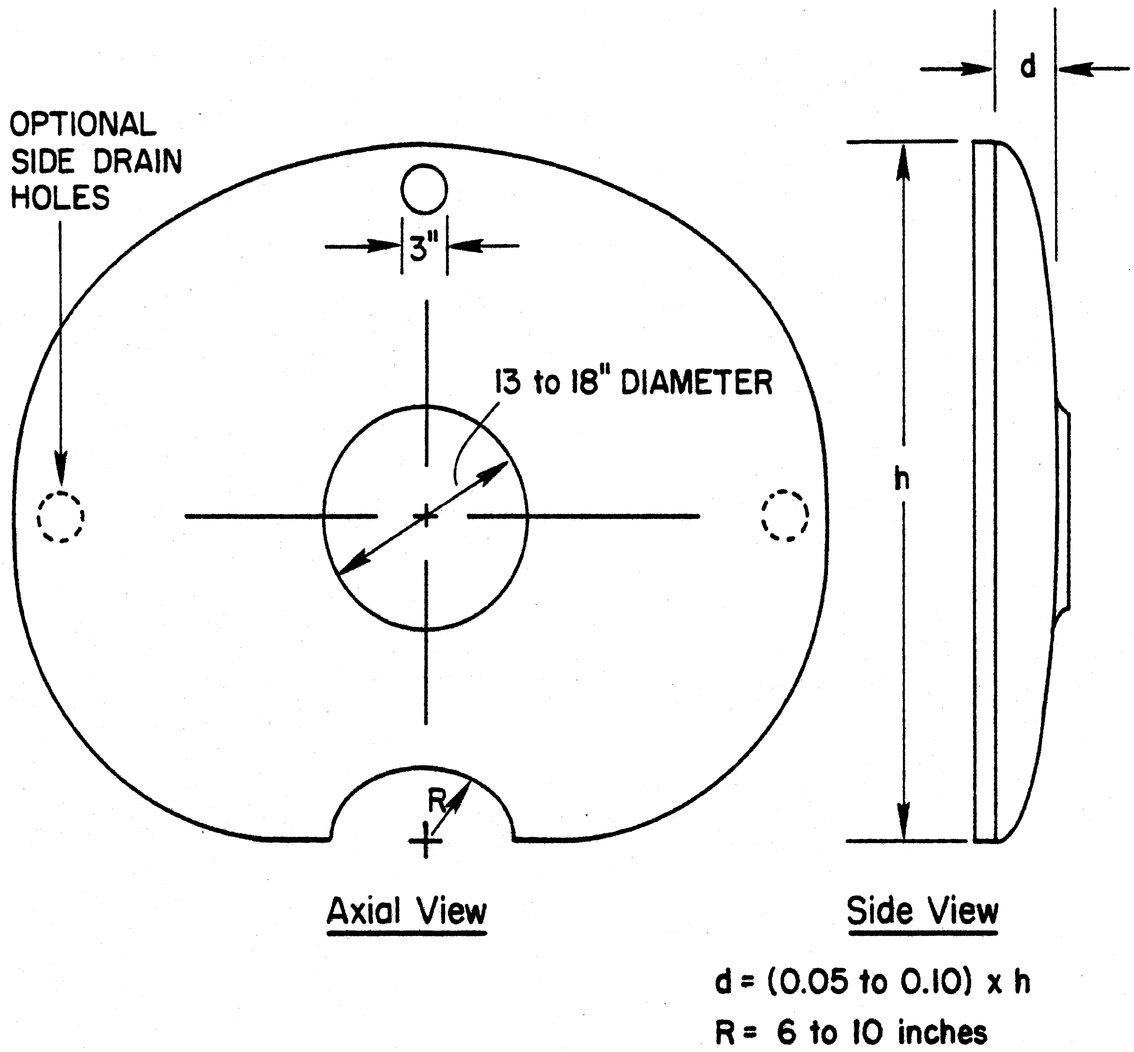


Figure 2. Typical transverse baffle.

engineering applications of tanks will be reviewed. Subsequently, detailed aspects of the mechanics of fluid slosh will be examined.

2.4.1 <u>An Overview of Slosh Problems in Various Tank Applications.</u> As outlined in the Introduction to this report, slosh-related problems have been encountered in the operation of various types of vehicles, including aerospace, marine, rail, and trucking applications. Outside of the transportation arena, there is also a substantial body of literature on the subject of oscillation in underfilled, slender, water towers which are excited by natural winds. In general, these studies have served to define the following:

1) the static and dynamic responses of liquids in underfilled vessles
2) the basic nature of the various slosh waves which are generated under the dynamic conditions which do prevail
3) the frequencies of excitation at which dynamic slosh waves resonate
4) the influences of tank shape, fluid viscosity, nominal fluid fill level, etc., on the response of the liquid
5) analytical simplifications relating geometric parameters of the tank and the fluid fill level to small amplitude sloshing behavior
6) the nominal effectiveness of baffles and other measures meant to mitigate the influence of slosh

The primary work prior to 1960 in the area of slosh dynamics was conducted by the aerospace community and is summarized by Abramson [6]. The major issue being confronted in the aerospace application concerns the lateral sloshing of liquid fuels in a manner which disturbs the attitude control systems of launch vehicles. Although transient slosh motions can be excited by wind shear loading as a rocket ascends through the atmosphere or by engine shutdown during a multiphased launch, the mere presence of a lightly damped mode of slosh motion in the vicinity of the natural frequency of the attitude control system has caused the failure of many early rockets [7]. Aerospace research on the subject of fluid slosh has provided very useful simplified models of slosh mechanics which, in fact, provide good first-order estimates of the slosh motions that arise in the case of road tankers. The aerospace literature also provides a good treatise on slosh mitigation techniques in the form of a NASA design manual entitled "Slosh Suppression" [7]. Moreover, the aerospace engineering community is primarily responsible for the advanced understanding of general slosh phenomena which exists today.

In the marine field, the primary problem posed by sloshing cargo is a structural one. That is, during long ocean voyages, the continual excitation of liquid cargo by sea waves serves to create dynamic loading which can cause structural damage to the containment vessels within the ship. The large dimensions of cargo tanks in commercial ships are such that the slosh waves can travel rather long distances at relatively shallow fluid depths as the ship ptiches and rolls. Unstable slosh waves, called "hydraulic jumps," can occur and produce high levels of impact force upon collision with the tank walls. A summary of the marine problem involving sloshing liquids is provided by Bass [8] in a paper published by the Society of Naval Architects and Marine Engineers. The research in this field has been useful in elucidating the road transportation problem posed by the longitudinal sloshing of liquid in unbaffled tanks at low fill levels. The hydraulic jump phenomenon which is especially adverse in marine practice has also been observed in the road tanker case involving candidate baffle arrangements which have a horiztonal plate at a shallow depth below the fluid surface. The typical marine problem differs intrinsically from that of road tankers, however, in that sea waves provide periodic excitation to ships, while the problematic type of slosh occurring in road tankers is produced, primarily, by the transient loading which arises in an occasional abrupt maneuver.

Rather little was found in the literature regarding the sloshing-liquid problem in rail tank cars. A 1960 paper by Irrgang [9] explains that "...although there are certain differences between tank cars with and without (baffles), these provide no advantages with regard to (danger of derailment), running characteristics, braking and shunting. Thus because of their disadvantages (regarding aggravation of structural stresses in the tank) they are not to be required in the future for new stock or for existing cars." (Interestingly, a classic concern of American manufacturers of road tankers has also been that the use of longitudinally oriented baffles would tend to locally stiffen the tank structure such that fatigue stress problems would arise.) The lack of a problem with slosh dynamics in the rail environment would appear to suggest either an infrequent incidence of partial loading in tank cars or the general unavailability of excitations having the needed frequency and amplitude characteristics to cause problematic sloshing.

The literature speaking directly to the mechanics of sloshing liquids in road tankers is, itself, quite substantial. Perhaps the most completely informative document which addresses the state of knowledge on the road tanker problem is a research report by Strandberg [10]. It is clear that the transient steering and braking inputs which attend accident-avoidance maneuvers produce large levels of longitudinal and lateral acceleration in the frequency ranges which can excite major slosh motions. Since the fluid responses are characteristically underdamped, overshoots occur which have significance for vehicle stability and control. The available information on fluid motions, natural frequencies of slosh resonance, sensitivity to geometric parameters and fluid viscosity, and the degradation in overall vehicle stability deriving from slosh are all reasonably complete in the case of road tankers. In the discussion of individual aspects of the slosh phenomenon, later in this section, research conducted on slosh in other transportation modes will be combined with that conducted peculiarly for road tankers in assembling the overall picture for the road tanker application.

The oscillatory problem encountered with slender water towers has involved excitation of the very lightly damped tower structure either by period gusts which produce disturbances in the direction of the wind, or by the periodic shedding of von Karman vortices, producing disturbances normal to the wind. When the excitation frequency approaches one of the natural frequencies of the structure, the sustained lateral motions of the tank can cause large amplitude wave motions to be built up in the liquid. Since the fill level in such tanks varies over a wide range each day, the potential for damaging slosh action is large. Accordingly, multiple baffles are recommended (see Berlamont, [11]) in order to damp slosh action and to raise the natural sloshing frequencies above the range of the structural modes. The water tower problem is rather unlike the concern with most road tankers since it requires that a lightly damped mode of vibration of the tank resonate with slosh dynamics over a large number of cycles. As will be shown, however, there is reason to suspect that road tankers constructed as full trailers, which are known to exhibit a lightly damped mode of yaw oscillation, may suffer an exaggerated resonant interaction with slosh waves.

2.4.2 The Mechanics of Slosh as it Applies to Road Tankers. This section will deal with the various aspects of fluid slosh in road tankers from the viewpoint of analytical and experimental findings which permit us to generalize on the phenomenon and its practical implications.

2.4.2.1 The basic nature of slosh motions. In the quiescent state, the fluid residing in an underfilled vessel exhibits a planar free surface and that plane is normal to the gravity vector. When other accelerations than that of gravity are present, the fluid surface assumes other orientations and shapes. In the common static case in which a tank vehicle is negotiating a steady-state turn at constant velocity, V, the fluid surface assumes a parabolic shape since the centripetal acceleration (V^2/R) imposed upon the respective elements of the liquid increases with increasing turn radius, R, across the width of the tank. For practical purposes, however, the turn radius is quite large relative to the width of the tank such that the liquid assumes an essentially planar surface whose roll orientation is normal to the resultant acceleration vector at the center of the tank. The roll angle of the liquid surface, phi, is simply defined by the lateral acceleration component, A_y, and the acceleration due to gravity, g, as:

$$\text{phi} = \arctan A_y/g$$

Shown in figures 3a and 3b is the relationship, developed by Isermann [12], between the steady lateral acceleration level and the net lateral and vertical displacements of the center of the fluid mass for circular and "superelliptical" tanks whose nominal dimensions are shown. The data show, for example, that at 0.25 g's of lateral acceleration, the liquid mass center in the 21-percent-filled circular tank experiences a lateral shift of 7.9 in (200 mm). The same condition with the superelliptic tank yields a lateral displacement of approximately 12.2 in (310 mm). Clearly, the shape of the tank is a strong determinant of the extent of displacement of the fluid mass deriving from the steady-turn condition, with the "flatter" tank shapes suffering the larger displacements for a given percent-full condition. In

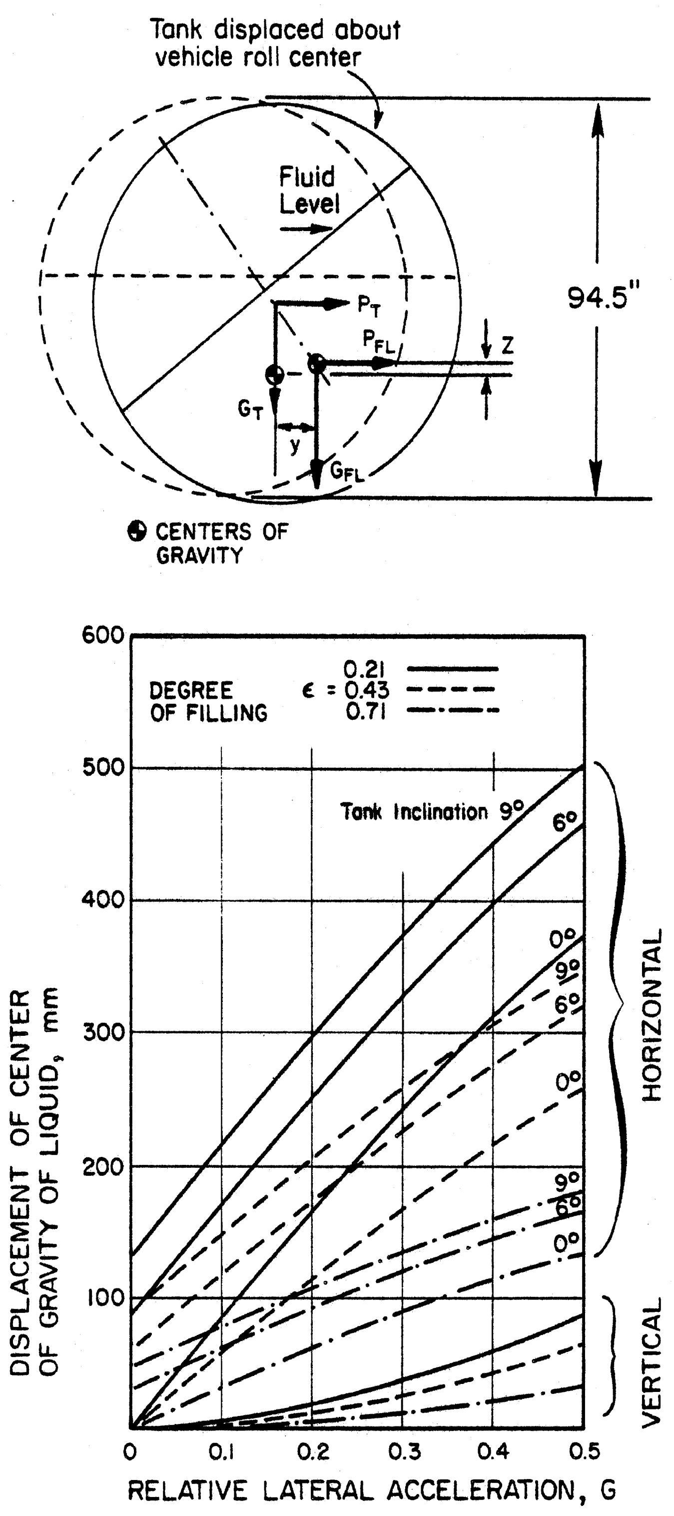


Figure 3a. Horizontal and vertical displacement of center of gravity of liquid in containers with circular cross-section at various tank angles-of-inclination.[12]

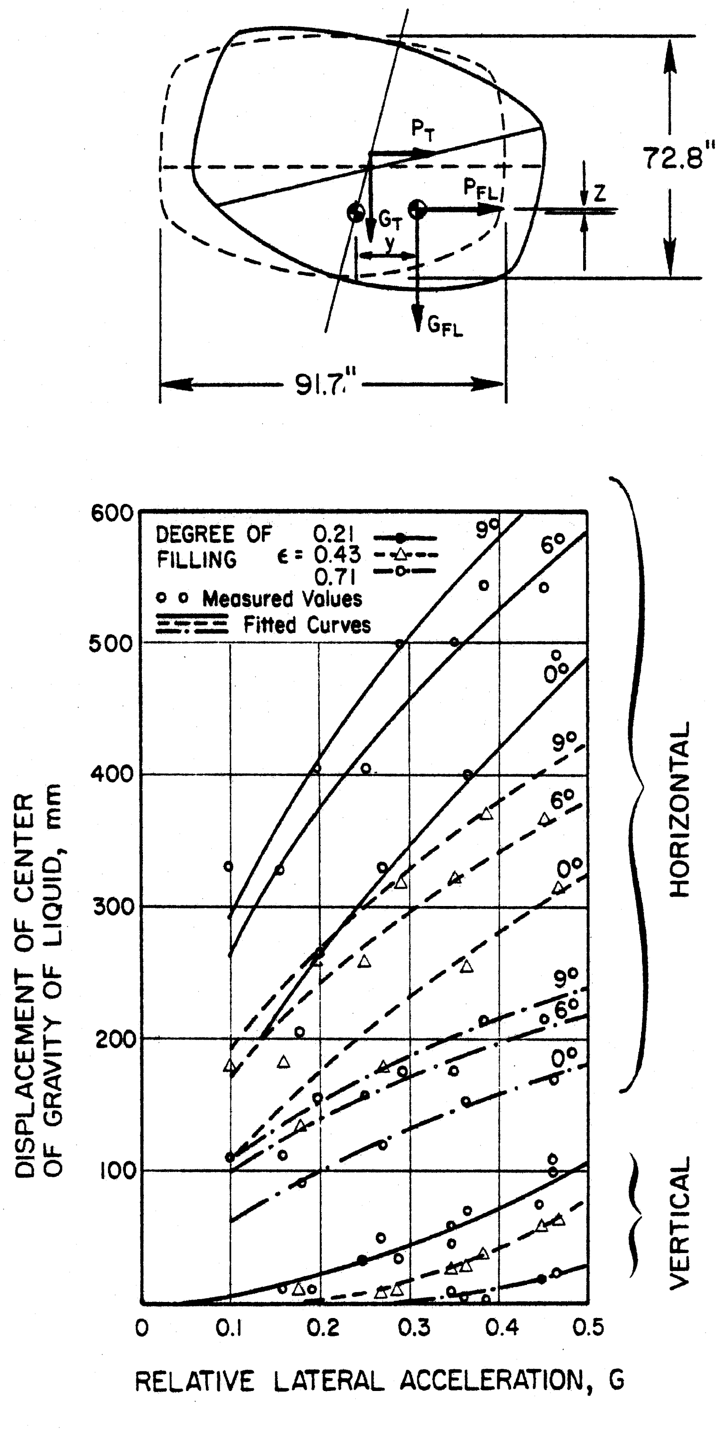


Figure 3b. Horizontal and vertical displacement of center of gravity in container with cross-section as shown above. [12]

section 2.5, it will be shown that such static fluid displacements constitute a powerful mechanism for degrading tanker stability.

Dynamic sloshing motions of the liquid are induced whenever a transient or steady-state oscillatory excitation is imposed. Although transient accelerations constitute the more important excitations which cause slosh to threaten the stability of road tankers, the steady oscillatory type of forcing is much more amenable to analysis and is more thoroughly covered in the literature. Since the qualitative nature of many transient responses can be inferred from "frequency response" information, it is useful to examine the nature of steady-state oscillatory sloshing.

Oscillatory sloshing waves have been classified by Su [13] according to four basic types, namely, standing waves, traveling waves, hydraulic jumps, and composite waves involving combinations of any of the former types. Su states that:

> "For a shallow liquid oscillating at a frequency much lower than its resonance frequency, a standing wave will be formed. As the frequency increases, the standing wave changes into a train of traveling waves of very short wavelength. Hydraulic jumps result from small disturbances and appear over a range of frequencies near the resonance frequency. As frequency increases, the jump will pass into a solitary wave."

Shown in figure 4 are photos produced in Su's laboratory experiments showing waves developed under nominally shallow and deep liquid fill levels. The figure shows the nature of the waves which form at these fill conditions as the frequency of roll angle excitation increases, from top to bottom. The waves produced with the shallow fill level, at the left, show a hydraulic jump developing at the third increment in excitation frequency. At the bottom left, the hydraulic jump response has become a solitary wave which propogates from right to left on the surface of an otherwise rather level liquid. At the deeper fill level, sloshing near resonance is characterized by the formation of large amplitude standing waves. This "first mode" wave becomes superimposed upon the surface of the steeply inclining bulk mass of the fluid, rendering the left- and right-going fluid shapes asymmetric. At large amplitudes of excitation, so-called "traveling waves" may combine with the

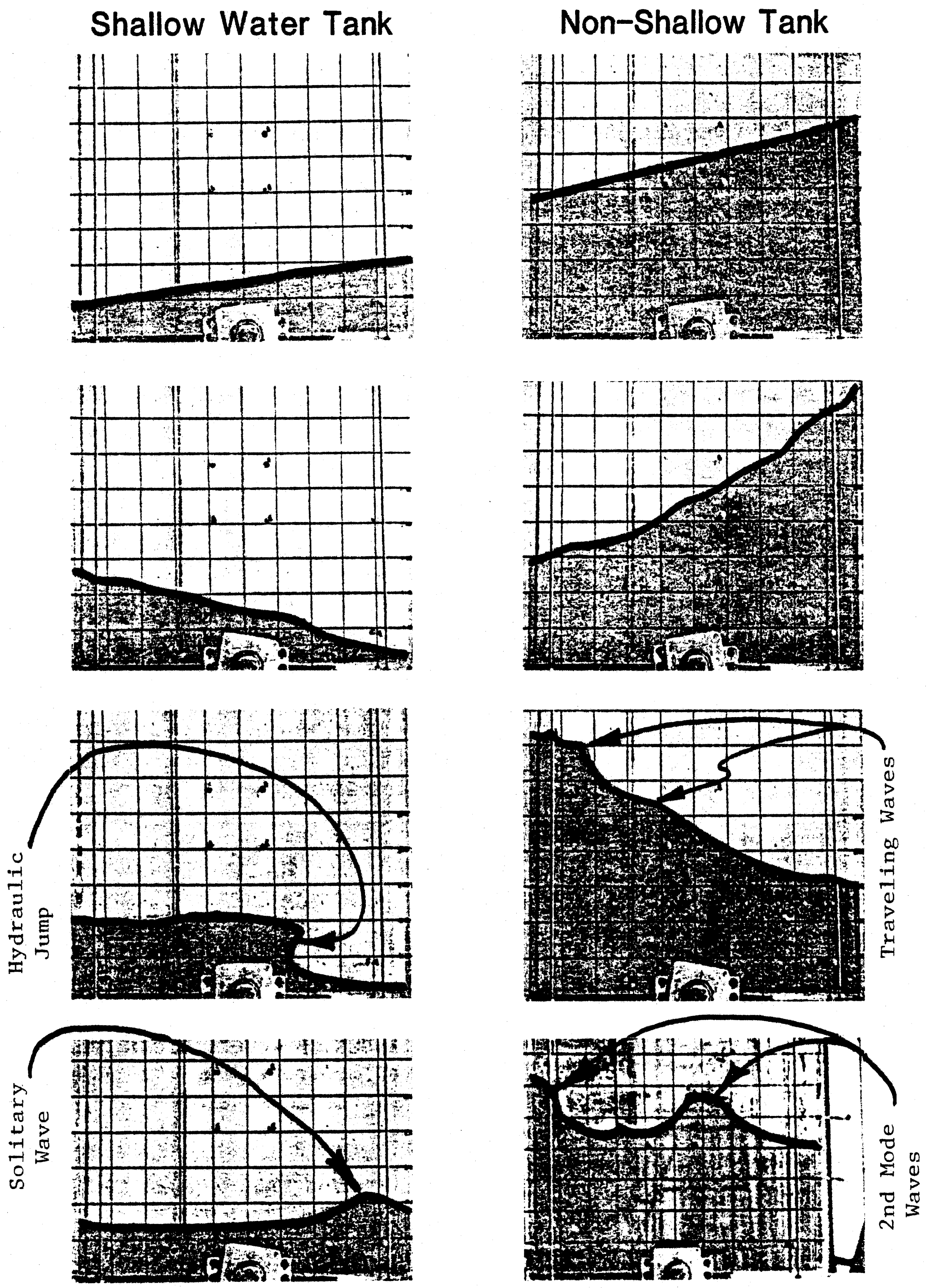


Figure 4. Characteristic wave types - Excitation frequency increases from top to bottom. [13]

standing waves, such as in the third case of excitation of the deeper-fill-level fluid. The traveling waves are seen as the small amplitude, short wavelength disturbances on the fluid surface. At frequencies very different from the resonant frequency, the slosh amplitude achieved with deep liquids is rather small until the second mode of wave development becomes excited, as in the bottom illustration. Such higher modes are generally beyond the range of frequencies, however, at which vehicle maneuvering activity occurs.

The force loadings applied to tank walls as a result of sloshing are classified by various investigators as either impulsive or non-impulsive. The primary mechanism for impulsive loadings appears to derive from hydraulic jump types of waves. That is, when the nearly vertical front face of the jump wave strikes the tank wall, an impact occurs which results in impulsive pressures lasting on the order of 1 to 10 msec. Su [13] indicates that impulsive pressures can also be caused by large amplitude, near-resonance, standing waves due to the rapid and continuous buildup of liquid surface, generally producing a pulse whose duration is on the order of one tenth of the sloshing period. The most severe impact pressures occur at the elevation of the quiescent filling level of the liquid or at abrupt intersections of tank walls.

Fortunately, the gently curved tank shapes used in typical road tankers tends to avoid the impact pressure problems which occur at the abrupt corners of, say, rectangular tanks. Clearly, the issue with impulsive loading involves the structural integrity of tanks. Since the impulsive loads generally contain frequencies which are high relative to slosh resonance frequencies, they do not significantly influence the gross motion behavior of vehicles.

Non-impulsive pressures are the ordinary dynamic pressures exerted on the container by an oscillating fluid. These pressures are developed at the nominal frequencies of the wave motions, themselves. As will be shown in section 2.4.2.4, the lateral and longitudinal forces produced in road tankers due to the resultant of such pressures in the horizontal plane amount to substantial loads influencing the cornering and braking trim on the overall vehicle. Further, in the cornering scenario, the lateral component of the fluid pressure reaction against the tank produces a transient roll moment which is important to the determination of roll stability.

2.4.2.2 The mechanics of slosh deriving from linear analysis. In 1960, Budiansky [14] published an analysis based on the linearized hydrodynamics of an inviscid fluid sloshing in a cylindrical tank. His theory was limited to tanks of circular cross section and to small amplitude fluid motions. His evaluation of natural frequencies of slosh motion were confirmed in experiments conducted by McCarty and Stephens [15]. The natural frequencies of lateral and longitudinal slosh motions for differing fill condition are expressed in nondimensional terms in figure 5, for circular "canals" having fluid depth, h, tank radius, a, and tank length, l. For both directions of excitation, the resonant frequencies go up with increasing fill level and down with increasing tank radius (or length).

Considering application of the natural frequency data in the figure to realistic road tanker dimensions, table 2 presents the natural frequency of the first, or fundamental, mode oscillations computed for an example circular tank, 84 in (213.4 cm) in diameter and 40 ft (12.2 m) in length.

Table 2. Parameters describing fundamental mode oscillations in a cylindrical tank trailer

Fluid Depth (in)	h/2a	Nondimensional Freq. Lat.	Nondimensional Freq. Long.	Temporal Freq. (Hz) Lat.	Temporal Freq. (Hz) Long.
12	.14	1.05	1.40	.51	.07
36	.43	1.10	1.55	.53	.11
48	.57	1.20	1.60	.58	.13
72	.86	1.60	1.90	.77	.19

It is clear from figure 5 that the tank dimensional parameters, a and l, have a first-order influence on the respective lateral and longitudinal natural frequencies. Fill height, on the other hand, has a lesser influence on the natural sloshing frequencies except for nearly full conditions at which the frequency tends to rise exponentially. Bauer [18] has observed that,

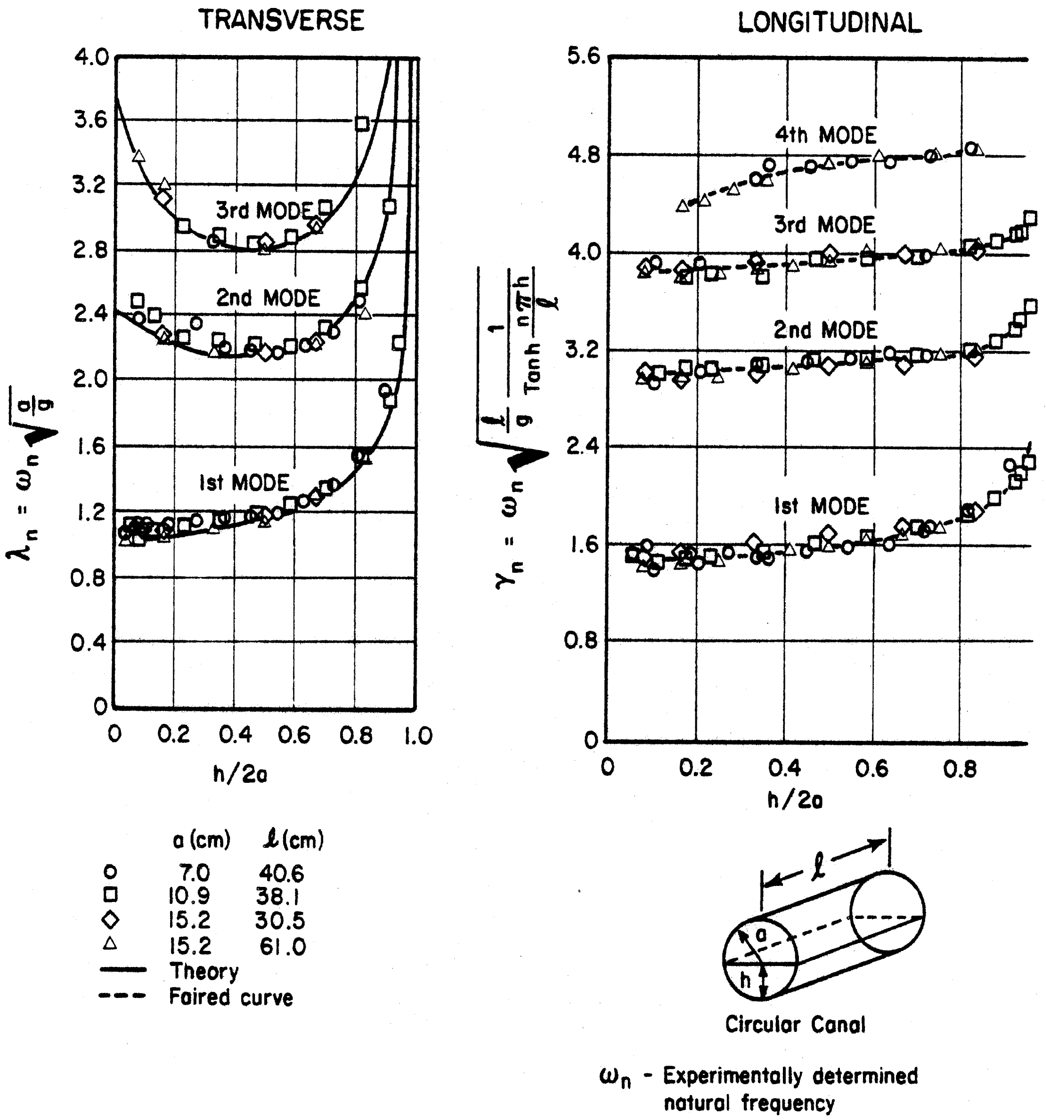


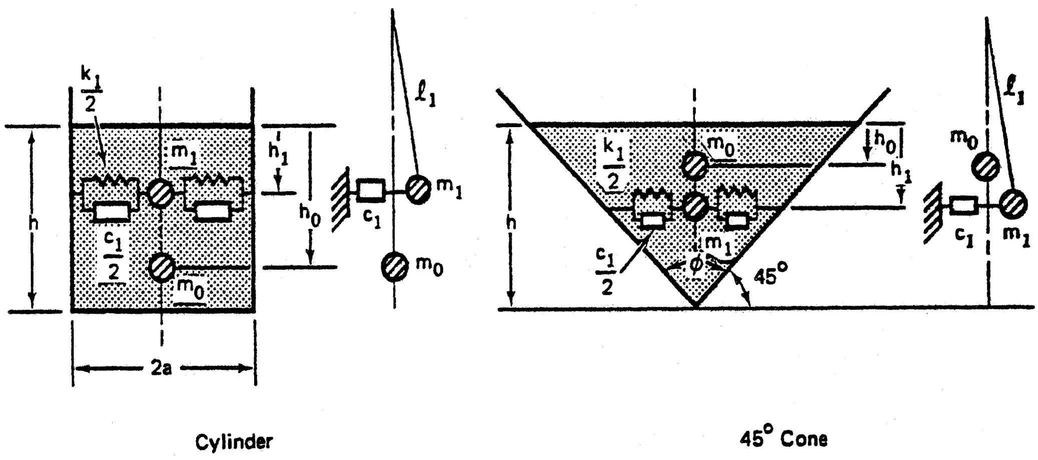
Figure 5. Variation of liquid natural frequency with depth for transverse modes in a circular canal.

"...for a small increase in liquid height, the first natural frequency increases only slowly, due to the fact that nearly all the liquid moves as a sludge, while for heights close to the diameter, only a smaller portion of the liquid participates in the free surface motion, which due to the rapid change of its area with increasing liquid height, shows a strong increase of the natural frequency."

Basically, Budiansky's analysis serves as a reasonable means to obtain a first-order estimate for the fundamental mode slosh frequencies occurring in road tankers hauling most common liquids. For example, a value of 0.5 to 0.6 Hz for the calculated natural frequency of lateral sloshing, with a fill level in the vicinity of 50 percent of tank capacity, basically matches the results obtained through the experimental work of Strandberg [10] on other tank shapes commonly found in road tanker applications. Additionally Su [13] combined results from differing investigators showing that even tanks having a rectangular cross section show natural slosh frequencies which are close to Budiansky's predictions for circular cylinders. For example, a half-filled rectangular tank having the 84-in width dimension used in the table above will show a natural frequency of 0.57 Hz for lateral slosh--within 3 percent of the value predicted by the data in figure 5 for a circular cylinder whose diameter is equal to the width of the rectangle.

Thus, another finding which can be drawn from the sum of these observations is that the cross-sectional shape of a tank is not a significant determinant of the natural frequency of lateral slosh motions, given a fixed value for the width dimension. Tank shapes which incorporate larger values of width will, however, exhibit lower natural frequencies for lateral slosh than will tanks whose shapes render a more narrow profile.

A linear, lumped-mass model which provides insight into the first-mode sloshing system has been identified in a NASA Design Criteria publication entitled "Propellent Slosh Loads" [16]. Shown in figure 6 are illustrations of a mechanical-type of modeling approach for representing the slosh motions in upright tanks having circular cross sections and cylindrical, conical, and ring profiles in the side view. Such tanks are of interest in aerospace vehicles. Numerical values for the nondimensional parameters of the



CHARACTERISTICS	CYLINDER	45° CONE
Natural frequency, ω_1	$\sqrt{1.841\ ga^{-1}\ \tanh(1.841\ ha^{-1})}$	$\sqrt{gh^{-1}}$
Sloshing-mass ratio, m_1/m	$0.4547\ ah^{-1}\ \tanh(1.841\ ha^{-1})$	0.75
Fixed-mass ratio, m_0/m	$1 - \frac{m_1}{m}$	0.25
Spring constant, k_1	$m_1 \omega_1{}^2$	$m_1 \omega_1{}^2$
Sloshing-mass location ratio, h_1/h	$1.08\ ah^{-1}\ \tanh(0.920\ ha^{-1})$	0.4
Fixed-mass location ratio, h_0/h	$\frac{1}{2}\frac{m}{m_0} - \left(\frac{m_1}{m_0}\right)\left(\frac{h_1}{h}\right)$	-0.2
Pendulum-length ratio, ℓ_1/h	$0.5432\ ah^{-1}\ \coth(1.841\ ha^{-1})$	1
Damping coefficient, c_1	$2m_1 \omega_1 \zeta_1$	$2m_1 \omega_1 \zeta_1$

Figure 6a. Basic data and mechanical models for representing first-mode lateral sloshing in circular cylindrical and 45° conical tanks. [16]

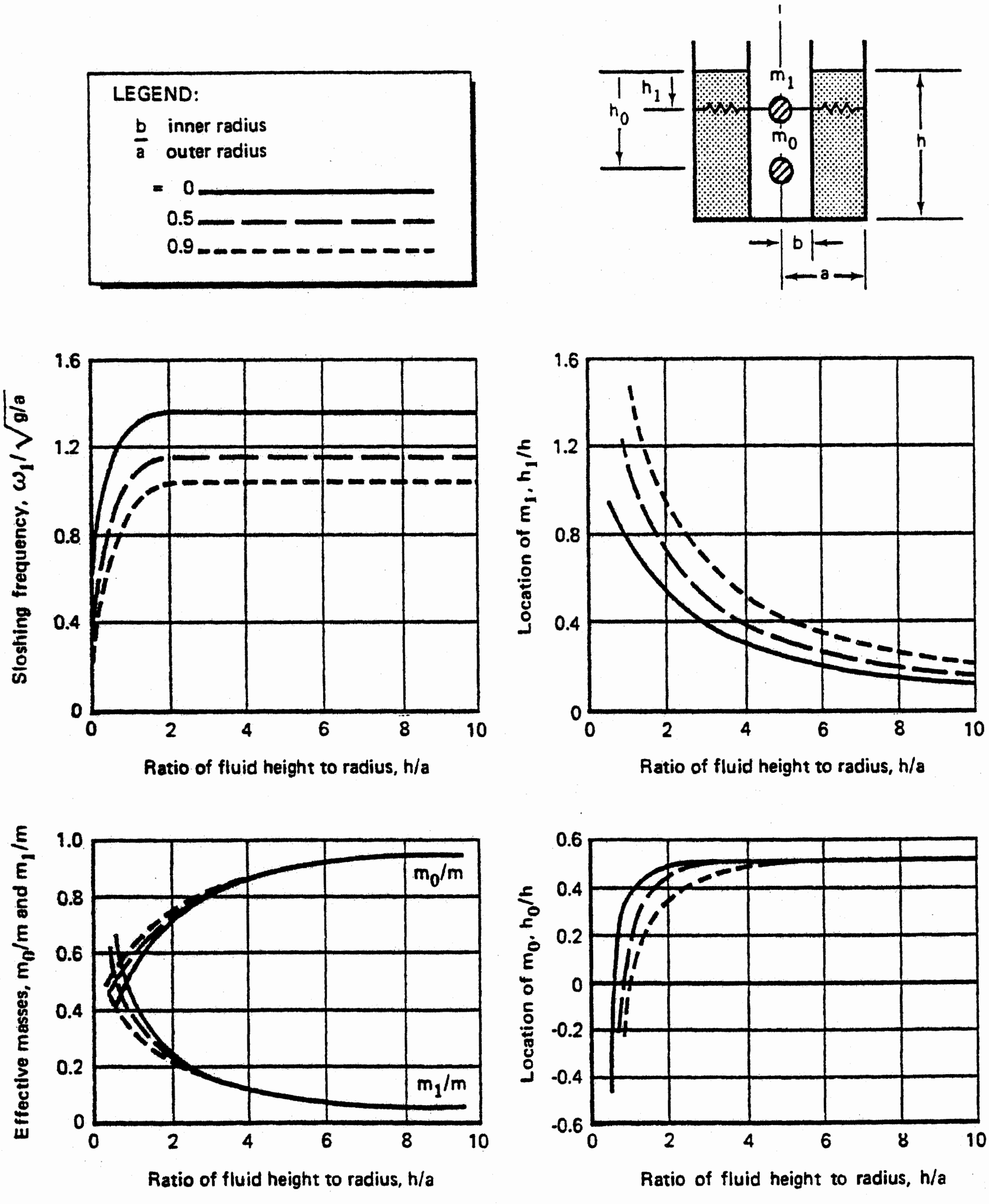


Figure 6b. Frequency, effective masses, and mass attachment points for the lumped spring-mass model representation of first-mode lateral sloshing in circular cylindrical ring tanks for various ratios of inner tank radius to outer tank radius. [16]

cylindrical tank shown in figure 6a are plotted in the graphs of figure 6b under the curves corresponding to b/a = 0.

The "mechanical models" introduce the notion that the sloshing phenomenon involves a "fixed" and a "sloshing" mass such as alluded to in Bauer's observations, above. The portion of the total fluid mass which can be considered sloshing is determined by the ratio of the fluid height, h, to the tank radius, a. While a thorough discussion of the utility of such models is given by Abramson [17], one useful application involves locating the vertical position of the slosh reaction load (at h_1) and estimating the size of the reaction force, given knowledge of the excitation forces. This simple scheme also provides an analytical method of determining the natural frequency of the fundamental mode of slosh motions.

The natural frequency of the fundamental slosh motion will be shown in section 2.4.2.6 to be of importance as a safety consideration because of the greater likelihood of exciting the motions which resonate at lower frequencies. This concern is identical to that expressed in the NASA manual "Slosh Suppression" [7] in regard to the desirability of compartmenting tanks so as to increase resonant slosh frequencies above the range of possible excitation. In road tankers, compartmentation not only aids by raising the longitudinal slosh frequency, but also by attenuating the effective magnitude of the "sloshing mass," in the sense established in the "mechanical modes" shown above.

The amplitude of the sloshing fluid motions is, of course, determined by the size of the excitation force, the proximity of the excitation frequency to the resonant slosh frequency, and the magnitude of the damping which opposes fluid velocity. The primary damping mechanism pertains to the viscosity of the fluid which is involved. Since road vehicles transport a wide variety of fluids which exhibit damping properties ranging from the extremely low viscosity levels found with most cryogenic liquids to the very viscous petroleum and food products.

Notwithstanding the wide range of viscosities, research has shown that road tankers experience slosh motions which are generally insignificantly influenced by fluid viscosity (see, for example, refs. [10] and [13]).

Strandberg [13] explains that this issue is properly addressed simply by examining the ratio of inertial to viscous forces produced within the slosh-induced flow. This ratio is commonly expressed as the Reynolds number which, for the ranges of density and viscosity of most commercial fluids carried in road tankers, assumes a rather high value when slosh flow velocities characteristic of the fundamental mode of motion are considered. Thus, inertial rather than viscous effects dominate in determining slosh flow responses in the fundamental mode of oscillation. This finding covers all liquids which are sufficiently fluid to be pumped to and from a road tanker (having viscosities up to approximately that of glycerin at 60 deg F—1200 centistokes (4200 Saybolt Universal seconds).

2.4.2.3 Complex wave motions examined through nonlinear analysis. Perhaps the most complete analysis of the complex flow phenomena which can occur due to sloshing has been reported by Su [13]. Although he cites a number of earlier studies, dating back to the fifties, the early work considered only nonlinear wave motions, while otherwise assuming linear boundary conditions at the tank wall, small amplitude tank motions, and an absence of impact conditions such as produce fluid spray, air entrainment, etc.

Su's work constitutes a complex numerical analysis of the time-dependent flow of incompressible fluids within tanks in a moving coordinate system. The tank can pitch or roll about defined axes and can experience rectilinear accelerations. The developed model takes into account the nonlinearities at the free liquid surface and at the liquid/tank interface.

The interested reader should consult Su's report to examine the many cases of tank configuration and excitation which were examined. An example of the work is shown in figures 7a and 7b. The progression of illustrations in this figure show that a large rectangular tank filled to 75 percent of capacity suffers harsh impact loads against its tank top due to the complex sloshing of liquid under the influence of a rolling oscillation. Paraphrasing Su's explanation, we see that soon after the motion has started, a large eddy has built up, in frames (g) and (h). In frame (h), an opposite current has developed near the free surface. This leads to a wave "overtopping," which appears in frame (i) and the subsequent air entrapping in frame (j). In frame

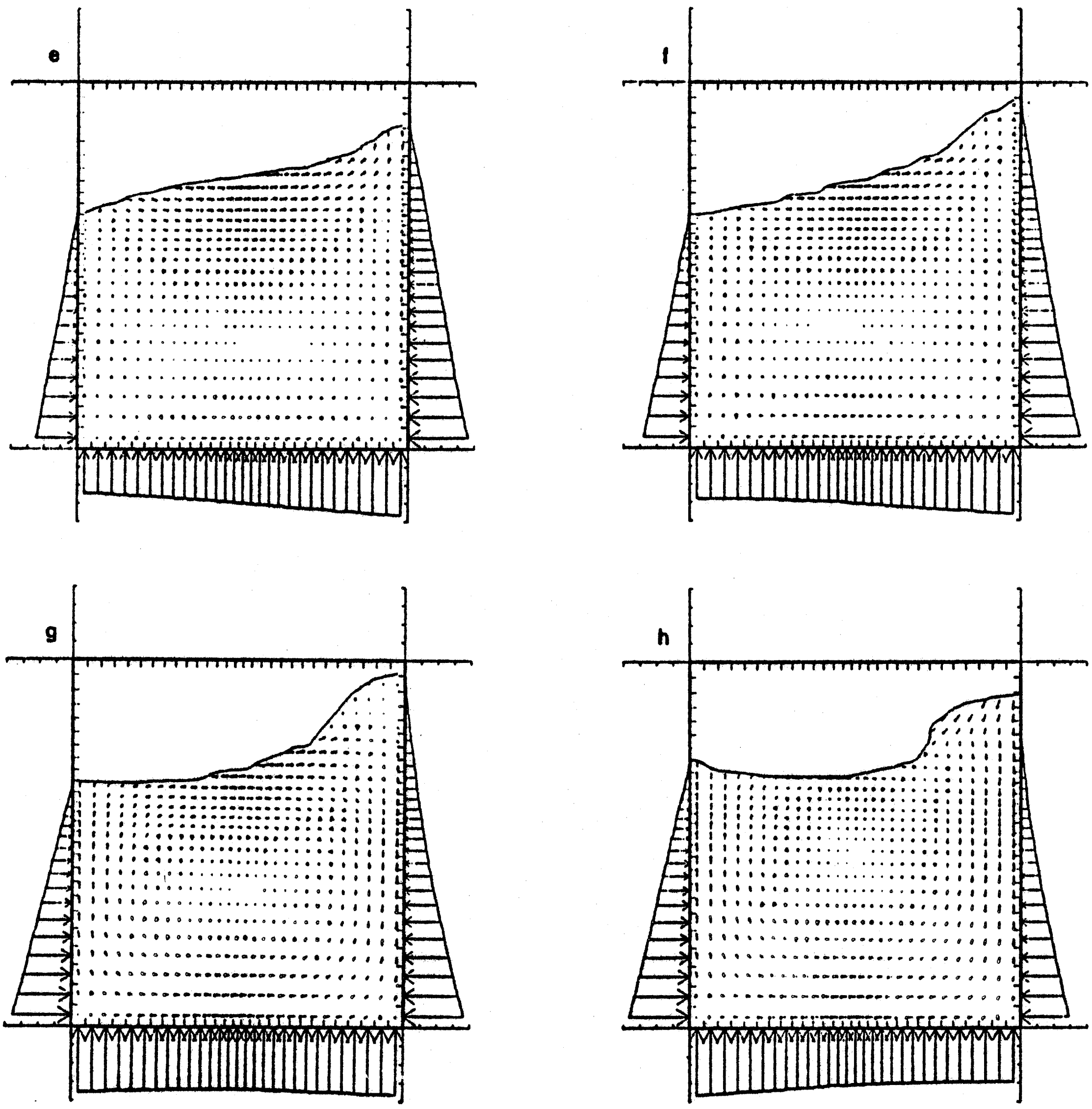


Figure 7a. Liquid sloshing in an unbaffled tank - 8° roll, $\omega = 0.85\,\omega_n$
(e) t = 1.52, θ = 0.1294 (f) t = 2.02, θ = 0.0716
(g) t = 2.15, θ = 0.0120 (h) t = 3.00, θ = -0.0923 [13]

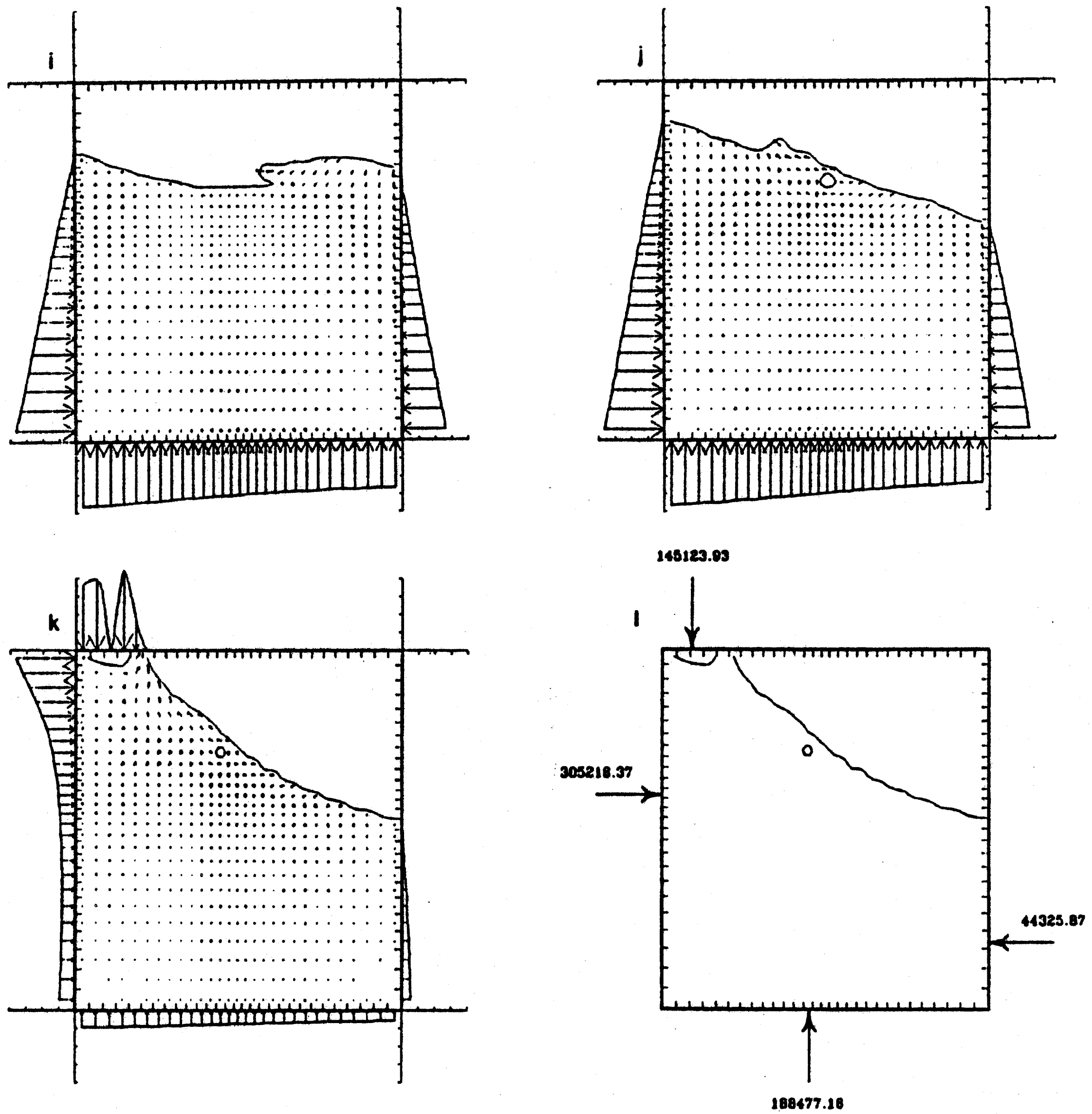


Figure 7b. (i) t = 3.50, θ = -0.1365 (j) t = 4.01, θ = -0.1261
(k) t = 4.50, θ = -0.0666 (l) t = 4.50, θ = 0.0666 [13]

(k), a wave has hit the tank top and produced a large impact pressure, many times larger than the hydrostatic pressure experienced at the bottom of the tank. Subsequent frames show the continuing development of the complex wave action involving even separated fluid volumes.

Highly complex nonlinear phenomena such as that illustrated above certainly may exist in the road tanker application, although it appears reasonable to conclude that warrants for such analyses exist onlyl when:

a) the magnitude of the slosh response is at issue, given viscous effects, or

b) the tank incorporates baffles obstructing the flow, or

c) fluid pressures due to impact conditions are of concern

2.4.2.4 <u>Forces on the tank due to sloshing</u>. Mechanical analogy models were described earlier for use in determining the natural frequency of fluid slosh. The same types of models may also be used to determine the magnitude of the resultant forces and moments exerted in the horizontal plane due to slosh. At another level, structural considerations demand that fluid pressures arising from slosh be evaluated such that localized dynamic loading of the tank shell may be assessed.

The National Aeronautics and Space Administration (NASA) has produced recommended practices for the design of space vehicle tanks which may be subject to sloshing fluids [16]. In this recommendation, equations are given for calculating the peak fluid pressures which will prevail at the resonant slosh condition as the consequence of harmonic excitation. It is readily observed, in this analysis, that a certain slosh amplitude is reached, given the frequency, in which the downward accelerations equal the acceleration due to gravity. At that condition, the sloshing waves break up into turbulent splashing, thus establishing an effective upper bound for slosh amplitude.

The experimental work which has been done in support of NASA's recommendations has involved the relatively low levels of lateral acceleration which are characteristic of the spacecraft problem. Strandberg [10] observed that these acceleration levels are much below that needed to achieve rollover of a road tanker. It is instructive to note, however, that low acceleration data of this type reported by Abrahamson [17] show sloshing forces on the order of seven times larger at resonance than the inertia force calculated for the same mass if it were rigid and fixed to the tank.

When Strandberg conducted his own experiments employing excitation amplitudes which approached the rollover limit of road tankers, the corresponding sloshing liquid force amplitudes were on the order of two to three times larger than the simple inertia force for an equivalent rigid load. Shown in figure 8 is a plot of Strandberg's measurements of the "lateral liquid force factor" versus a "sloshing factor." The ordinate variable is simply the ratio of the peak lateral forces due to the slosh response to a harmonic lateral oscillation to the corresponding force level of a rigid load. The abscissa variable is the ratio of "overturning factors" for cases of sloshing liquid (R_{OS}) and rigid load (R_{OR}), where each overturning factor is defined as the peak fraction of the vertical load which has been transferred from the tires on one side to the tires on the other. Of course, the vehicle will roll over when an overturning factor is equal to 1.0. Values of the "sloshing factor" greater than one simply indicate that the peak load transfer attained in the sloshing case exceeds that for a rigid load, at the same level of lateral acceleration amplitude. The data in the figure represent a range of excitation frequencies passing through the slosh resonance value with each tank.

It is not surprising, of course, that the data in the figure show that the buildup of resultant lateral force due to sloshing closely follows the value of the sloshing factor which reaches its highest levels at fluid resonance. Note that the figure identifies data points for three tank shapes, namely, cylindrical (C), elliptical (E), and superelliptical (S)--which describes a rather flattened ellipse.

In addition to the lateral force implications of fluid slosh, the importance of the slosh phenomenon to the roll stability of road vehicles is also determined by the effective lateral translation of the fluid mass center as a result of the lateral wave motion. Shown in figure 9 is Strandberg's estimation of the lateral translation of the liquid mass center corresponding to a 50-percent-full load over the range of sloshing factors shown in the

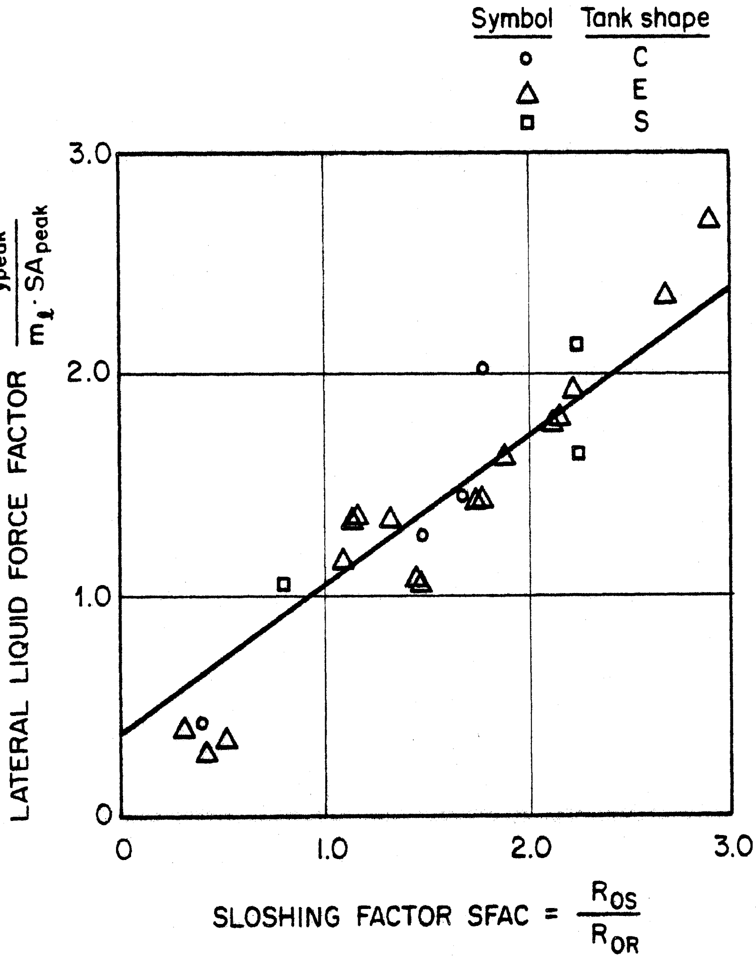


Figure 8. Harmonic oscillation at different frequencies and different tanks with 50% load volume. Y-values: Lateral liquid force peak divided by corresponding value for rigid load. X-values: Overturning factor for sloshing load divided by do. for rigid load. Line drawn from linear regression. Correlation coefficient r = +0.80. [10]

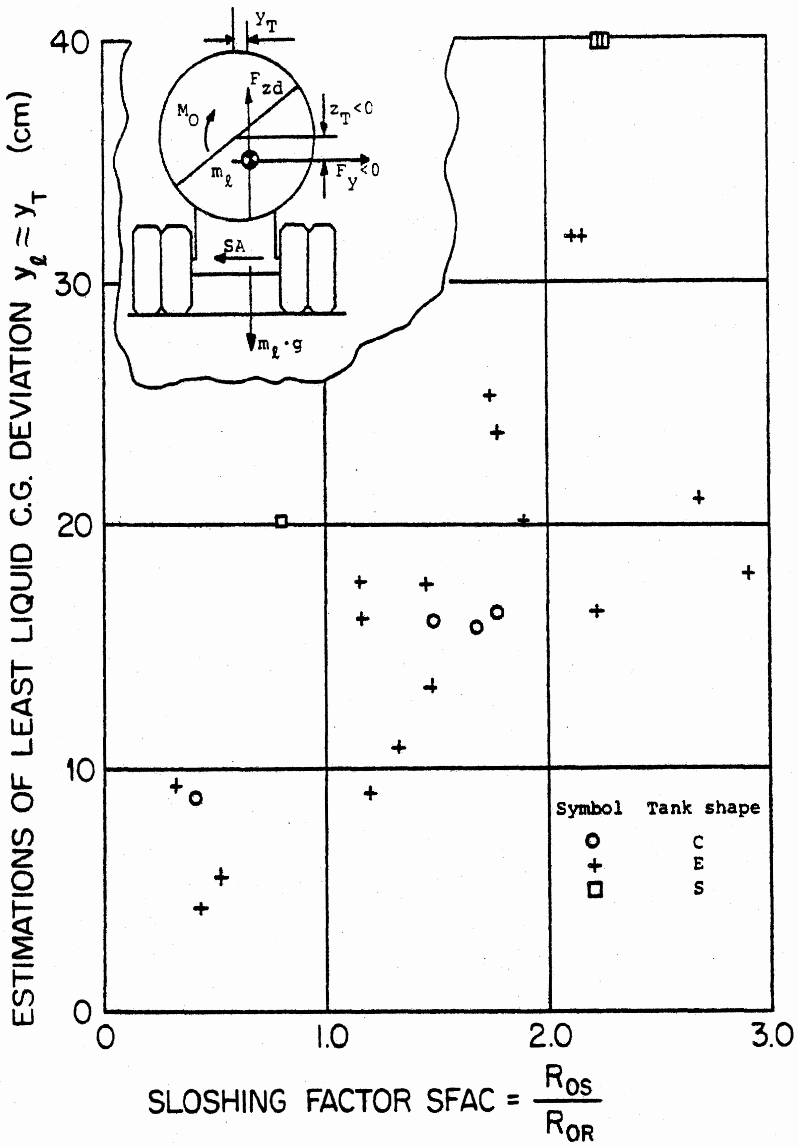


Figure 9. Approximate least values for the lateral deviation of the liquid's center of gravity plotted against the so-called sloshing factor. Harmonic oscillation at different frequencies and different tanks with 50% load volume. [10]

preceding figure. The indicated values for lateral translation of the fluid mass are notable insofar as they imply a large fraction of the half-track-width dimension of typical road vehicles. Clearly, the lateral translation measure is of importance insofar as it locates the lever arm about which the stabilizing "gravity moment" will act in resisting rollover. Indeed, the net issue involving the influence of sloshing forces on vehicle roll stability pertains to the overturning moment, M_0, shown in the figure, which is dependent upon both the magnitudes and lines of action of the lateral sloshing force and the resultant vertical load. Although the magnification of sloshing forces in the tanker case do not approach the times-seven level seen in Abrahamson's results for spacecraft, Strandberg has shown them to be nonetheless large, and of distinct concern relative to vehicle rollover.

With regard to sloshing forces developed due to braking with unbaffled tankers, Weir [19] has reported experiments in which the longitudinal surging of fluid in an underfilled tank truck produced fluctuations in longitudinal acceleration of as much as 0.1 g. Notwithstanding the disturbance which these fluctuations imposed upon the braking process, the authors observed that the most significant effect of the longitudinal slosh forces may relate to the structural integrity of the vessel itself, as well as its fastening to the truck chassis.

By way of his rather complete nonlinear time domain analysis, Su [13] evaluated the nature of longitudinal slosh motions and resulting forces. Shown in figure 10, for example, a tank filled to 50 percent of capacity is braked at 0.5 g's, resulting in a transient flow toward the front of the tank. Approximately one second following brake application, a longitudinal force equal to 1.06 times the weight of the fluid is exerted against the front bulkhead. For a set of such calculations, the results are as shown in table 3.

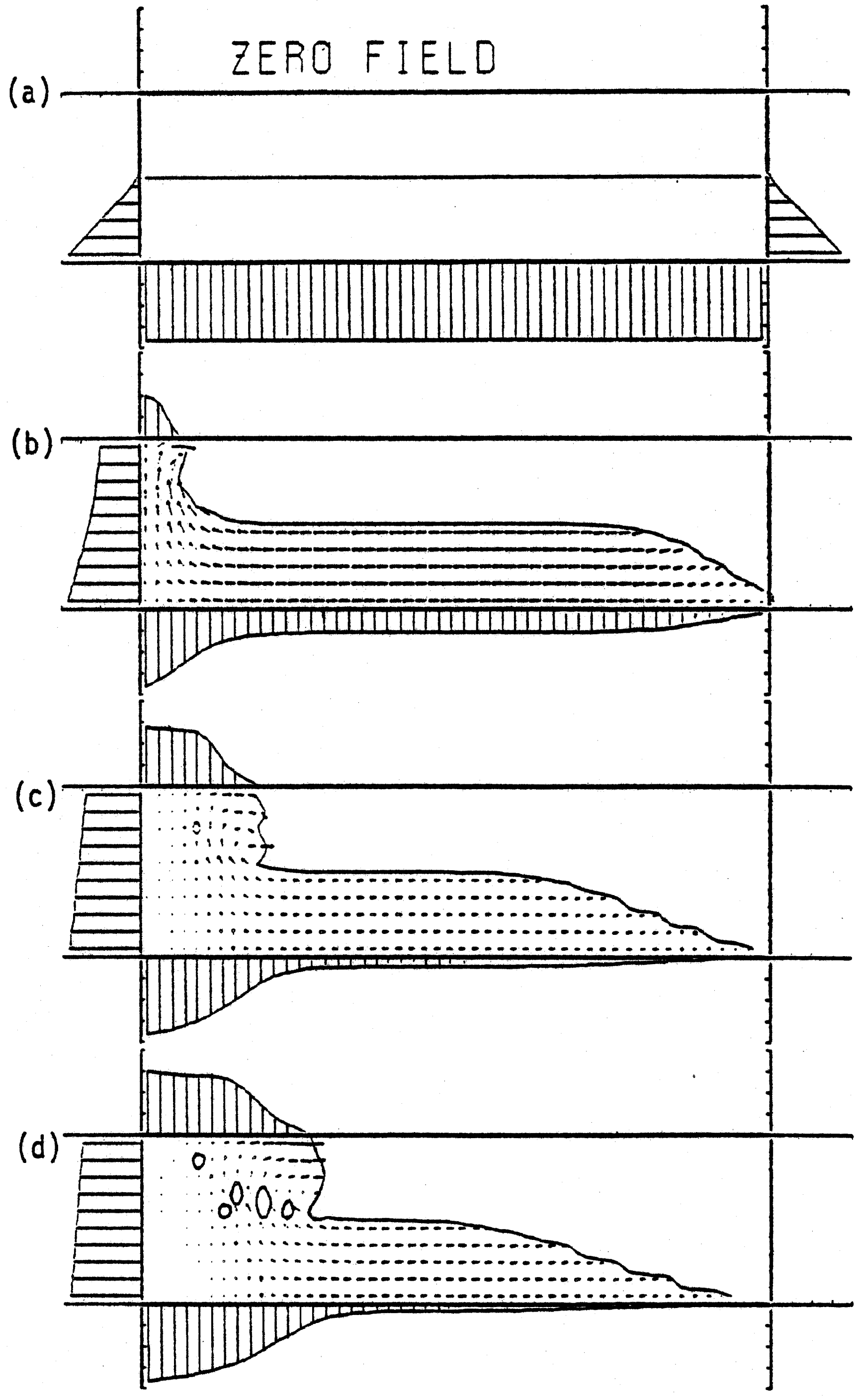


Figure 10. Longitudinal sloshing in an unbaffled tank - d=2 ft, a=16.1 ft/s^2
(a) t=0.0 sec (b) t=0.64 sec (c) t=0.96 sec
(d) t=1.12 sec [13]

Table 3. Ratio of longitudinal slosh force to total fluid weight, for selected values of tank fill level and braking acceleration.

Tank Fill Level, %	Braking Acceleration, g's	
	0.25	0.50
50	.25	1.06
75	.52	1.16

The results reveal why it is that truck drivers hauling underfilled liquid loads in unbaffled tanks apply the brake in a very tender fashion. That is, abrupt hard braking leads to quite severe jerking motions which can be sufficiently strong as to cause the driver to strike his head on the back of the cab, or at least to cause a significant whiplash motion of the head and neck.

Another subtle parameter which has a significant influence upon the magnitude of the longitudinal slosh forces produced during braking is the nominal pitch angle, or "tilt" of the tank centerline. A publication of the L'Air Liquide Corporation of France [20] cites that tankers have been built with the tank inclined downwards toward the rear in order to lower the height of the center of gravity. L'Air Liquide suggests, however, that longitudinal slosh during braking with an underfilled load will produce a net lower level of overall stability since the fluid will rush up against the front bulkhead in hard stops. Perhaps the more significant reason for avoiding such tank orientations, however, is established in calculations which Su [13] reported for a tank which was inclined downward at the rear by five degrees. Su determined that the longitudinal slosh forces were twice as high during braking in a 50-percent-full tank having a 5-degree rearward tilt than in a corresponding horizontal tank. Considering a particularly troublesome limit case, the tank with a downward tilt toward the rear will more easily encounter the very shallow fill depths needed for developing a hydraulic jump type of wave during braking. As was discussed in section 2.4.2.1, the hydraulic jump phenomenon would yield impulsive fluid contact with the front bulkhead such that structural damage becomes a serious concern.

2.4.2.5 Experimental methods for examining slosh. A number of investigators have conducted experiments using scale models of tanks to examine the mechanics of slosh responses (for example, Su [13], Strandberg [10], Dalzell [21], and Abramson [17]). In such experiments, it is necessary to scale the variables according to certain dimensionless quantities in order to achieve "dynamic similarity" between the experiment and the full-scale conditions of interest (assuming, of course, that the experiment is to entail a less-than-full scale model). It has been conventional practice that the analysis which is performed to determine the scaling relationships ignore the effects of tank deformations as well as the surface tension and compressibility of the liquid.

The scale similarity requirement has been satisfied by most researchers by simply establishing:

a) A length ratio which is constant, establishing the same scale between model and full scale, in all three dimensions. (An exception is made, however, when liquid motion is simply not to be excited along one dimension such that its scale is inconsequential. For example, Strandberg [10] induced only lateral excitations such that his model tanks could be constructed with a conveniently smaller scale along the longitudinal dimension.)

b) A model excitation frequency, $omega_M$, which is scaled according to the established length ratio, by the relationship,

$$omega_M/omega_F = (L_F/L_M)^{1/2}$$

where the subscripts M and F refer to the model and full-scale parameters, respectively.

c) a fluid kinematic viscosity in the model case which is ratioed to the full-scale kinematic viscosity according to the length scale by the relationship:

$$(Visc_M)/(Visc_F) = (L_M/L_F)^{3/2}$$

(In most common applications of road tankers, however, viscosity scaling is unnecessary because the viscous forces are very small relative to the inertial forces within the moving liquid [10]. It has also been noted that modeling of liquid natural gas or other specialized liquids may require viscosity scaling, although suitably low model viscosities may be difficult to obtain [13].)

Strandberg [10] has considered scaling for the conditions producing cavitation, or vaporization, of the fluid in the model experiment. Recognizing that the potential for cavitation relates to the nominal pressure in the ullage space above the liquid, relative to the vapor pressure of the fluid, he suggests that ullage pressure in the model case may be the convenient parameter to vary when experiments calling for cavitation scaling are of concern. For most fluids carried in road tankers, however, cavitation is seen as a rather improbable condition.

Given the scaling considerations above, the relationships between forces, F_M and F_F, and moments, M_M and M_F, applying, respectively, to the model and full-scale cases, are given by the following scaling identities:

Forces, $$\frac{F_M/L_M}{rho_M\ g\ l_M^2} = \frac{F_F/L_F}{rho_F\ g\ l_F^2}$$

Moments, $$\frac{M_M/L_M}{rho_M\ g\ l_M^3} = \frac{M_F/L_F}{rho_F\ g\ l_F^3}$$

where: L_M and L_F are the respective lengths of the model and full-scale tanks

rho_M and rho_F are the respective fluid densities

l_M and l_F are the respective tank widths

g is the acceleration due to gravity

Strandberg's [10] experimental apparatus is illustrated in figure 11. The figure shows that a hydraulic servo was employed to excite the scale model tank at the scaled frequency conditions of interest. The force and moment

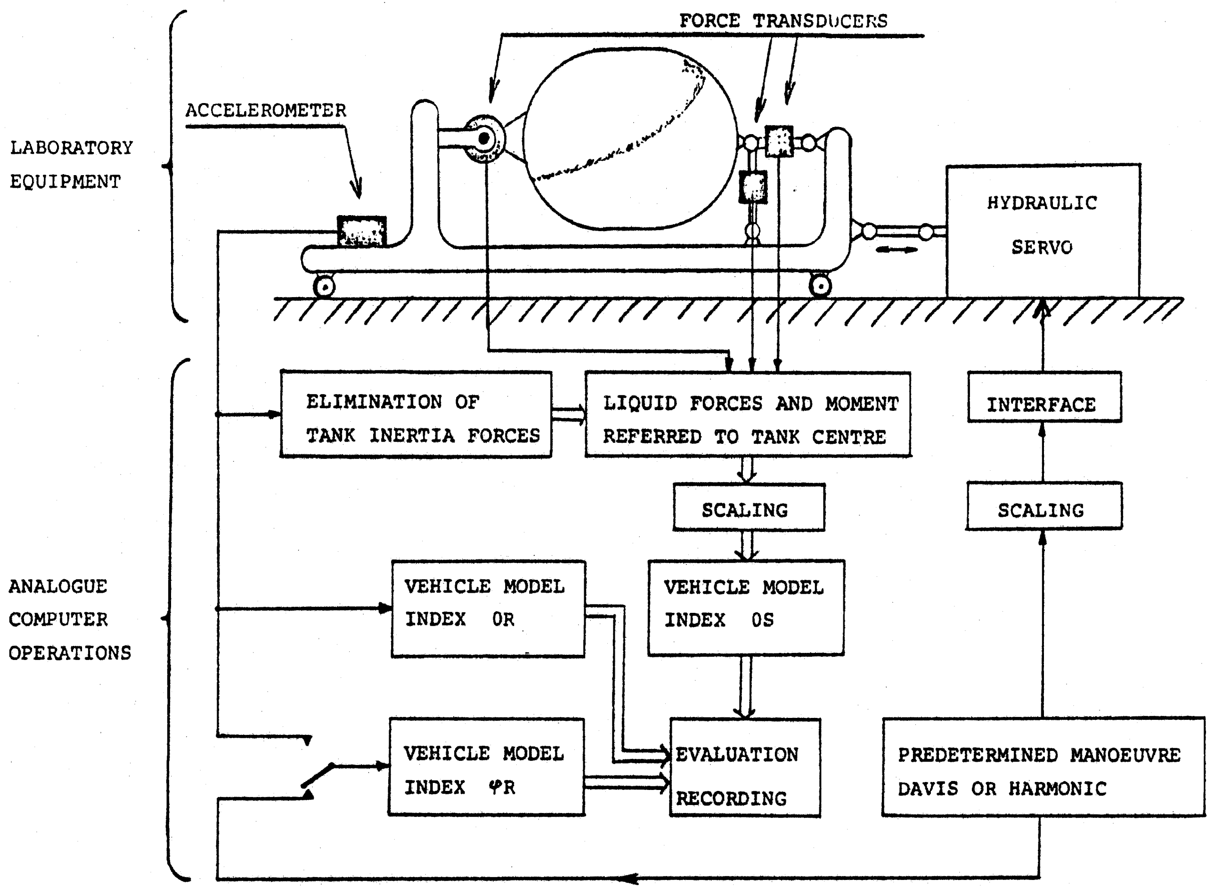


Figure 11. Experimental configuration and computing scheme used by Strandberg [10].

responses of the sloshing liquid were measured by strain gauge transducers and corrected for the inertial components due to the accelerations imposed on the mass of the model tank itself. The force and moment signals were then scaled according to the equations shown above and used as disturbance inputs to a vehicle model in order to study tanker roll response to sloshing. Such experimental approaches have provided the bulk of the substantive information available today which speak directly to the sloshing problem which threatens tanker roll stability.

Various parties have conducted full-scale vehicle tests in order to assess the importance of slosh motions to vehicle response [3,19,22]. Tank vehicles have been loaded to various levels, usually with water as the test fluid, and maneuvering experiments have been performed, affording both longitudinal and lateral input excitation. The test vehicles have been instrumented in varying degrees in order to measure the control input variables as well as the gross motion responses of the vehicle.

In general, these studies have produced mixed results in their ability to confirm the disturbances which arise due to fluid slosh in underfilled tanks. As a particular shortcoming, the full-scale tests have suffered from their inability to methodically examine the pertinent range of excitation frequencies such as has been accomplished in the laboratory. Further, full-scale tests have not provided clear evidence of the reductions in stability level which derive as a result of slosh, regardless of the precision of the frequency input. Given the limited state of productivity of full-scale tests to date, reductions in vehicle roll stability due to lateral slosh will be developed in the next section primarily with the aid of laboratory measurements which have provided careful characterization of the slosh load inputs for computerized vehicle models.

2.5 The Influence of Slosh on the Stability and Control of Tankers

It has been shown that slosh phenomena produce force and moment disturbances upon the containing vessel. When the vessel is mounted upon a motor truck or trailer, the disturbances can produce reductions in the stability and control characteristics which would derive relative to that obtained with a rigid load. The influence of slosh on vehicle dynamic behavior will be discussed in terms of the respective longitudinal and lateral modes of slosh motion.

2.5.1 Disturbance in Longitudinal Response Due to Slosh During Braking. The available literature indicates that the longitudinal slosh motions obtained during braking in unbaffled tankers produces only a minor degradation in longitudinal response of the vehicle. Weir [19] noted fluctuations in longitudinal acceleration of 0.1 g amplitude due to the sloshing of liquid in a tank truck following an abrupt brake application. Such measured disturbances were seen as having minor significance to vehicle control or to stopping capability and were suggested to be of more concern relative to the structural integrity of the tank than to the dynamic response of the vehicle. Similarly, Culley [3] measured the braking performance of three tractor-semitrailer tankers under various states of underfilling and found only modest and inconsistent variations in stopping capability as a function of fill level. Although Culley also examined braking in a turn with underfilled tankers, no notable degradation in performance was observed.

Although no research was uncovered to address more complex braking situations, there seems to be a conceptual basis for concern over the case of braking at low speed in a short-radius turn with an underfilled tractor-semitrailer tanker while the tractor is significantly articulated with respect to the trailer. Under such conditions, it can be hypothesized that rollover will be aggravated by:

a) the longitudinal slosh of the liquid such that the tank load is borne predominantly on the tractor suspensions which are less able to constrain the rolling motion of the trailer, and

b) the articulation response, since the tractor's fifth wheel coupling affords a declining roll moment reaction to the trailer as the articulation angle increases.

A likely scenario for such conditions might be the abrupt maneuvering of a tanker into a terminal area or other site where the close quarters demand large articulation angles and a somewhat hasty driving technique leads to abrupt braking.

2.5.2 Reductions in Roll Stability Due to Lateral Slosh. In preceding sections, the general nature of the lateral slosh phenomenon has been shown to involve lightly damped fluid motions which can produce both static and dynamic forces on the tank vessel, as well as translations of the fluid mass center away from its position in the quiescent state. Depending upon the complexity of the wave action, together with the dynamics of the vehicle maneuver which precipitated the fluid motions, the phase relationships between lateral force development and lateral translation of the fluid mass may also influence the tendency toward a rollover response. While no direct comment on the phase issue has been apparent in any of the cited publications, it would appear that the lateral force and lateral translation responses are rather nearly in phase with one another. The net effect of these two components of the lateral slosh response is to generate a rollover moment. In the case of, say, a steady-state turn, there is no issue of phase relationship and the roll moments can be simply determined by locating the displaced, or translated, mass center of the fluid load. In this section, the static and dynamic considerations of slosh as a mechanism aggravating roll stability will be discussed.

2.5.2.1 Static considerations. We can gain a qualitative view of the challenge which lateral slosh places upon rollover under static, or steady turn, conditions by reference to figure 12. The figure shows Su's computed results for the vertical and lateral pressure distribution upon the walls of a rectangular tank subjected to a steady lateral acceleration condition of 0.25 g's. A slight ripple is still evident at the fluid surface as a result of lingering transients following the onset of lateral acceleration. Integration of the roll moment about the center of the tank due to the distributed pressure condition would fully characterize the implications of the steady-state slosh response as a contribution to the rollover process. Of course, the pressure distribution in this static condition simply follows the Bernoulli relationship relating the lateral and vertical components of acceleration and the effective "depths" of fluid in both directions.

Strandberg [10] has incorporated analogous information deriving from his model experiments into an analysis of a tanker suspended upon representative tires and suspension springs, producing the overturning limits shown in the bar graph of figure 13. Note that the suspended vehicle experiences lateral motion of the fluid in the tank due to both the lateral acceleration

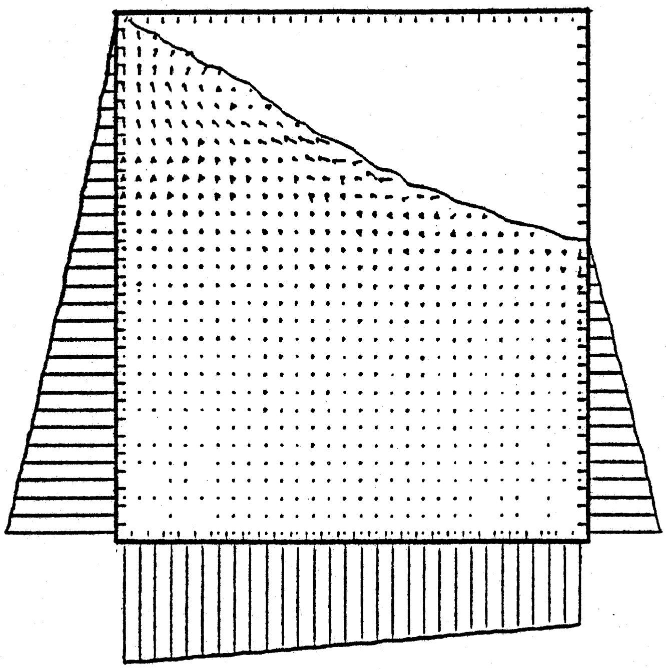


Figure 12. Flow field kinematics at t=3.15 seconds due to a constant transverse acceleration equal to g/4. [13]

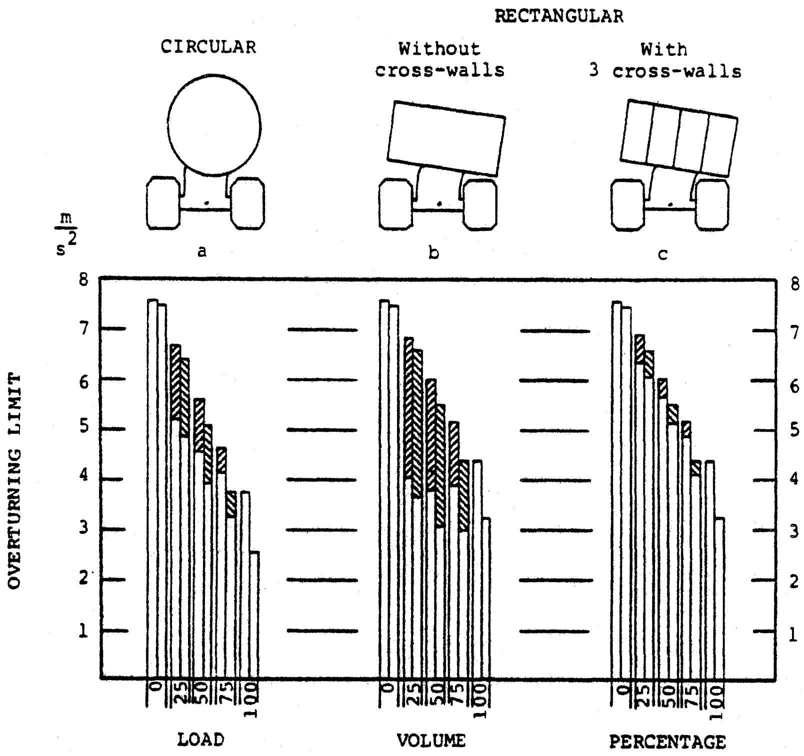


Figure 13. Overturning limits for steady state cornering. Vehicles with different tank cross sections and load volumes.

Right hand bars represent standard roll stiffness $k=0.6 \cdot 10^6$ Nm/rad and left hand bars high roll stiffness $k=1.2 \cdot 10^6$ Nm/rad for two axles.

Shaded, partly hidden, bars represent rigid load fixed to the tank and white bars unrestrained liquid.

Calculations by Lidstrom (1976).

Example: The rectangular tank (b) loaded to 50% volume with standard roll stiffness withstands 3.14 m/s^2. High roll stiffness increases the cornering performance to 3.8 m/s^2. Complete restraining to liquid motion gives 5.5 m/s^2 while 3 cross-walls (c) give 5.2 m/s^2 with standard roll stiffness. [10]

condition, in inertial coordinates, as well as the component of gravity which lies along the inclined lateral axis of the tank. Cases of cylindrical and rectangular tank shapes are shown. The height of the bars having cross-hatched sections shows the maximum lateral acceleration level tolerable without rollover when the load is represented to be rigid. The height of the white sections of those bars represents the steady rollover threshold obtained when the fluid at the indicated fill percentage is allowed to slosh. The slosh condition is seen to cause a maximum reduction of 23 percent in the steady-state rollover threshold of the cylindrical tank and 44 percent in the case of the rectangular tank. In general, however, the slosh deriving from a steady turn does not cause the rollover threshold of the underfilled vehicle to become lower than would occur on the same vehicle in its fully loaded condition.

Isermann [12] produced results showing the lateral and vertical translations of the mass center of the fluid during steady turning at differing levels of lateral acceleration. These results were shown earlier as figure 3. One convenient way to employ these results rather generally is to combine the indicated lateral and vertical translation dimensions with results, reported by Ervin [2], relating static mass center location to the steady rollover threshold. Evin's analyses showed that typical heavily loaded tractor-semitrailers suffered reductions in their static rollover threshold at a rate of approximately 0.0002 g's per mm of vertical translation of the mass center of the payload and at a rate of 0.0004 g's per mm of lateral translation off of the vehicle centerline. Taking Isermann's cylindrical tanker case, at a 43-percent-filled condition, the lateral and vertical translations for the condition approaching the rollover threshold indicate an approximate 0.10 g reduction in rollover threshold relative to the "rigid" case. This result is nominally the same as that reported by Strandberg (figure 13) in his most nearly equivalent condition, namely, the 50-percent-filled case. A similar exercise contrasting the Isermann payload translations for the "superelliptical" tank design, and their accompanying rollover threshold implications, with the threshold results reported by Strandberg for his rectangular tank show that the superelliptical tank shape is tending toward the limit rectangular case.

These results, in total, show that the influence of slosh on the static rollover threshold is very large and that the influence is easily summarized on the basis of the lateral and vertical translations of the fluid mass center, which derives from the sum of the slosh motions within the tank and the rolling action of the tank on its suspensions.

2.5.2.2 Dynamic considerations. The more profound influence of fluid slosh response on roll stability occurs under dynamic conditions in which the lightly damped lateral slosh mode is excited near its resonant frequency. In section 2.4.2.2, schemes for predicting the resonant frequencies of lateral slosh were presented. It was shown that for a broad range of tank fill conditions, the natural frequency of lateral slosh in a typical road tanker of cylindrical shape was between 0.5 and 0.8 Hz, with the lower frequency range applying to the less-full cases.

A significant question, then, in evaluating whether lateral slosh resonance is likely to be encountered, concerns the issue of the frequency content of driver steering inputs. Shown in figure 14 is a set of data illustrating the frequency spectra of steer inputs provided by passenger car drivers under conditions of differing sight distance [23]. Although corresponding data are not known to exist for truck drivers, these data indicate that some small portion of the steering activity of car drivers is in the frequency range at which slosh resonance would be excited. (It is this author's view, however, that steering inputs approaching 0.5 Hz are probably applied by truck drivers only when an unusual avoidance maneuver is called for. Thus, it is suggested that the steering spectrum which may actually apply to truck driver behavior probably lies somewhat to the left of those shown in figure 14.)

The connection between slosh resonance and the reduction in vehicle rollover limits is shown in Strandberg's results presented in figures 15 and 16. In figure 15, we see that vehicles outfitted with cylindrical, elliptical, and superelliptical tanks which are loaded to 50 percent of capacity yield minimum values of overturning limit at frequencies in the vicinity of 0.35 to 0.55 Hz. The "resonance curves," expressed in terms of overturning limit, are seen to be sufficiently broad that rather low values of this limit are achieved over a fairly significant range of frequencies. This

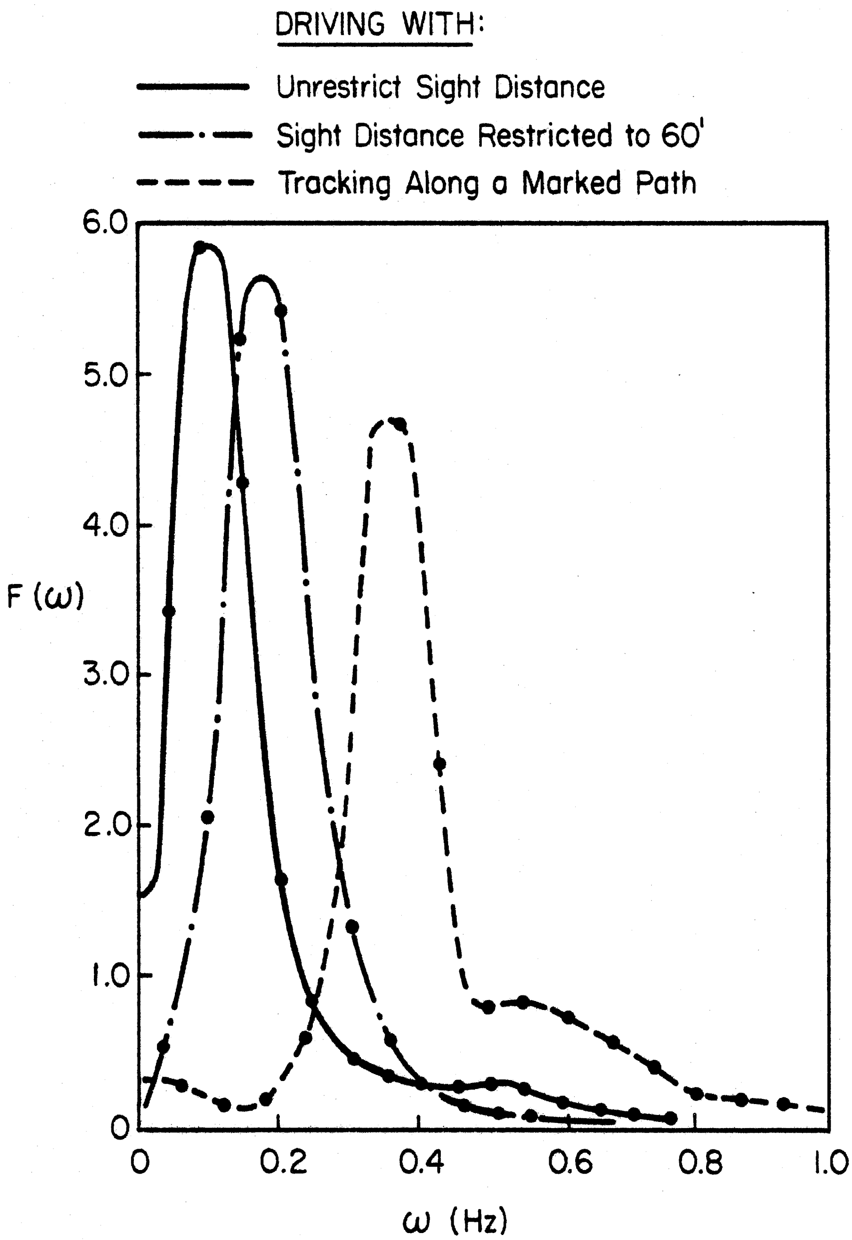


Figure 14. Typical normalized spectral density functions obtained from steering-wheel angle records. [23]

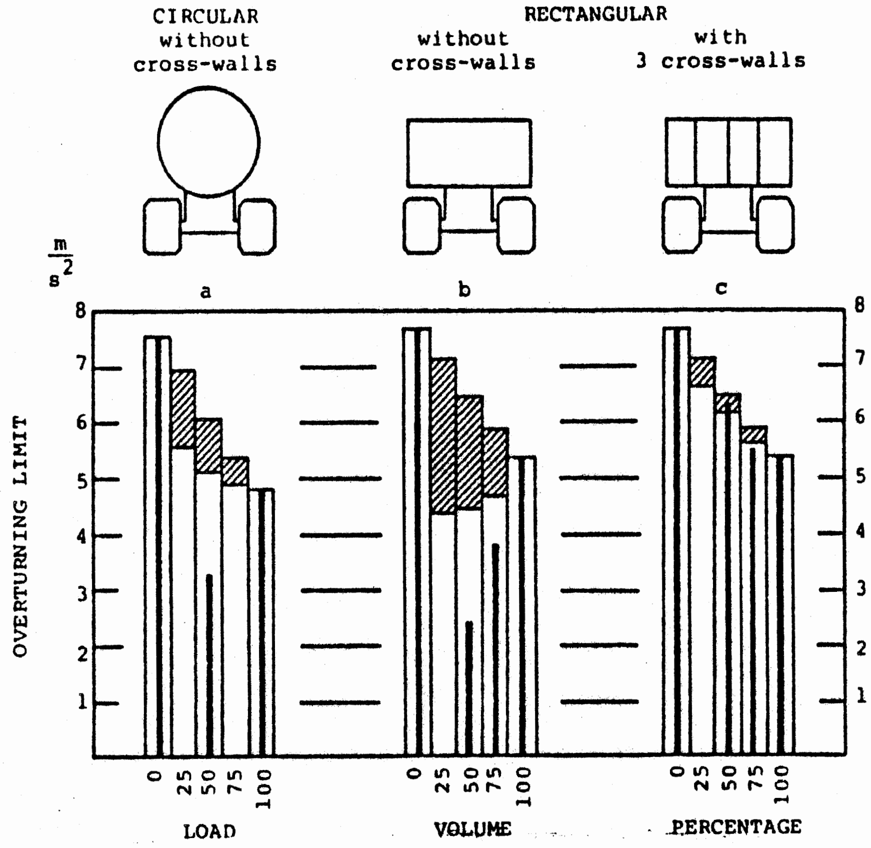


Figure 15. Overturning limits for steady state cornering. Vehicles with different tank cross sections and load volumes. Roll motion neglected.

Shaded, partly hidden bars represent rigid load fixed to the tank and white bars unrestrained liquid. Calculations by Lidstrom (1976).

Black narrow bars represent 0.5 Hz harmonic oscillation with circular tank from phase II (a) and with "elliptic" (not rectangular) tank from phase III (b and c). [10]

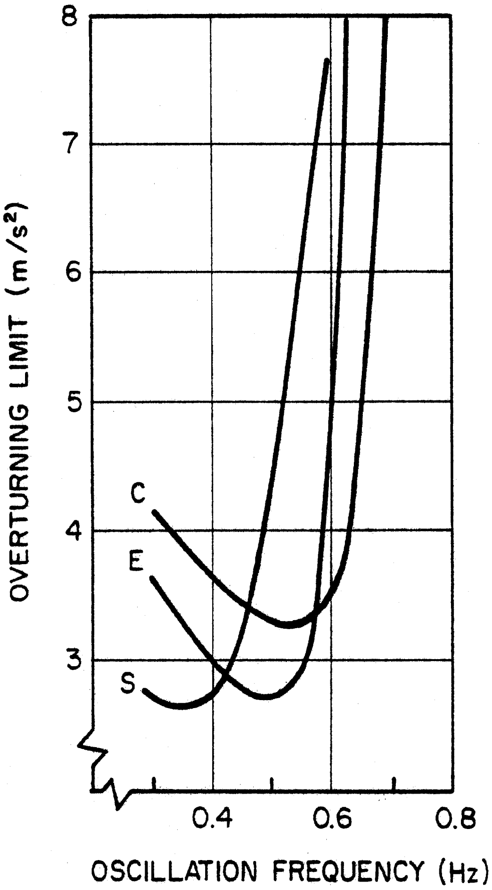


Figure 16. Approximate overturning limits (SA_{LIM}) as functions of the harmonic oscillation frequency for 50% load volume in different tank cross sections. The curves are approximated from a few data points and represent a schematic normalization method - Acceleration peak interval 1.92-2.20 m/s^2. [10]

observation is important in establishing that the detrimental aspects of fluid slosh do not depend upon a very finely tuned resonant condition, but rather can be excited from a more broad band of steer input frequencies.

In figure 16, the black narrow bars indicate the overturning limits achieved at the 0.5 Hz excitation frequency, while the white bars indicate the limits obtained in a steady turn, for various fill states. The data in this figure clearly indicate that the reductions in rollover threshold obtainable with a harmonically oscillated fluid load can be well below that obtained in the steady turn condition. Further, the 50-percent-full condition appears to reasonably approximate the worst-case slosh loading.

Generalizing further upon the "resonant" response issue, it should be noted that the underdamped character of the lateral slosh response suggests an overshoot to even a step function of lateral acceleration—that is, a sustained oscillation is not strictly required for development of a significant lateral slosh motion. Figure 17, for example, illustrates the concept of an overshooting slosh response to an abruptly developed lateral acceleration condition. The fluid is depicted to be sloshing in a transient manner, over time, such that peak displacement conditions accrue at points (d) and (h). When the peak displacements occur, the maximum roll moments will have been developed, perhaps producing rollover even though the nominal lateral acceleration level of the turn is below that needed for rollover at steady state.

The worst transient maneuvers which are likely to be occurring in actual service are thought to be those in which one or more full cycles of steer oscillation are applied in conducting, say, an obstacle-avoidance maneuver. An abrupt lane change, for example, will entail essentially one full cycle of steering whose waveform may reasonably approximate a sine wave. An "over and back" maneuver, in which the driver achieves a lateral position in the adjacent lane and then recovers his original lane position, will entail two full cycles of steering. When the nominal frequency of such steer inputs approach the resonant slosh frequency, slosh amplitudes approaching the steady-state harmonic excitation results such as reported by Strandberg [10] will develop. (As noted in the previous section, it appears that no full-scale tests of the proper design have been conducted to date to illustrate

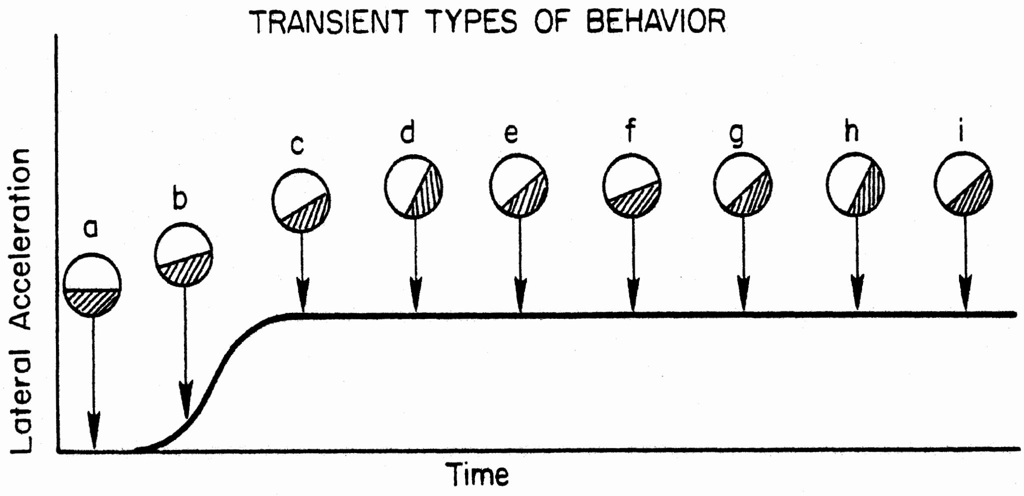


Figure 17. Motions of the surface of a slosh load in steady-state and transient maneuvers. [41]

that partially loaded tankers do, indeed, exhibit the stability reductions which have been predicted.)

Su conducted additional calculations to examine the influence of the height of the roll axis on the slosh response obtained in a suspended tank [13]. The results indicated that vehicles whose suspensions establish a roll axis closer to the undisturbed free surface of the liquid would suffer less in terms of lateral slosh responses. Clearly, the lower the roll axis, the greater is the lateral component of fluid accelerations deriving from rolling. A roll axis mounted at the height of the undisturbed free surface of the fluid merely permits vertical fluid motions at the surface, as a consequence of roll motion. The finding has some utility in considering the stability of real vehicles since it is known that the suspensions employed on typical heavy vehicles vary substantially in their roll axis locations [24].

Another issue of particular interest for tankers configured as full trailers, either in truck/full trailer or doubles combinations, involves the matter of the inherently oscillatory yaw responses of the full trailer which may resonant with the lateral mode of fluid slosh. In reference [32], for example, the full trailer of a Michigan-style double tanker was seen to exhibit an oscillatory mode of yaw/sideslip response at 0.6 to 0.8 Hz--a frequency range which encompasses the typical values of slosh natural frequency cited in section 2.4.2.1. Although more detailed analysis is required, there seems ample reason to hypothesize that underdamped trailer yaw oscillations could well interact with lateral slosh in a most undesirable manner. (The author's communications with a major oil company operating truck/full trailer tankers in the State of California reveals that a problem of this type has been observed in the field and the company has adopted a practice of avoiding any slosh loading of its full trailers.)

Gillespie [25] addressed the issue of the lateral slosh problem which remains in tankers having multiple compartments which are, themselves, loaded in an underfilled condition. Assuming the compartments have been emptied in a sequence which does provide a reasonable fore/aft load distribution, Gillespie considered the consequences of having an indicated percentage of the remaining load free to slosh. Figure 18 shows an estimate of the rollover threshold in a transient maneuver for an elliptical tanker as a function of the percent of

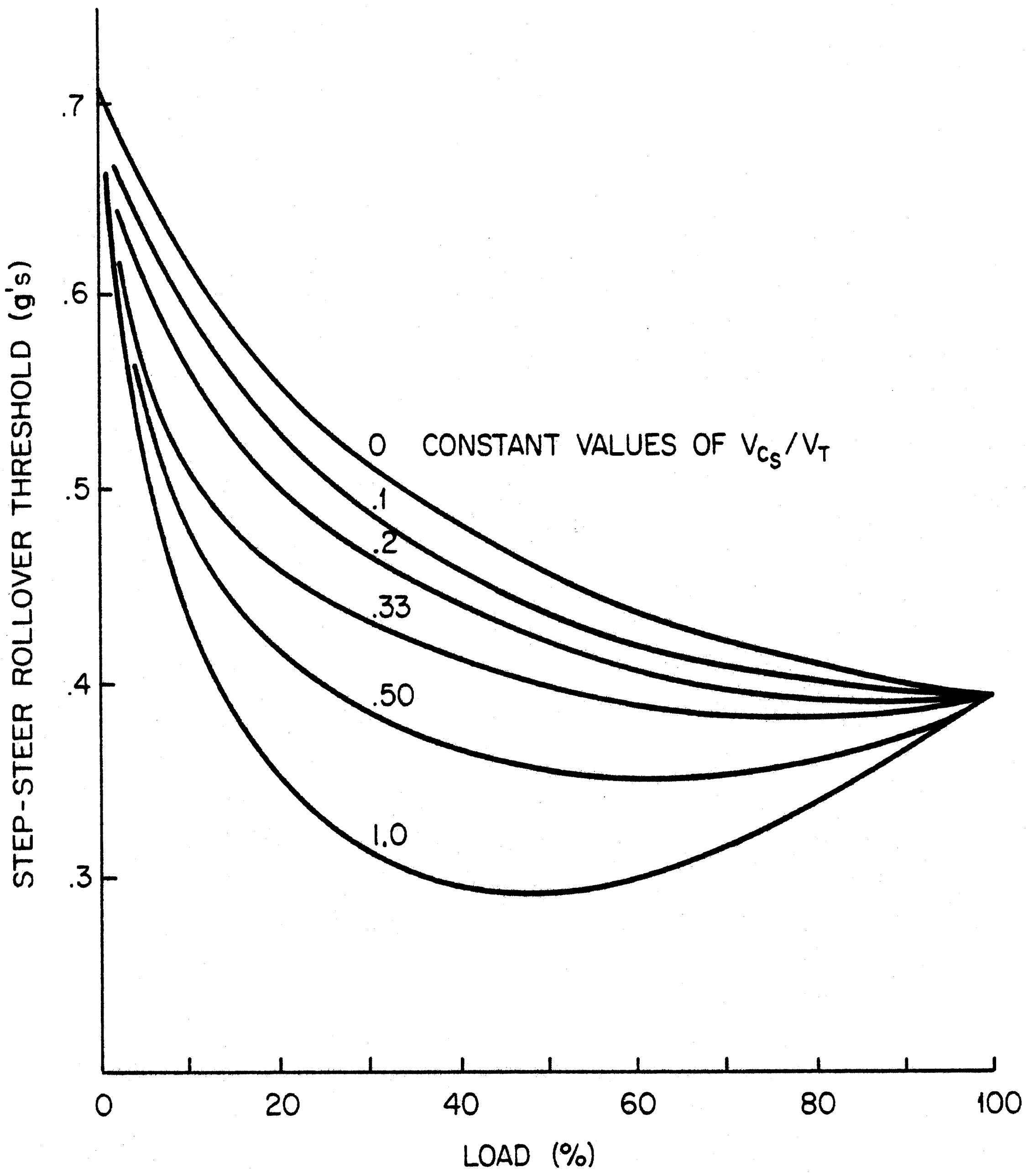


Figure 18. Rollover threshold as a function of load percentage and fractional slosh volume. [25]

full capacity load being carried. The figure shows the rollover threshold for constant lines of V_{cs}/V_T, which is the fraction of the total liquid which is in compartments that are loaded between 25 percent and 75 percent of their respective capacities. We see that the worst condition prevails when the vehicle is loaded to approximately 45 percent of its total capacity 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 percent full). The key observation which can be drawn from this analysis is that the rollover threshold in this dynamic maneuver will not be below that of the fully loaded unit as long as the portion of the fluid load which is free to slosh is no more than approximately 20 percent. Thus, if tankers having multiple compartments are used in such a way as to keep the underfilled compartment status within the bounds implied by the "20 percent of remaining load" criterion, dynamic slosh will not be peculiarly problematic.

2.6 Approaches Toward Mitigating the Effects of Slosh

Having seen that slosh force and moment disturbances are large and that wholesale reductions in tanker stability can result from both static and dynamic slosh phenomena, mitigation of slosh effects seems an important issue. The aerospace community saw the need for specialized features in spacecraft design to mitigate the effects of slosh within the tanks of liquid-fueled rockets. A NASA document from the late sixties entitled "Slosh Suppression" outlines a number of the techniques by which the slosh problem is alleviated in rocket design [7]. The general form of the suppression techniques identified for space applications can be divided into three categories which also usefully distinguish the approaches toward controlling slosh in road vehicles, namely,

a) reductions in the size of the "sloshing mass" relative to the total fluid mass

b) alteration in the slosh resonant frequencies such that tuning with the available excitation sources is less likely or pronounced

c) damping of the dynamic fluid motions such that peak slosh amplitudes are reduced

In typical road tankers, some degree of slosh suppression per category (a) is implemented in those types of vessels which are separated into multiple compartments. The effectiveness of conventional compartmentation or any other approach toward subdividing the load can be understood by reference to the prior discussion of the "sloshing" and "fixed" masses which are distinguished in the so-called "mechanical model" approach presented in section 2.4.2.1. Shown in figure 19 is a reproduction of the plot of mass ratios from the prior figure 6b. Although this illustration is derived for an upright cylindrical tank, the results are qualitatively applicable to other common tank shapes. We see that as the ratio, h/a, goes down, representing tanks or tank compartments which are broad relative to the fluid height, an increasing fraction of the total mass becomes "involved" in the slosh motions which are developed. For a typical road tanker having, say, cylindrical or elliptical tank shape and a 50-percent-full liquid load, the (h/a) value associated with lateral motions will be near 1.0 such that half or more of the liquid is involved in the "sloshing mass." For tank shapes having a wider and lower profile, lateral slosh will be of greater potential detriment because of the larger fluid mass involved in the slosh motions. For tanks which are compartmented along the longitudinal dimensions, the (a) parameter will define the compartment length (assuming no lateral baffles to impede the sloshing flow). Given the typical tanker dimensions presented in section 2.3, it is apparent that many tank semitrailers employ sufficiently long compartment lengths that partial loads in the vicinity of 50-percent-filled would easily involve more than half of the liquid as the "sloshing mass."

Clearly, the size of the sloshing mass is strongly influential in determining the magnitude of the slosh forces which are imposed upon the tank. In aerospace applications, the liquid fuel tanks are often subdivided by vertical walls which increase the (h/a) values such that the sloshing mass, and thus the slosh force disturbance, is reduced. Of additional importance to the transient conditions imposed on road tankers during braking is the influence of the compartment length dimension on the velocity of fluid impact against the front bulkhead of the tank. The greater the length dimension, the

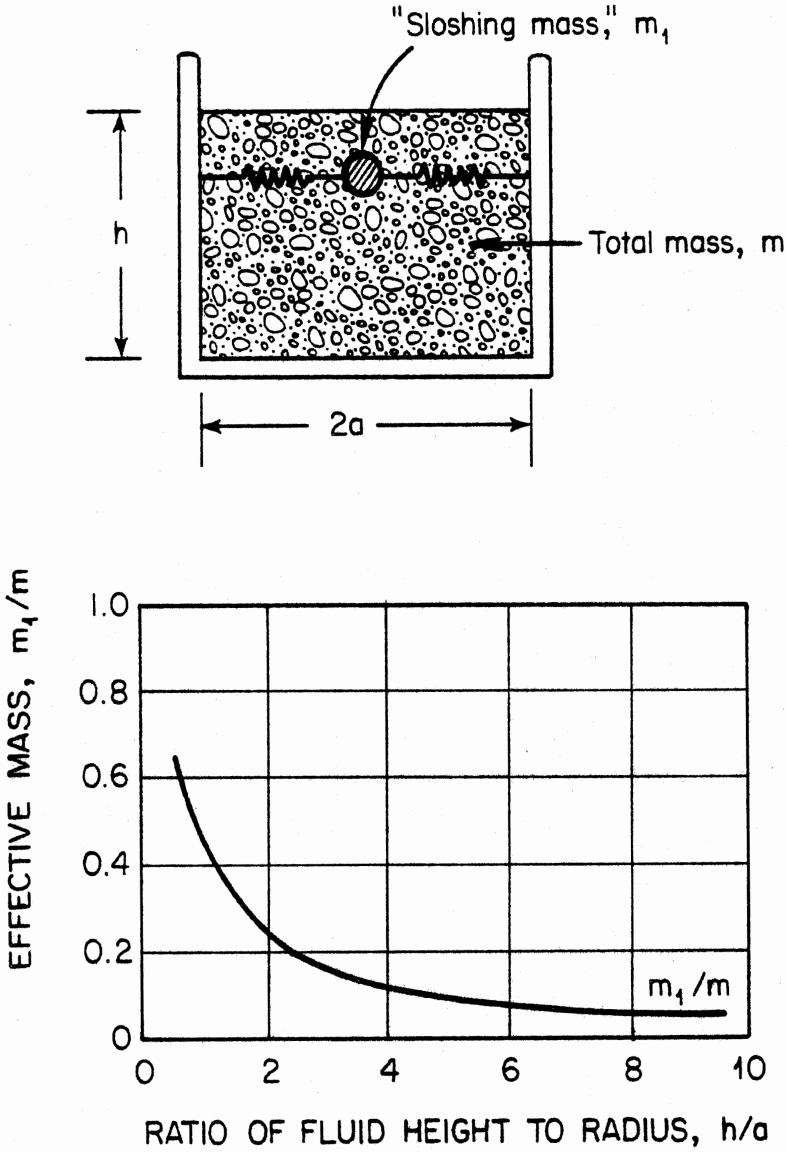


Figure 19. Influence of the height to radius ratio, h/a, on the ratio of "sloshing mass", m_1 to total mass, m. [16]

greater will be the velocity of the fluid relative to the front wall at the time of impact of, say, a hydraulic jump wave generated at a low fill level.

Of course, it is recognized that the primary contribution which compartmentation provides to slosh mitigation is simply the prospect that the delivery mission of the vehicle can be satisfied with all compartments either completely filled or completely emptied. Obviously, the premise behind the slosh mechanism is that the fluid must be contained in an underfilled state in order to exhibit slosh motions. One intermediate approach toward the achievement of an "always full" condition is found in the so-called "positive expulsion" devices employed in various aerospace applications. As shown in figure 20, various "accumulator"-type devices have been employed to assure that the bulk fluid is carried without sloshing and that it is dispensed through an outlet without injestion of vapor in the output flow. The devices have employed bellows, piston, and bladder types of expulsion mechanisms for displacing the liquid which has been discharged. No applications of this type are known to have been made in road tankers for controlling low viscosity liquids (although the author is aware of one trailer design in which a gas-driven piston of full-bore diameter was employed for discharging high viscosity lubricating grease from a bulk transport tank [26]).

Directly linked to the reduction of the ratio of the sloshing and fixed masses is the natural frequency of the slosh motion. Figure 21 has been derived from the earlier figure 6b, showing the influence of the (h/a) ratio on the normalized sloshing frequency. Figure 21 shows that lower values of slosh natural frequency derive when the fluid height approximates, and falls below, the radius of the containing vessel (which is, of course, a common case for road tankers). Clearly, with road tankers, lower slosh frequencies raise the potential for excitation of a lateral slosh resonance since, as follows from the discussion in section 2.5, reduced values of slosh natural frequency will more closely approach the common steer input frequencies which drivers employ. Conversely, the further subdividing of the vessel in any road tanker into smaller compartments has the doubly effective result of reducing the portion of the mass which is sloshing and increasing the slosh resonant frequency toward the higher range of values in which excitation is less probable.

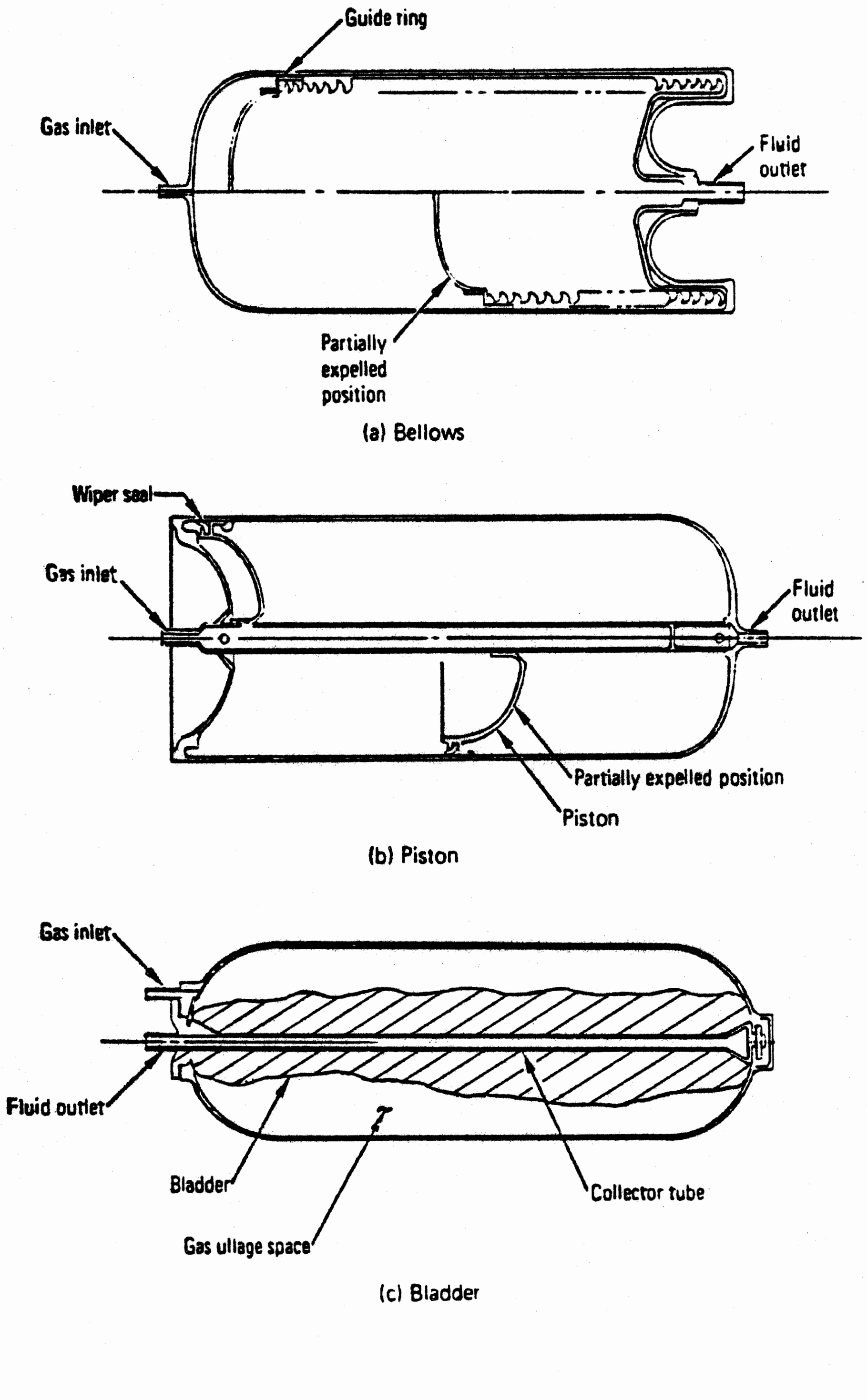


Figure 20. Types of positive displacement devices. [7]

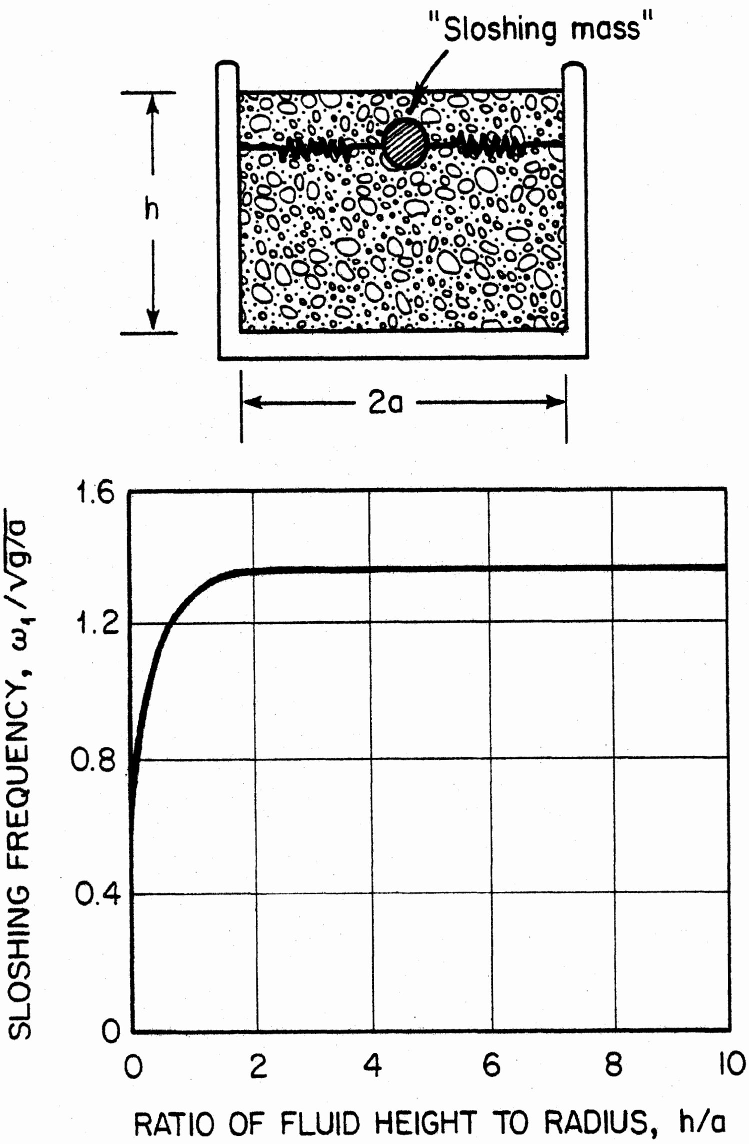


Figure 21. Influence of h/a on fundamental slosh frequency. [16]

The third general category of slosh suppression techniques involves the introduction of flow impediments which absorb slosh energy through viscous shear. Among such countermeasures are baffles which create shear as the fluid flows past a sharp edge or along a boundary wall. For baffles to be effective, they must be placed within the container at a position which results in relatively high velocity flow past the baffle. In spacecraft design for missions in which the engine would be shut off and restarted at selected points in the flight, for example, ring-type baffles are placed along the length of liquid fuel tanks such that the fluid level prevailing at each engine shutdown lies just above a baffle [7]. Thus, the sloshing portion of the fluid mass becomes immediately involved in the damping action of the nearby baffle at those occasions in the mission for which a large disturbance is expected due to shutdown and restart of the engines.

The damping action of a given baffle can be increased to some degree by means of perforation of the baffle plate. Abramson points out, however, that one must be cautious to note that excessive perforation of walls which otherwise subdivide the liquid load into compartment-like volumes will improve the damping level at the expense of lowering the resonant frequency [27]. For tanks which are peculiarly subject to adverse harmonic input or broadband random excitations, the concern over slosh resonance may outweigh the benefits associated with the nominal damping level, per se.

Flexible baffles have been employed in certain spacecraft applications and a potential level of effectiveness which is above that of rigid baffles has been reported [16]. It is noted, however, that tuning of flexible baffles is more critical since the superior level of performance is achieved only under a rather narrow range of fill conditions [28].

Although no literature was uncovered to speak to the concept of damping slosh motions by means of a metal mesh introduced within the tank volume, it is known that such developments have been applied for both slosh prevention and flame arresting in the wing tanks of fighter aircraft. The feasibility of such concepts for incorporation in road tankers appears to be questionable for many applications, however, because of the relatively high percentage of the fluid which adheres to the mesh following discharge of the product, as a result of capillarity and surface tension. Since many road tankers are employed in transporting differing liquids (such as the various grades of motor fuel, for example), the retention of substantial percentages of a given product poses the problem of contamination with the next load of a different product.

The classic principles of slosh mitigation, via reduction in sloshing mass, elevation of resonant frequency, and damping of fluid flow energy are illustrated in figure 22 from measurements obtained in Strandberg's model experiments [10]. The figure shows normalized side force levels (Strandberg's "side force coefficient") developed as the tank is excited harmonically at a peak lateral acceleration value of 0.2 g. The plotted measure shows the extent to which slosh dynamics have amplified or attenuated the side forces which must be generated by the tires in order to sustain this maneuver at 0.2 g peak lateral acceleration. (Also, it should be noted that the measure incorporates the vertical component of fluid force reaction on the tank which modifies the instantaneous vertical load that the vehicle is imposing upon its tires.)

The figure presents data for the case of an elliptical-section tank which is loaded to 50 percent capacity. The tank configurations include (A) a cleanbore vessel, (B) a vessel having lateral, horizontal baffle plates which extend equally from both sides, each of which covers 26 percent of the major axis of the ellipse, (C) a vessel which is bisected by a vertical compartment wall, and (D) a vessel having three vertical partitions which divide the major axis of the ellipse into four approximately equal lengths. We see that the cleanbore tank exhibits a times-two magnification of the side force levels over that of the rigid load, with resonance occurring at approximately 0.5 Hz. Case (C), which involves the simple division of the tank into two side-by-side compartments, exhibits almost identical behavior, except that the resonant frequency is increased substantially. In this case, the introduction of the vertical wall in the center of the tank has apparently increased the ability of the sloshing liquid to produce lateral reaction forces, thereby offsetting the expected benefit deriving from the reduced fraction of the liquid included as the "sloshing mass" (see figure 19). Case (D), with four separate compartments side by side, shows the wholesale reduction in slosh force response which occurs when the resonant frequency has been markedly increased, and the effective "sloshing mass" greatly reduced as a result of the large

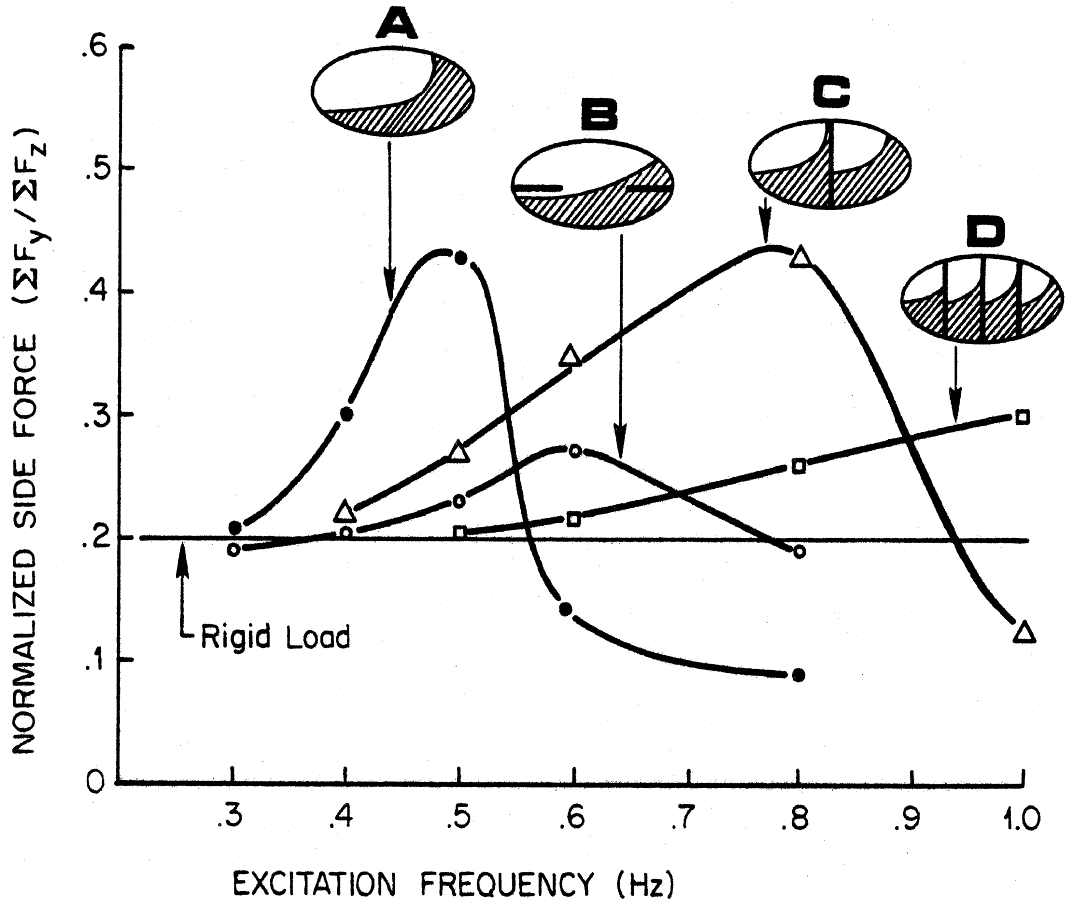


Figure 22. The influence of baffle and compartment concepts on the normalized side force levels of fluid sloshing in a 50%-filled elliptic tank. [10]

values of (h/a). The split horizontal baffle arrangement in case (B) is seen to provide for quite effective damping in this half-full condition, while also resulting in a modest increase in the resonant frequency, relative to the cleanbore case.

Strandberg presents other results from his experiments which establish that the above cases involving various baffle and partition installations show somewhat differing relative improvements over the cleanbore case when the fluid level and excitation amplitude are varied. For example, the split horizontal baffle arrangement, case (B), becomes less advantageous when the tank is loaded to the 75-percent-full level since the baffle becomes submerged to a depth at which the fluid is in a nearly quiescent state. Conversely, the bisecting partition arrangement, case (C), yields a greater advantage relative to the cleanbore case in the 75-percent-full condition--presumably because the small surface area per compartment renders a substantially reduced "sloshing mass."

In the nonlinear analyses conducted by Su [13], the complex interactions between sloshing fluid and partial baffle plates were examined in some detail. In the next series of figures, examples of these computed flow responses will be discussed, for uniform conditions of a 50-percent-full rectangular tank rolling harmonically about the center of the tank bottom. The half-amplitude of roll motion is 8 degrees and the excitation frequency is 84 percent of the linear natural slosh frequency for this mode of excitation. Shown in figure 23 is a set of "snapshots" of the flow field after approximately 2 cycles of excitation, showing the maximum amplitude displacement as well as intermediate portions of a cycle. Note in the illustration in the upper left of the figure, that the flow velocity vectors exhibit the greatest length (highest velocity) near the surface of the liquid, revealing that the "sloshing mass" is comprised primarly of the top 30 percent, or so, of the fluid volume. Clearly, baffles which are placed to disturb this portion of the flow field will be most effective.

Figure 24 shows the flow field, at the same three points in the excitation sequence, for the case of a vertical baffle which extends to just below the surface of the at-rest fluid. The illustration at upper left indicates that a rather concentrated layer of fluid flows over the top of the baffle at a relatively high velocity. The maximum redistribution of the fluid

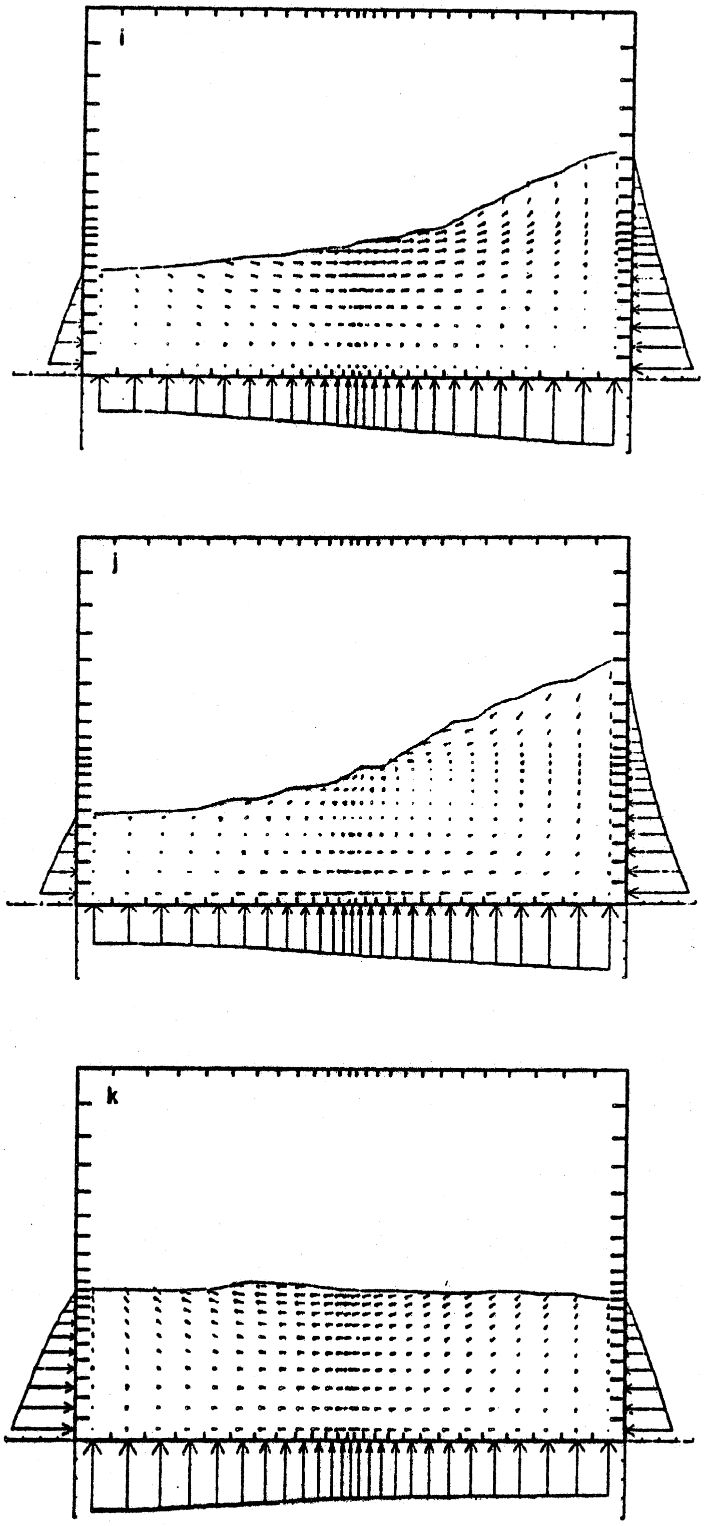


Figure 23. Flow field - no baffles. [13]

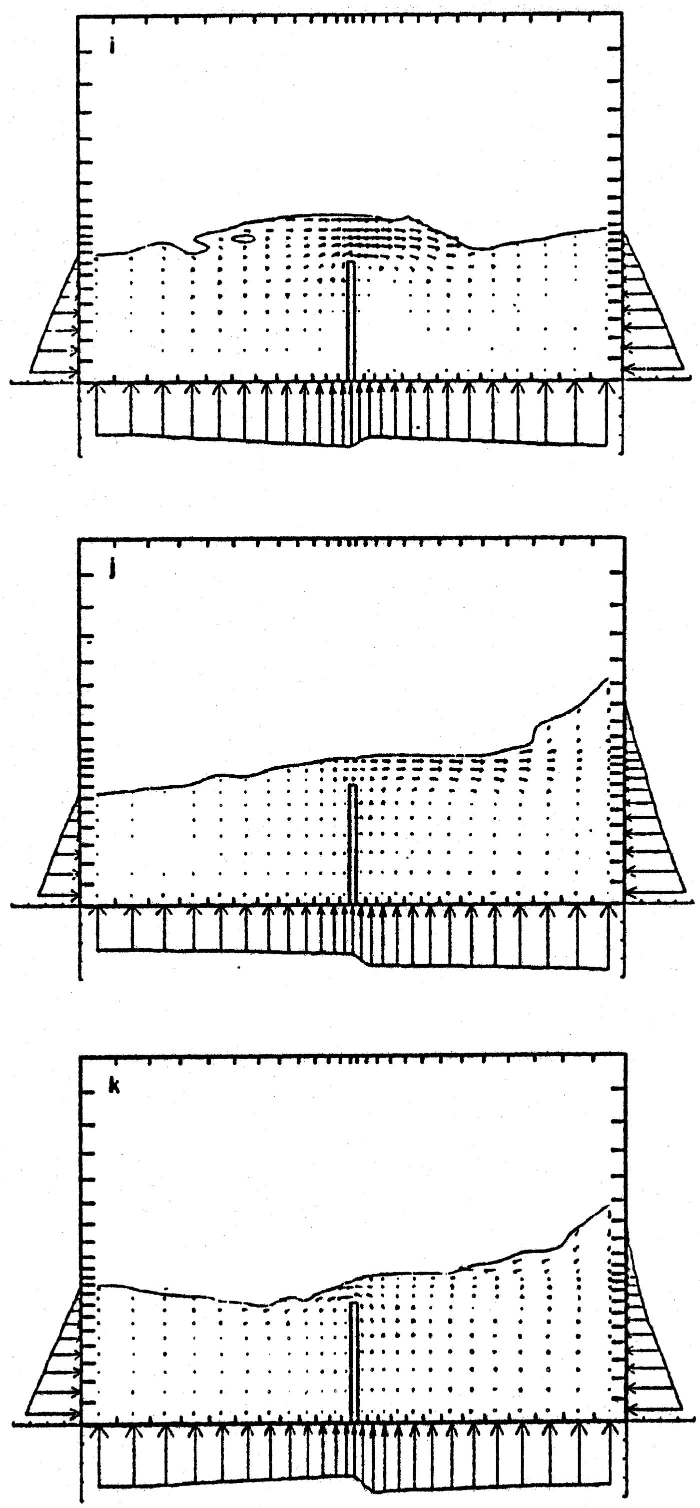


Figure 24. Flow field - vertical, partial baffle. [13]

mass at the peak of the slosh wave, in upper right, yields a much more balanced fluid load than in the unbaffled case. Note that in none of the three samples of the flow field are significant flow velocities observed below the top edge of the baffle plate, indicating that a large portion of the fluid volume is maintained in a virtually static state. Su also reported that the indicated responses in another case were virtually unaffected by a 100-fold increase in the fluid viscosity, notwithstanding the increased shear activity over the top of the baffle.

In figure 25, a horizontal baffle is represented, with its upper surface at the same elevation with respect to the surface of the at-rest fluid as considered with the preceding vertical baffle. We see that the flow over the horizontal baffle exhibits the so-called "shallow water" effects which are characterized by hydraulic jumps, wave overtopping, and air entrainment. These more violent types of wave action are effective for dissipating flow energy such that the overall redistributions of the fluid mass are reduced substantially relative to the unbaffled case. It is apparent, however, that substantial flow velocities are observed below the level of the baffle since the horizontal plate does serve to direct some of the flow into that area.

In figure 26, a T-shaped baffle is represented, serving to eliminate all flow below the horizontal element and concentrating all of the major slosh flow at shallow depths across the horizontal plate. Again, we see that a hydraulic jump is formed, at upper left, and the overall redistribution of the fluid mass due to slosh is minimized.

While it is apparent that the three simple baffle sections considered above are effective in mitigating the effects of slosh, it should be clear that the level of effectiveness of such partial baffles is heavily dependent upon the relationship between the tank fill level and the level of the upper extremity of the baffle. Further, since the fluid motions are complex, no simplified schemes for predicting the effectiveness of such baffle designs are available.

As a final example of Su's nonlinear analyses applied to longitudinal slosh in a tank having multiple, partial-height baffle plates, figure 27 shows the flow following a step input of longitudinal acceleration equal to 0.25

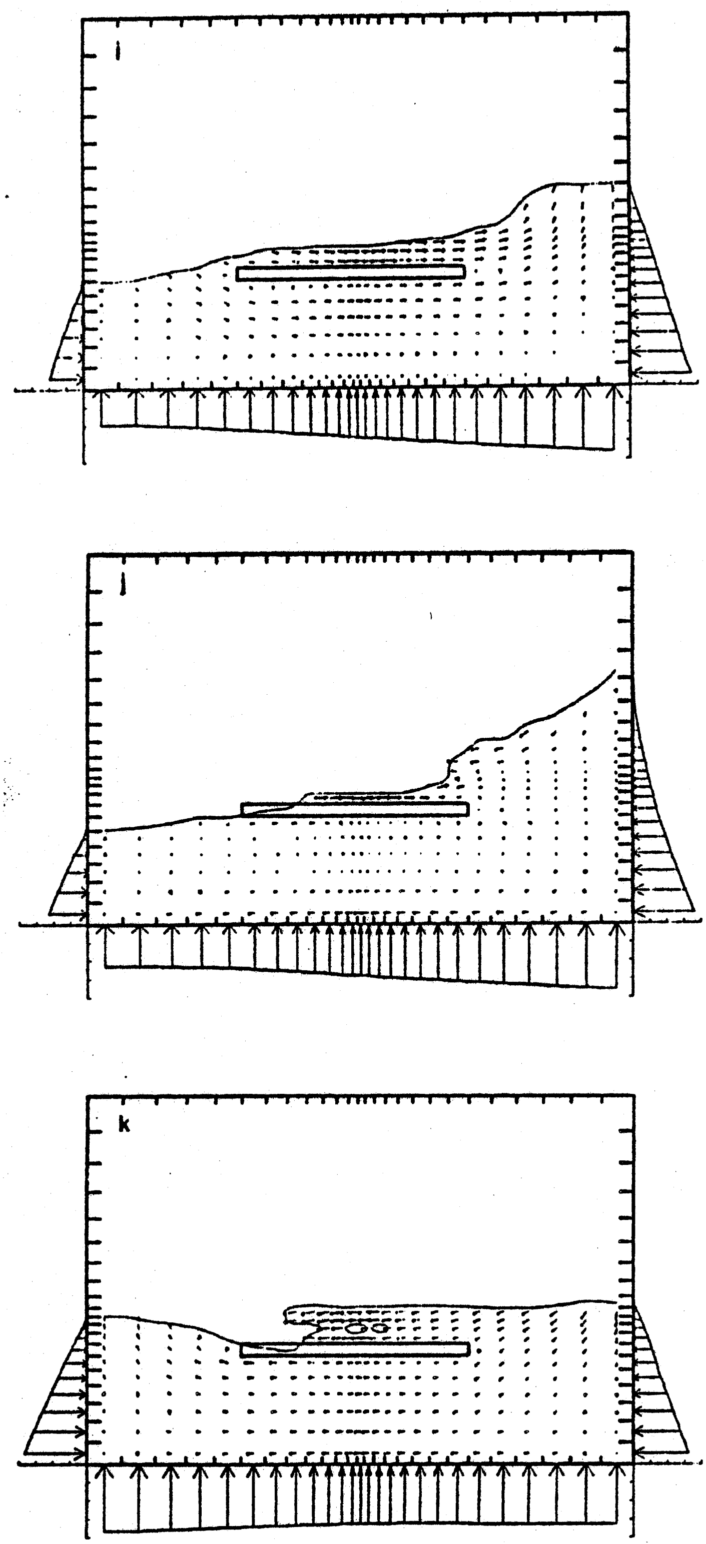


Figure 25. Flow field - partial horizontal baffle. [13]

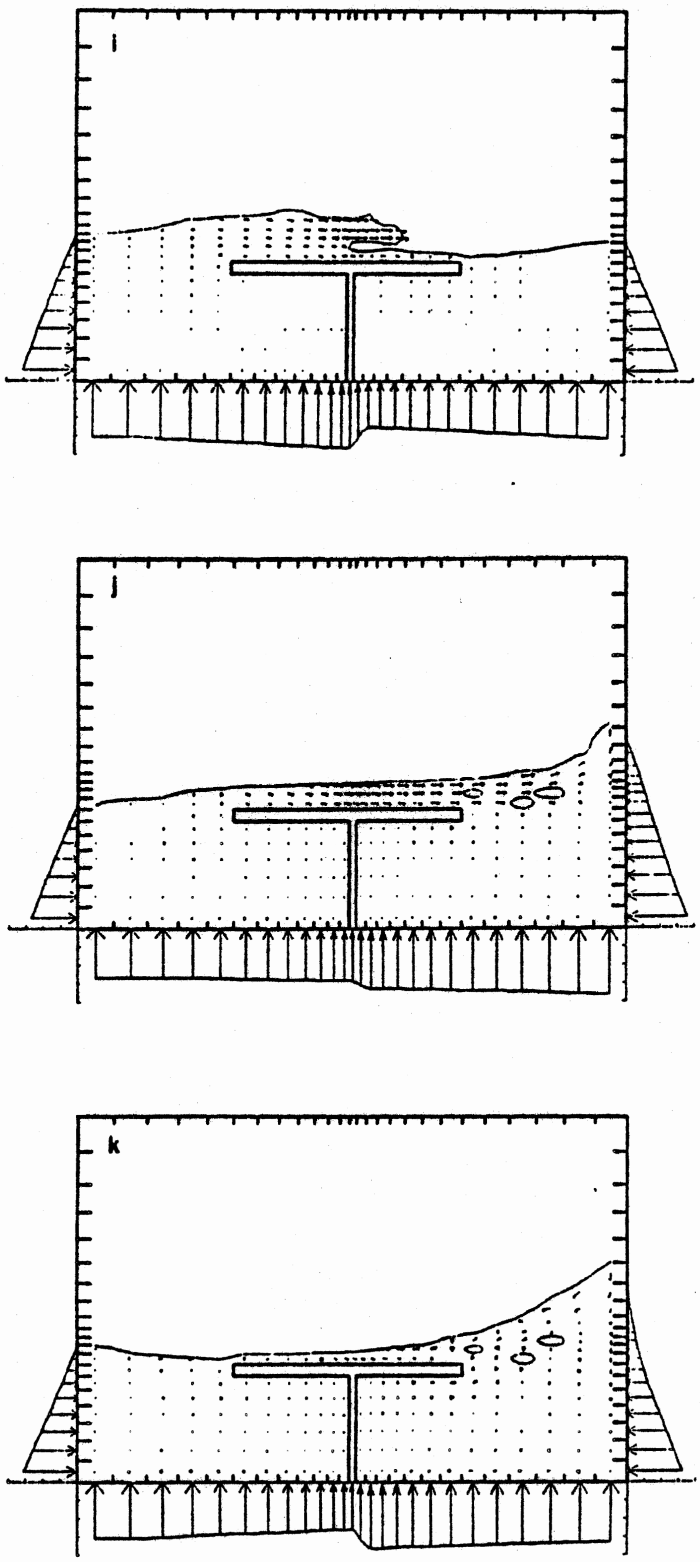


Figure 26. Flow field - tee baffle. [13]

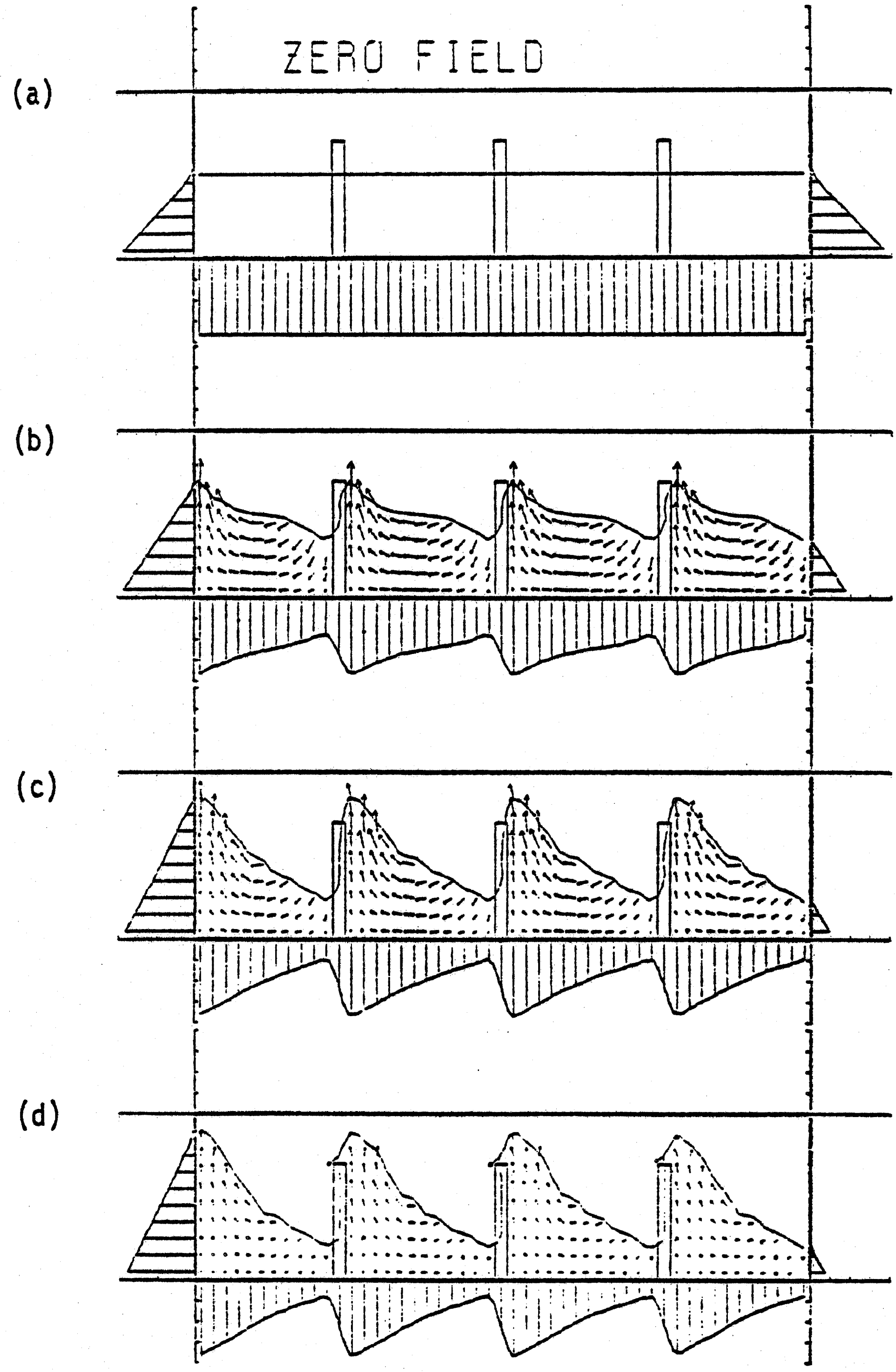


Figure 27. Longitudinal sloshing in a tank with V2 baffle - d=2 ft, a=8.05 ft/s^2
(a) t=0.0 sec (b) t=0.41 sec (c) t=0.71 sec
(d) t=0.80 sec [13]

g's. The multiple baffle elements serve to maintain a reasonable distribution of fluid load along the tank despite strong flow toward the top of the baffles.

3.0 REGULATIONS PERTAINING TO THE DESIGN AND OPERATION OF BULK LIQUID TANKS

Various regulations have been identified within the U.S. and other countries which speak either directly or indirectly to the issue of the design or operations of tankers for transporting liquids in bulk. These regulations have been reviewed with the intention of focusing upon the tank design features which might influence the occurrence or severity of liquid slosh conditions. Although existing regulations, in general, include only a few cases in which slosh-mitigating features are required, the discussion presented below addresses the sum of the known laws which speak even tangentially to tank configuration.

Regulations imposed by foreign countries were reviewed based upon responses to an inquiry letter which was sent to 83 foreign organizations and regulatory bodies. The inquiry letter asked for citations of all regulations or industry standards addressing the problem of sloshing of liquid load in tankers. The presented review of this material includes a summary of the responses received from each country.

3.1 U.S. Regulations

It is only for liquids defined as hazardous that the United States Department of Transportation imposes mandatory standards which affect the construction of tank trucks hauling these liquids. The relevant regulations are contained in the Code of Federal Regulations, Title 49--Transportation, Chapter 1--Research and Special Programs Administration, Subchapter C--Hazardous Materials Regulations, Part 178--Shipping Container Specifications, Subpart J--Specifications for Containers for Motor Vehicle Transportation.

Sections 178.341, 178.342, and 178.343 provide construction requirements regarding material thickness, closures for fill openings and manholes, vents, emergency flow control, and gauging devices for cargo tank specifications MC 306, MC 307, and MC 312, respectively.

MC 306 applies to cargo tanks designed to carry nonpressurized flammable liquids, such as gasoline and fuel oil.

MC 307 applies to cargo tanks designed to carry flammable liquids under low pressure, such as plastic resins and certain chemical solvents. Such tanks must have a design pressure of at least 25 psig and must be circular in shape.

MC 312 applies to cargo tanks designed to carry corrosive liquids, such as acids and caustics.

In addition, Section 178.340 provides some construction requirements which apply to all three cargo tank specifications. These cover quality of materials, structural integrity, joints, supports and anchoring, circumferential reinforcement, and accident damage protection. Section 178.340-7 on Circumferential Reinforcement contains the following provisions relevant to reducing liquid slosh in these cargo tanks.

(a) Tanks with shell thicknesses less than three eighths of an inch shall in addition to the tank heads be circumferentially reinforced with either bulkheads, baffles, or ring stiffeners. It is permissible to use any combination of the aforementioned reinforcements in a single cargo tank.

(1) Location. Such reinforcement shall be located in such a manner that the maximum unreinforced portion of the shell be ...in no case more than 60 inches.

(b) Baffles: Baffles or baffle attachment rings if used as reinforcement members shall be circumferentially welded to the tank shell. The welding must not be less than 50 percent of the total circumference of the vessel and maximum unwelded space on this joint shall not exceed 40 times the shell thickness.

Also, material thickness tables in Specifications MC 306, MC 307, and MC 312 permit thinner tank walls when the distance between bulkheads, baffles, or ring stiffeners is 36-54 in, and even thinner walls when the distance is under 36 in. While reducing liquid slosh is not mentioned as a purpose, these federal regulations provide encouragement for cargo tank manufacturers to install reinforcing internal bulkheads or baffles at least every 60 inches in a cargo tank, although external ring stiffeners are also a legitimate alternative.

Sections 178.337 and 178.338 provide construction specifications for two other types of cargo tanks. Specification MC 331 covers cargo tanks constructed of steel, primarily for transportation of compressed gases, such as chlorine, liquified petroleum gas (LPG), ammonia, carbon dioxide, etc. These tanks must be seamless or welded steel construction or combination of both and have a design pressure between 100 and 500 psig. They must be designed and constructed in accordance with and fulfill the requirements of the American Society of Mechanical Engineers Boiler and Pressure Vessel Code (ASME Code).

Specification MC 338 covers insulated cargo tanks intended for carrying cryogenic liquids at temperatures below -130F, such as liquified oxygen, hydrogen, argon, and helium. The design pressure of the tank must be at least 25 psig, but not more than 500 psig. These tanks also must be designed and constructed to meet the requirements of the ASME Code.

In addition, Section 178.342-1(b) requires that Specification MC 307 cargo tanks with a working pressure in excess of 50 psig must be designed in accordance with the requirements of the ASME Code. Similarly, Section 178.343-1(b) requires that cargo tanks built under Specification MC 312 that are unloaded by pressure in excess of 15 psig be designed and constructed in accordance with and fulfill all the requirements of the ASME Code.

The ASME Boiler and Pressure Vessel Code is an extensive and frequently amended document contained in 24 loose-leaf binders. Section VIII, Division 1, contains the Rules for Construction of Pressure Vessels. These are in three subsections: General Requirements, Requirements Pertaining to Methods of Fabrication, and Requirements Pertaining to Classes of Materials. Under General Reqluirements, UG-27 covers Thickness of Shells Under Internal Pressure. Provisions (c) and (d) provide formulas for determining minimum thicknesses for cylindrical and spherical shells, respectively, using inside radius, design pressure, maximum allowable stress value for material, and joint efficiency. Provision (e) states:

When necessary, vessels shall be provided with stiffeners or other means of support to prevent overstress or large distortions...

However, the only other provision possibly relevant to internal baffling is UG-47 covering Braced and Stayed Surfaces. It provides a formula for the minimum thickness of braced and stayed flat plates which takes into account design pressure, maximum allowable stress for the material, and maximum pitch which seems to mean the maximum distance between stays. The shorter the pitch, the smaller the permitted thickness.

Thus, the ASME Code does not specify any minimum placement for reinforcing bulkheads or baffles in these pressurized tanks, but it does seem to encourage such placement. On the other hand, one provision of Specification MC 338 seems to discourage the placement of internal baffles in insulated cargo tanks. Section 178.338-1(c)(3) states:

Design and construction details of the tank interior may not allow collection and retention of cleaning materials or contaminants. To preclude the entrapment of foreign material, the design and construction of the tank must allow washing of all interior surfaces by the normal surging of the lading during transportation.

There are apparently no federal or industry standards for the structural characteristics of milk tankers. However, the United States Food and Drug Administration model Grade A Pasteurized Milk Ordinance contains the following relevant provision.

ITEM 11p. CONSTRUCTION AND REPAIR OF CONTAINERS AND EQUIPMENT. All multiuse containers and equipment with which milk or milk products come into contact shall be of smooth, impervious, corrosion-resistant, nontoxic material; shall be constructed for ease of cleaning; and shall be kept in good repair.

The Michigan Department of Agriculture Regulation No. 407 on Milk Manufacture supplements the above federal standards with the following relevant provisions:

R 285.407.3 Cleaning and sanitizing pickup trucks and milk transport tanks. Rule 3 (1) The owner or lessee of a pickup tank or over-the-road milk transport tank, or the agent of such owner or lessee, shall be responsible for maintaining tank and milk contact surfaces clean and in good repair. Milk and milk products shall not be placed in such tanks unless the tanks have been properly cleaned and sanitized.

(2) Suitable facilities for cleaning and sanitizing pickup tanks and over-the-road transport tanks shall be provided, and the washing and sanitizing of the tanks shall be carried out by the receiving milk plant, transfer station, or receiving station, unless other mutual agreements, approved by the department, are made to have the tanks washed and sanitized. The owner, lessee, or the agent of the owner or lessee shall be responsible for cleaning the hose, pump, and valves. After the cleaning and sanitizing operation is completed, a suitable record shall be made showing who did the work, the date, and the location of the operation. The owner, lessee, or the agent of the owner or lessee, after inspection of the tank, shall indicate on the record that the tank has been cleaned to that person's satisfaction. A copy of this record shall be kept with the vehicle until it is washed and sanitized again.

(6) A pickup tank or an over-the-road milk transport tank may be used to haul potable water, or other wholesome liquid food products, if the milk contact surfaces are properly cleaned and sanitized prior to picking up the milk.

Milk tank manufacturers have used the requirements for frequent and easy cleaning-in-place as a reason for not compartmentalizing or baffling milk tankers.

In transporting water, most fire-fighting equipment conforms to Section 1901 of the National Fire Protection Association's National Fire Codes (Vol. 12). Under Tank Construction, this includes the following provisions:

6-1.1.3 The water tank shall be provided with at least one swash partition. Any water tank shall have a sufficient number of swash partitions so that the maximum dimensions of any spaces in the tank, either transverse or longitudinal, shall not exceed 46 in. and shall not be less than 23 in.

6-1.1.4 When an elliptical tank is furnished, swash partitions may be waived if so specified by the purchaser in Special Provisions.

6-1.1.5 Swash partitions shall have suitable vents or openings at both top and bottom to permit movement of air and water between spaces as required to meet the flow requirements as specified in 6-1.2.3 of this Standard.

The NFPA requirement for "swash partitions" at least every 46 inches along the transverse and longitudinal dimensions of the tank constitutes the most demanding anti-slosh provision found in any government or industry code.

3.2 Foreign Regulations

In order to ascertain if any regulations or standards are currently in force which address the problem of liquid-load shifting, 83 letters requesting the identification of such regulations or standards were sent to some 31 countries. The agencies within the countries contacted were typically the ministry of transport, road and safety research facilities, standards associations, and national petroleum and energy institutes.

A total of 31 responses were received. Of these responses, agencies in Japan, Canada, Great Britain, Israel, Germany, New Zealand, and South Africa all state that there are no regulations which specifically deal with alleviating liquid-load shifting, or tanker-loading requirements.

Most responding agencies cited their standard or regulation which they felt most closely addressed liquid-load shifting problems. The following represent any quoted portions from each agency's response and the identity of the cited regulation or standard.

AUSTRALIA

Australian Road Research Board - The Research Board referred to Australian Standard 2016-1977 "Road Tank Vehicles for Flammable Liquids" which will be discussed below. It was noted that these standards do not have any legal standing unless or until adopted in State legislation and thus are not mandatory.

Standards Association of Australia - The Standards Association referred to the Draft Standard Number 84083 issued in April 1984. Part 4, Tankers for Toxic and Corrosive Cargoes, was cited as containing a small section on rollover protection, Clause 3.3.10. The draft itself was not forwarded and it was stressed that the provisions in this regard were only tentatively proposed.

Australian Institute of Petroleum Ltd. - As did the Australian Road Research Board, the Institute of Petroleum referred to Australian Standard Number 2016. The AIP response further points out that Phase III of the Australian Road Research Board study entitled "Lateral Dynamic Performance of Articulated Vehicles" will address liquid movement problems late this year. The Institute also noted that they are anxious to hear of further information on the sloshing effects of liquids in vehicles, particularly in relation to LPG tankers.

Australian Department of Transport - The Department of Transport coordinated a mailing to the States and Territories in Australia to determine which regulations and standards they adhere to. As explained by the Transport Department, the States and Territories have their own regulations and have the responsibility for administering them. However, the "Australian Code for the Transport of Dangerous Goods by Road and Rail" has been published as a basis for the States and Territories to establish uniform national legislation for the safe transport of dangerous goods. This Code has been adopted by several Australian States and Australian Capital Territories, with remaining States and the Northern Territory expected to implement the Code by early 1985.

Also included in the response from the Transport Department was an updated copy of the Australian Standard 2016-1982 "Road Tank Vehicles for

Flammable Liquids." Selected sections concerning tank construction are outlined below.

Section 2 - 2.1.2 Stability. "The height of the centroid of the tank cross-section at tank half-length shall fall within an isosceles triangle having a base length at ground level equal to the overall width between the outside walls of the outside tyres of the major load axle or axles, and base angles not exceeding 62 degrees for a semitrailer tank or 64 degrees for a rigid tank. Where the cross-section of the tank varies along the tank length, the height requirement shall apply to the centroid of the mean cross-section over the length of the tank." (For a semitrailer tanker having a 96-inch width dimension across the tires, this requirement provides that the tank center be no more than 90.3 inches high—an elevation which is approximately 6 inches above that of the typical gasoline tankers in the U.S. and approximately 8 inches below that of, say, an LPG tanker.)

Section 3 - 3.2.2 Tank Shape. "A large compartment tank shall be circular in cross-section. A small compartment tank may be any shape."

Section 3 - 3.2.3 Stiffening of Heads, Bulkheads, and Baffles. "Unless a proven equivalent form of stiffening is provided, the following requirements shall apply:

(a) Heads and bulkheads for large-compartment tanks shall be dished to a depth, exclusive of the flange, of not less than 250 mm, with a knuckle radius of not less than 50 mm.

(b) Heads and bulkheads for small-compartment tanks shall be dished to a depth, exclusive of the flange, of not less than 80 mm per meter of depth of the minor axis of the tank cross-section, but in any case not less than 100 mm."

Section 3 - 3.2.4 Circumferential Reinforcement. "The tank shall be reinforced circumferentially by stiffeners, bulkheads, or baffles (or in any combination) in accordance with the following requirements:

(a) Reinforcements shall be located so that the maximum unreinforced length shall not exceed that specified for the particular shell thickness...,"

(b) The reinforcements shall be located within 25 mm of points where the longitudinal alignment of shell sheets changes direction by more than 10 degrees, unless otherwise reinforced sufficiently to keep stresses within the specified limits."

What follows is a brief summary of the information received by the Transport Department from various agencies throughout the country.

Department of Transport and Works, Northern Territory of Australia - This agency stated that they were adopting the National Code which in turn refers to Australian Standards 2016 "Road Tank Vehicles for Flammable Liquids" and 2090 "Uninsulated Road Tank Vehicles for Compressed Liquified Gases."

Transport Department, Tasmania - The only relevant national standard this agency was aware of was the Australian Standard 2016.

Main Roads Department, Queensland - The Main Roads Department reported that their discussions with the Queensland Transport Department indicate that the Australian Code for the Transport of Dangerous Goods by Road and Rail will be enforced in the future and particularly mentions Code Standards AS2016 and AS2090. The Main Roads Department also refers to the Inspection of Machinery of the Machinery Inspection and Safety Regulations. Regulation 25 entitled Motor Vehicle Containers for Transport of Flammable Liquids section 4, part (3) states:

"A tank compartment exceeding ninety inches (90") in length shall be baffled or otherwise reinforced and the maximum distance between any such reinforcement or between any such reinforcement and the end of a tank compartment shall not exceed sixty inches (60")."

Division of Road Safety and Motor Transport, Kilkenny - As did several other agencies, the Division of Road Safety referred to the Australian Standards and the Australian Code for the Transport of Dangerous Goods by Road and Rail. Also included in their response is the mention of The Boiler and Pressure Vessels Act, specifically AS 1210-1982 "Pressure Vessels Code." However, selected portions or the actual document were not forwarded.

Dangerous Goods Branch, New South Wales - The Agency reports that the Australian Code for the Transport of Dangerous Goods, 1975, applies in New South Wales. Also noted is the Australian Code for the Transport of Dangerous Goods by Road and Rail, and section AS 2016.

No special requirements exist, however, for other liquid cargo such as milk. The Dangerous Goods Branch included in their response a copy of the Draft Australian Standard for Comment No. 84080 April 1984, which revises the Standard entitled Road Tank Vehicles for Dangerous Goods 1982, Part 1-General Requirements sections 2016 and 2090. The revisions primarily address vehicle stability, in terms of the "angle of stability," 62 versus 64 degrees, which will apply in differing kinds of service.

Department of Territories and Local Government, Canberra - As did the Dangerous Goods Branch, the Department of Territories and Local Government reports that the Australian Capital Territory prescribes to the Dangerous Goods Ordinance 1984. Also noted is that, subject to certain modifications as set out in Schedule 2 of the Ordinance, the Dangerous Goods Regulation 1978 of New South Wales applies also in the Australian Capital Territory.

GREAT BRITAIN

Department of Transport - "Conveyance by Road in Road Tankers and Tank Containers Regulations 1981." Section 1059 item 6 states that "tank containers should be properly designed, of adequate strength and of good construction from sound and suitable materials." Codes of Practice which provide more specific tanker construction guidance are in the process of formulation and it is likely that they will contain requirements on vehicle stability, tank mounting, allowable stress, and baffles.

The Department also included the Health and Safety Commission Code of Practice recommending that "drivers should have a general knowledge and understanding of the design and construction characteristics of their tanker, with special reference to the effects of surge of bulk liquid loads in both single- and multi-compartment tanks on the handling of the vehicles during acceleration, cornering and braking."

The Deparptment of Transport also reports Great Britain's membership in the European ADR agreement and that it is a "competent authority" for issuing the approval of certificates for tank vehicles engaged in ADR journeys. Forwarded were ADR-TV1 and ADR-TC1 forms entitled "Explanatory Guide for Manufacturers and Users of Fixed Tanks and Demountable Tanks and Batteries of Receptacles for the Carriage of Dangerous Goods in Accordance with the Provisions of the European Agreement Concerning the Carriage of Dangerous Goods by Road (ADR)" and "Explanatory Guide for Manufacturers and Users of Tank Containers for the International Carriage of Dangerous Goods under RID and ADR," respectively.

These ADR sections address the strength testing, shell thickness, tank compression limits, and agencies approved to inspect tank vehicles. These documents do not address internal tank construction loading requirements or any means which concern mitigation of problems involving the sloshing of liquid loads. However, document ADR-TC1 notes that the regulations concerning the use, construction, and testing of tank containers of a capacity of more than $0.45m^3$ for the transportation of liquid, gaseous, powdery, or granular substances are contained in Appendix B.1(b) of the ADR regulations. The ADR Purpose, Scope and General Procedures were also forwarded. This document includes sections on the Approval of Vehicles by the ADR regulations, Driver Training requirements to receive ADR approval, and the Approval of Fixed Tanks, Demountable Tanks and Batteries of Receptacles.

Health and Safety Executive - The response from the Health and Safety Executive Office stated that there are currently no regulations in existence in Great Britain which deal with liquid cargo tank design or loading requirements. This Office also mentions the draft Code of Practice which will likely include reference to the center of gravity of tank vehicles. This Code of Practice is as yet not available.

Department of Industry, National Engineering Laboratory - The National Engineering Laboratory reported that their experience is limited to pressurized tanks for conveying liquid gas. The response identifies part BS 5045: Part 4 of the draft standard entitled "Specification for Transportable Gas Containers." This section, currently in preparation, will cover some of the aspects of stress encountered during acceleration in three directions.

However, the evaluation of these stresses is restricted to those imposed on the vessel and support structures only.

SWEDEN

The Swedish Road Safety Office - National Regulation No. 10-01-09-01. This regulation will be enforced on October 1, 1985, but will not apply to tanker vehicles which were inspected before that date. The new regulation was unofficially translated as stating:

"The volume of the tank shall be in correspondence with the maximum load permitted for the vehicle. The weight of the load, with the tank(s) filled, must not exceed the maximum load by more than 10%. Undivided tanks or cisterns, the length of which exceeds 2 meters and which is designed for carrying liquids, must be fitted with one or more transversal walls preventing the liquid from splashing when the vehicle is moving (splash wall). These walls are to be fitted in such a number that the divided space does not exceed 1.5 meters. Such walls must each have a surface of at least 80% of the cross-sectional area of the tank. However, such dividing walls are not required if the tank, or equivalent, is designed solely to be used with a full tank or a completely empty tank, and also provided that it carries a sign to this effect.

Tanker vehicles fitted out for the transportation of inflammable oils belonging to Class 1 (petrol etc.) shall be calculated with a specific weight of 0.72, and for the transportation of inflammable oils of Class 3 (engine oils and fuel oils) with 0.85.

In order for a tanker vehicle to be considered as being fitted out for the transportation of inflammable oils of Class 1, it shall be constructed according to the relevant instructions from the Inspectors of Explosive."

Swedish National Society for Road Safety - The Society responded as did the Road Safety Office with a translated excerpt of Regulation 10-01-09-01.

ISRAEL

The Israel National Council for the Prevention of Accidents was the original contact in Israel. This agency forwarded the study request to the Ministry of Transport who responded as follows.

Ministry of Transport, Department of Vehicles and Maintenance Services - Israeli Standard No. 922, Section 205.2, Baffles. "Every tank or a cell thereof, the length of which exceeds 2.25 m (7'5") shall incorporate baffles. The baffles may be of any form, including flat. The baffles shall be mounted across the tank or cell (in their lateral direction). The shape of the baffles shall enable complete cell drainage by gravity. Each baffle shall be accessible from both sides. The longitudinal distance between adjacent baffles, or between a baffle and an adjacent head, or between a baffle and an adjacent bulkhead shall not exceed 1.5 m (5'). The projected plan area of each baffle shall not be less than 80% of the tank cross-section area."

It was noted in the Israeli response that, for the transport of liquids, tanks are customarily built with compartments to reduce sloshing, however, this is not mandatory by law.

FRANCE

The Ministry of Transport - This agency responded to the inquiry with both an adminsitrative approach as well as a technically based solution to the transportation of hazardous substances such as petroleum. The first states that, for payloads exceeding 10 tons, the vehicle speed be restricted to 50 km/hr in an urban area, 60 km/hr on a rural road, and 80 km/hr on limited access freeways. The second method refers to the use of triple-axle semitrailers with single tires which results in a greater width between the trailer tires. Thus, the tank can rest lower between the wheels, therefore reducing the c.g. height of the vehicle and improving vehicle stability.

Petroleum France Institute - The Petroleum Institute enclosed untranslated excerpts from two publications. These two documents, entitled "Regulations for the Interior Transportation of Dangerous Materials," May

1983, and "Transportation and Handling of Chemical and Petroleum Products," 1982, were partially translated to determine if any portions alluded to addressing the problem of liquid-load movement. It was determined, however, that none of the forwarded regulations outline means designed specifically to reduce liquid-load movement.

JAPAN

Ministry of Transport, Traffic Safety and Nuisance Research Institute - The Institute identified one regulation and one standard which they felt most closely addressed the problem of liquid-load shifting. The first is Article 5, "The Safety Regulations for Road Vehicles." This article states:

"Any motor vehicle shall comply with the following requirements as to its stability:

1) The total load imposed upon the road-contact points of steering tires in the unloaded state and in the loaded state shall not be less than 20% (18% in the case of a three-wheel motor vehicle) of the vehicle weight and of the gross vehicle weight, respectively.

2) In the case of a tractor, the requirement of the preceding item shall be complied with even in the state when a trailer is coupled thereto.

3) In the case of a two-wheel motor vehicle with a sidecar, the load imposed upon the road-contact point of the wheel of a sidecar in the unloaded state and in the loaded state shall not be more than 35% of the vehicle weight and of the gross vehicle weight, respectively.

4) Any motor vehicle (except motorcycles without sidecars and trailers) in the unloaded state shall not capsize when slanted to the left and right side at an angle of 35 degrees.

5) In the case of a trailer (except pole trailers), the requirement of the preceding Item shall be complied with in the state where a tractor in the unloaded state is coupled thereto.

6) In the case of a pole trailer, the distance between the centers of the road-contact points of the left and right outermost wheels shall not be less than 1.3 times the height of the loading floor above the ground in the unloaded state.

In addition to the above, any motor vehicle carrying dangerous articles shall comply with the Motor Vehicle Inspection Standard 4-3-3. This standard sets the maximum stable inclination angle of the vehicle installed with the tank carrying high pressurized liquid petroleum gases and liquid natural gases as being 36 degrees or more."

Japanese Standards Association - The Association did not respond to the request directly. Forwarded with their response was the Japanese Industrial Standards Catalogue with information on standards ordering procedures. In reviewing the catalogue, no standards are listed which pertain to tank construction, or devices incorporated which address the problem of liquid-load shifting.

SWITZERLAND

International Organization for Standardization - The ISO response states that there is currently no International Standard directly concerned with reducing rollovers involving liquid cargo shifting and stability. However, the response does point out technical reports written by the ISO concerning Vehicle Dynamics. One such report being carried out by the subcommittee ISO/TC 22/SC 9 is entitled "Vehicle Dynamics and Road Holding Ability." The following ISO standards were identified as maybe being of marginal interest. Also pointed out are two standards from the International Union of Railways.

ISO 1496/3-1981 Series: Freight containers-Specification and testing Part 3: Tank containers for liquids and gases.

ISO 3164-1979 Earth-moving machinery-Laboratory evaluations of rollover and falling object protective structures - Specifications for the deflection-limiting volume.

ISO 3471-1980 Earth-moving machinery-rollover protective structures-Laboratory tests and performance requirements.

ISO 4138-19982 Road vehicles - Steady-state circular test procedure which includes; Measurement of road surface friction, high friction test track surface, braking in a turn--open-loop, terminology of road vehicle dynamics, transient response test procedure--sinusoidal input, and transient response test procedure--random output.

UIC 573 - Technical conditions for the construction of tank wagons.

UIC 573-1 - Technical conditions for the construction of the tanks of wagons intended for the transport of dangerous liquids.

Swiss Council for Accident Prevention - Forwarded from the Council was an untranslated regulation regarding the "Transport of Dangerous Goods on Roads" contained within the "Construction and Equipment of Road Vehicles" regulation. Included in this portion are guidelines concerning driver training and operation. Also, regulations for the construction and equipment for transport vehicles. Article 44:2 of this regulation has been unofficially translated and states:

"Tanks for transporting of liquids with a volume greater than 7500 liters must be provided with compartments. Any compartment site shall not exceed the above 7500 liters. Openings between compartments shall not exceed a total of $0.3m^2$.

GERMANY

Road and Transportation Research Association - In responding to our request, the Research Association noted that the study request was out of their scope. They did, however, contact the German Ministry of Transport and relayed that no special regulations for liquid loads were currently enforced.

SOUTH AFRICA

South African Bureau of Standards - The Bureau of Standards stated in response that no specific research or attention has been given to the problem of liquid-cargo shifting. The Bureau also confirmed this with the National Institute for Transport and Road Research. Included, however, are standard which they identify as speaking to separate compartment requirements partially to ensure load stability, and maximum ullage amount recommendations. These standards are:

SABS 1187-19978 The tanks and auxiliary equipment of milk tankers.

SABS 1398-1983 Road tank vehicles for flammable liquids.

SABS 0189-1983 The operation, handling and maintenance of road-tanker vehicles for flammable liquids.

National Institute for Transport and Road Research - The Institute reported that they are primarily concerned with regulations relating to the carriage of flammable liquids and that there are no regulations which currently address the problem for flammable liquid loads. However, they state that some regulation may be produced in the near future under extensions to the Hazardous Substances Act.

NEW ZEALAND

Ministry of Transport, Road Transport Division - The Road Transport Division advised in their response that there are no regulations administered by the Division specifically dealing with liquid cargo tank design or loading requirements intended to reduce rollover accidents. Their response did include, however, a translated portion of Section 2.11 "Stability of Tank Wagons" in the Code of Practice for Vehicles Transporting LP Gas by Road and issued by the New Zealand Department of Labor. Selected portions of this section state:

2.11.1 "The geometric center of a cross section of the tank or tanks, taken in a vertical plane midway along the length of the tank(s) shall fall within an isosceles triangle having a base length at ground level equal to the overall width between the outside walls of the tires of the major load axle or axles of the vehicle, and base angles of 65 degrees, with the tank(s) unladen.

2.11.2 As an alternative to 2.11.1, the entire tank wagon, including prime mover in the case of a tank semitrailer, shall be demonstrated to be capable of being statically tilted to an angle representing a transverse loading of 9.33 times the all up weight of the tank wagon and its load (under all conditions of load) acting at the center of gravity of the loaded tank wagon without rollover occurring.

2.11.2.1 As an alternative to physical demonstration of compliance with paragraph 2.11.2, compliance may be claimed by production of calculations to the satisfaction of the Chief Inspector of Dangerous Goods showing that the tank wagon would meet the requirements of paragraph 2.11.1 if so tested."

Standards Association of New Zealand - The Standards Association identifies Standard NZS 5433:1983 Section 6 entitled "Code of Practice for the Transport of Hazardous Substances on Land" as dealing with the problem of liquid cargo surging in tanks. Also noted is Standard NZS 5418:1983 part 1 entitled "Transportation Containers for Hazardous Substances, Part 1, Specification for Tanks for the Multi-Modal Transportation of Hazardous Liquids, concerning tank design for transporting hazardous liquids." Neither of the standards or portions of were quoted in the response.

AUSTRIA

Federal Ministry for Science and Research - This response acknowledged that regulations to ensure safer transport of liquid loads are currently being enforced. However, for the precise identification of these, the request was forwarded to the Ministry for Transport. As of this date, no response from the Ministry of Transport has been received.

CANADA

Transport Canada, Regulatory Requirement, Transport of Dangerous Goods - This agency advised that the "Canadian Regulations on Transport of Dangerous Goods by Road" is in the process of preparation, and thus they could not forward any information at this time.

INDONESIA

Department of Mining and Energy, Legal Affairs Bureau - The Bureau forwarded an untranslated copy of two mining regulations concerning oil transportation. The first is entitled "Petroleum Transport Ordinance" (1927), the second "Petroleum Transport Regulation" (1928). Both documents were only partially translated as the material is dated and concerns the transport of oil products by ship.

FINLAND

Central Organization for Traffic Safety in Finland - This agency forwarded translated portions from Finnish legislation Ref. No. 84/1844/kw/dt/am/l. Section 1.3 Tanks, of the General Requirement area, is the only one which discusses methods which help reduce liquid load movement and interior tank construction. The section states:

"A tank can be made either of steel or aluminum sheet. The thickness of the walls of a steel tank must be at least 3 mm and the aluminum walls at least 4 mm. The tank may also be made of plastic.

The volume of the tank may not exceed 6 m^3 except for transport of heating oil.

For every 5 m^3 or part thereof in the tank, there must be a splash plate covering no less than 80% of the cross-sectional area of the tank. The material and the thickness of the plate must be the same as that of the tank itself. The splash plate must have a working aperture no less than 450 mm in diameter."

NORWAY

State Road Administration, Division of the Department of Transportation - The Road Administration response stated that specific legislation concerning lateral stability of road tankers exists only for the transport of flammable liquids. Included were translated portions of legislation pertaining to stability. Section 1.2.1 outlines provisions that specify surge-plates when a compartment has a capacity exceeding 3000 litres and length exceeding 2.0 m. These plates should be spaced at a distance not exceeding 1.5 m. Generally, the capacity of a single compartment shall not exceed 5000 litres. Section 1.3, Height of the Center of Gravity, states:

"1.3.1 Tanks shall be mounted on the automobile in such a manner that the ratio between the unladen height (H) of the centre of gravity of the load and the track width (B) of the vehicle is equal to or less than 1.0 for an automobile that is $H/B \leq 10$, 0.7 for the trailer that is $H/B \leq 0.7$.

The track width of the vehicle (B) shall in the case of twin-mounted tires be measured at the centre of the area of contact between the outer tire and the road surface, otherwise, at a point 10 cm inside the outer edge of the area between tire and the road surface.

1.3.2 For trailers fitted with anti-roll bars or other devices capable of giving the vehicle corresponding cornering properties, the height of the centre of gravity (h) may be increased, but the ratio H/B must not exceed 1.0."

Finally, the Road Administration quotes the European Agreement on the Transport of Dangerous Goods by Road section Appendix B.1, marginal 211 128. However, the Road Administration views this particular ADR requirement of no value.

NETHERLANDS

Ministry of Transport and Public Works - The Ministry response identified two articles which are part of the ADR European Agreement concerning the carriage of dangerous goods across international borders. These articles are detailed in the following discussion concerning the ADR Agreement. The Ministry also forwarded an untranslated document entitled "Requirements for Double Trailer Combinations." This document was not translated since it dealt only with the requirements on how trailer components are to be attached and which manufacturers supply approved trailer-locking mechanisms and towing rings. Interior tank construction, loading practices, or devices which may negate liquid loading were not part of the forwarded document.

ADR European Agreement

In responding, The Netherlands, Norway, Sweden, and Great Britain refer to their signatorie in the "European Agreement Concerning the International Carriage of Dangerous Goods by Road" or the ADR. Members of the ADR also include Austria, Belgium, Denmark, Finland, France, The German Democratic Republic, The Federal Republic of Germany, Hungary, Italy, Luxembourg, Poland, Portugal, Spain, Switzerland, and Yugoslavia. The purpose of the ADR is to ensure that dangerous goods being conveyed by road are able to cross international frontiers without hindrance, provided that the substances concerned have been safely packed and are being safely carried.

Included in the response from the Ministry of Transportation and Public Works in The Netherlands were two articles within the ADR regulations which were identified as the most closely related to liquid load shifting problems. These two articles are 211.128 and 211.173.

Article 211.128 states "The overall width of the ground-level bearing surface (distance between the outer points of contact with the ground of the right-hand tire and the left-hand tire of the same axle) shall be at least equal to 90 percent of the height of the centre of gravity of the laden tank-vehicle. In an articulated vehicle the weight on the axles of the load-carrying unit of the laden semi-trailer shall not exceed 60 percent of the nominal total laden weight of the complete articulated vehicle."

Article 211.173 states "When tanks intended for the carriage of liquids are not divided by partitions or surge-plates into sections of not more than 7500 liters capacity, they shall be filled to not less than 80 percent of their capacity unless they are practically empty."

Driver training also falls within the scope of the ADR regulations. The ADR regulations require that "The driver of a transport unit carrying a tank or tank container or containers, the total capacity of which is more than 3000 litres, on an ADR journey, is required to be in possession of a Certificate of Competence (DT 19920) to certify that he has undergone training at an Approved Training Centre in the particular requirements that have to be met during the carriage of dangerous goods by road."

The agency responses and the quoted portions of existing standards and regulations which address liquid load movement as contributing to vehicle instability relate primarily to the transportation of hazardous substances. The ramifications of liquid-load shifting of nonflammable or nontoxic substances does not appear to be a priority for regulatory agencies. As pointed out in the response from the National Institute for Transport and Road Research in Pretoria, South Africa, "Our major problem at the moment is keeping the tanker contents inside their tanks during normal usage."

Canada, Great Britain, and Australia all refer to research or draft regulations and/or standards being prepared which will focus on liquid-load movement problems. Whether these regulations will be applied only to hazardous substance transport was not made clear. Also, since these materials are in draft form or still in the research stage, documents outlining any findings were not forwarded. The Australian Petroleum Institute and the National Institute for Transport and Road Research in South Africa both expressed interest in the study outcome, and agreed that liquid-load movement is a problem of importance, particularly in transporting dangerous substances.

4.0 THE PROSPECT FOR FUTURE REGULATORY AND SAFETY MANAGEMENT COUNTERMEASURES

Going beyond current regulations, there is need to consider the theoretical issue of the need for slosh countermeasures as well as the various mechanical and operational approaches which might constitute a countermeasure. The theoretical issue is dealt with in the form of an analysis of the risks which might ensue from the use of road tankers with and without slosh protection. The issue is addressed using gasoline transportation as an example for which the needed supporting data exist. The prospects for slosh countermeasures are then discussed essentially as a summary of the findings which have been presented in earlier sections of this report.

4.1 The Risk Associated with Sloshing Liquids

The risk that a heavy tractor-trailer combination will roll over on the highway is substantial, as a category within the overall accident record. For example, studies using the BMCS accident data file show that rollover constitutes some seven to eight percent of all reported accidents with commercial vehicles [29,30]. Further, it has been established that the spillage of large quantities of liquids from bulk tankers is overwhelmingly a rollover problem. In a study of tanker accidents in Michigan, for example, it was shown that 27 out of 27 tanker overturning accidents resulted in spillage, with an average of approximately 4,500 gallons of motor fuel spilled per incident, while only 2 out of 12 non-overturn collisions caused fuel spillage--and then 30 and 1,000 gallon quantities were spilled in the two incidents, respectively [25]. Thus, if spillage of product is the primary safety concern when transporting liquids in bulk, then rollover accidents are the focal accident type.

The involvement of liquid slosh, however, as a contributing factor producing rollover is not explicitly known. Thus, it is the purpose of this section to present an analysis of an estimate of the potential role which liquid slosh might play in determining the frequency of tanker rollover accidents. The analysis is intended to approximate the magnitude of the benefit which might accrue if a completely effective countermeasure were implemented. The result of this analysis is thought to be valuable in assessing the warrants for regulations in the area of slosh countermeasures.

1) The analysis projects the accident experience of the common tractor/tank semitrailer combinations which conform to the MC-306 specification and which transport gasoline from pipeline and marine terminals to local retail stations and commercial customers. (Since gasoline transportation produces by far the most frequent hazardous material emergency in the U.S., gasoline was chosen as the most suitable commodity for illustrating the benefits of slosh countermeasures.)

2) The analysis calculates the total number of rollovers of gasoline tankers which should be expected in a one-year period for each of two cases representing alternative scenarios of fluid slosh involvement. In the first scenario, the gasoline transportation system is considered to be operating as it has in recent years, with no additional slosh countermeasures in place. In the second scenario, it is assumed that a completely effective countermeasure has been implemented such that fluid slosh does not occur in the process of transporting gasoline by tank truck. The warrants for regulation will then rest upon the difference between the total annual rollovers expected with and without slosh occurring. Although the final result, then, is expressed in the form of a difference, the analysis attempts to reasonably approximate the total number of rollovers so that the absolute value of the rollover difference finding is essentially accurate.

3) It is assumed that the accident exposure of the national fleet of gasoline tankers, expressed in terms of total loaded truck-miles, is determined by:

a) The total annual consumption of gasoline in the U.S. The annual rate of gasoline usage in the U.S. is taken to be 1.16 x 10 to the 11th gallons which was the estimated national consumption value in 1982 [31].

b) The average length of the loaded portion of a delivery trip. In a study of the transportation of gasoline in the State of Michigan [32], a survey of Statewide operations showed an average urban trip length of 43 miles (69 km) and an average rural trip length of 74 miles (119 km). Weighting these figures by the respective total mileage covered on the urban and rural road systems, an average of 62 miles (100 km) is obtained. Considering that the Michigan data showed that the loaded miles were virtually equal to the empty miles in such delivery service, the average loaded trip length was set at 31 miles (50 km). (Note that the analysis considers only the loaded miles since both the slosh phenomenon and the prospect for spillage require that the vehicle be carrying product.)

c) The average volume of gasoline transported per trip. Interstate Commerce Commission statistics [33] show that the average gasoline shipment by truck is 8,400 gallons. Recognizing that the typical gasoline tanker has a capacity of 8,800 gallons, and that the great majority of gasoline shipments closely approach the capacity of the tank, the ICC value of 8,400 is seen as a quite reasonable figure (even though it was determined in 1972).

The total level of vehicle exposure deriving from the figures in a, b, and c is 4.28 x 10 to the 8th vehicle-miles traveled with tankers in the loaded condition.

4) The incidence of slosh-loading among shipments of gasoline in bulk was established in the study of Michigan transportation practices [32]. The study determined, by the survey of individual delivery trips, the number of compartments in each shipment which were in a nominal "slosh-loaded" state. Overall, some 21.3 percent of the total miles over which gasoline was being hauled involved semitrailer tankers having one or more compartments which were less than 80 percent but more than 20 percent filled with liquid.

5) Using this nominal definition for "slosh-loaded" operations, an average stability level measure was evaluated, using the results of a computerized analysis reported in ref. [25], to characterize each of the respective slosh-loaded and non-slosh-loaded vehicles. The computerized analysis considered the dynamic overshoot in the motion of the sloshing liquid in order to account for a reduced rollover threshold in a particular tanker which was sized to carry 13,200 gallons of gasoline. (Note again that the rollover threshold measure represents the maximum value of lateral acceleration, in g's, which the vehicle will tolerate without rolling over.) The analysis took the results of the survey of loading practices [32] and

determined average rollover threshold values for this vehicle, assuming three operating conditions, namely,

a) an average partial load condition, assuming that the fluid is free to slosh (for which the corresponding average value for rollover threshold was 0.374 g's)

b) the average partial load condition, assuming that no slosh can occur (for which the rollover threshold is 0.424 g's)

c) the fully loaded condition (for which the rollover threshold was 0.393 g's)

6) Since the cited computerized analysis [25] had considered a very stable baseline tanker design, with a total capacity of 13,200 gallons, the calculated rollover limits needed to be scaled down for application to the case of the more conventional 8,800-gallon MC-306 tanker used over most of the nation. The results cited in item 5, above, were simply proportioned according to the differences in calculated values of rollover threshold for the fully loaded tankers having the respective 13,200- and 8,800-gallon capacities. Thus, the calculated rollover limits for slosh and non-slosh partial loading of the 13,200-gallon Michigan vehicle were multiplied by the factor:

$$\frac{\text{Rollover Threshold, 8,800 gal vehicle, = .320 g}}{\text{Rollover Threshold, 13,200 gal vehicle, = .393 g}} = 0.814$$

7) Using this proportioning factor, the nominal rollover threshold representing the average slosh-loaded, 8,800-gallon, tanker was 0.302 g. For the same vehicle transporting the same partial loads of gasoline, but with a completely effective slosh countermeasure installed, the nominal rollover theshold was 0.342 g. (Note that the rollover threshold value of 0.302 g for the slosh-loaded vehicle falls below the value of 0.320 g cited above as the nominal rollover threshold for the 8,800-gallon tanker. The reduced rollover

threshold value of the slosh-loaded vehicle reflects the detrimental influence of fluid overshoot on roll stability. When the vehicle is partially loaded, with slosh prevented, the higher rollover threshold value of 0.342 is obtained, reflecting the rigid load condition and the lower height of the center of gravity which derives from the removal of payload.

8) The rollover threshold of tractor-semitrailers has been related to the incidence of rollover accidents by means of a previously-reported analysis [25] of the accident file maintained by the Bureau of Motor Carrier Safety (BMCS). Shown in figure 8, is a curve deriving from this processing of the BMCS data for the years 1976 through 1979. The figure shows that a strong correlation exists between the percent of rollovers occurring among single-vehicle accidents (SVA) involving tractor-semitrailers and the calculated value of rollover threshold for each accident-involved vehicle. This plot represents some 9,000 single-vehicle accidents involving three-axle tractors pulling two-axle, van-type semitrailers. Among these 9,000 accidents, more than 2,000 rollovers were recorded. These data were resolved into the indicated format with the aid of an analysis for calculating rollover threshold of such vehicle combinations, given the value of gross vehicle weight which is reported to BMCS with each accident. Knowing the gross weight, the analysis assumes that payload was placed in a fashion representing medium-density freight. Typical values for tire, spring, and geometric properties were then employed to calculate rollover thresholds for each increment of gross weight in the accident file.

Given the rollover threshold values which were computed above for the tankers with and without slosh, the probability of rollover, given a single vehicle accident, PRP/SV, can be determined from Figure 28, as follows:

PRP/SV, partial load with slosh, = 0.56

PRP/SV, partial load without slosh, = 0.46

PRF/SV, full load (without slosh), = 0.52

9) Since the connection to the BMCS data file was by means of the single-vehicle accident statistic, it is necessary to determine a value for the single-vehicle accident <u>rate</u>, PSV. In the cited Michigan study [25], a

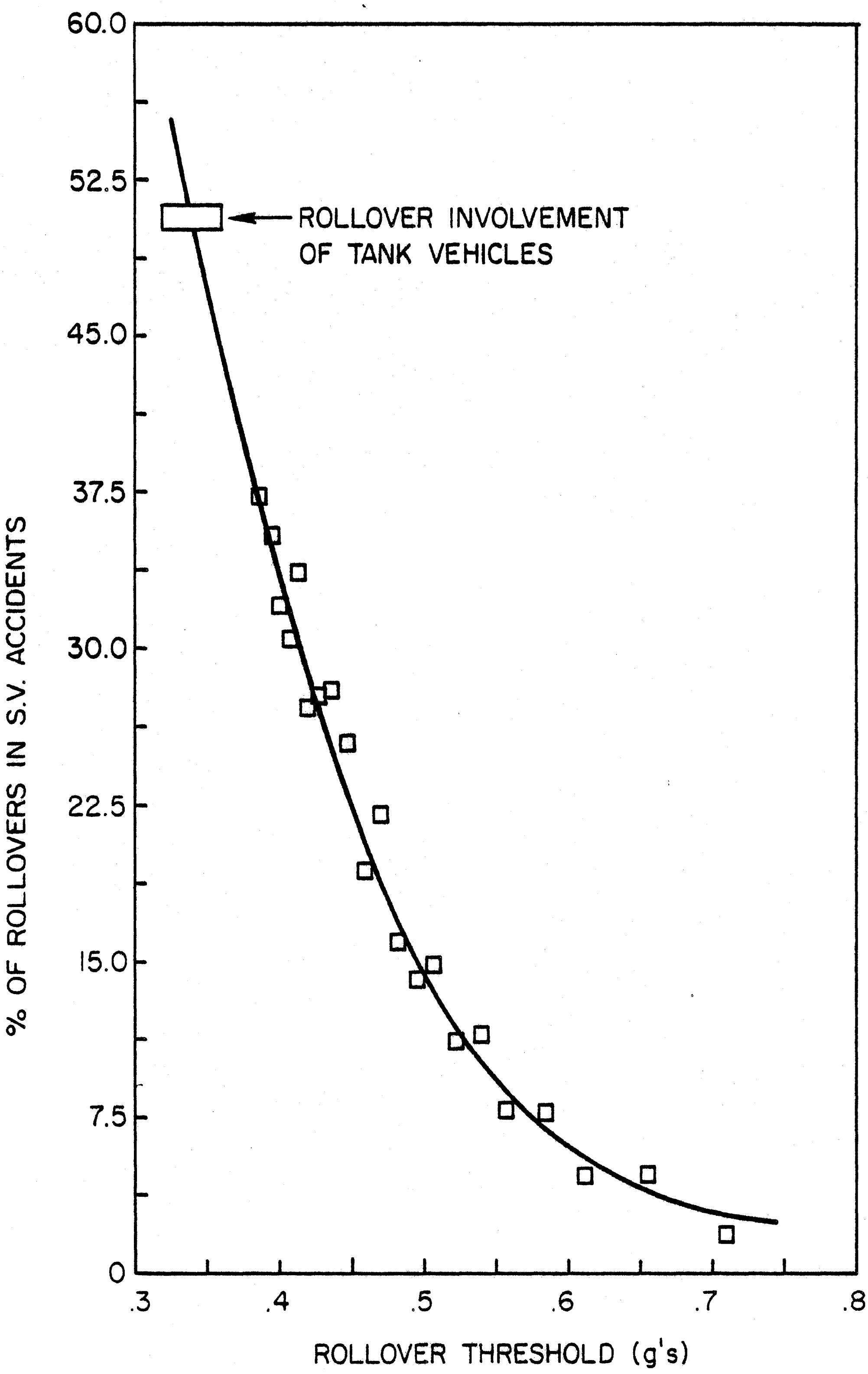


Figure 28. Relationship between rollover threshold and rollover accident involvement. (Based on BMCS accident data for the years 1976-78.) [25]

value of 0.93 single-vehicle accidents per million vehicle miles was derived for PSV from accidents reported over a four-year period by the Michigan State Police. It was also shown that such a number is likely to be somewhat conservative as an estimate for the single-vehicle accident rate of petroleum transport vehicles.

10) The statistics compiled over the above-mentioned steps are then employed in a simple calculation of the total annual incidence of rollover in the transportation of gasoline, for the two cases concerning the slosh condition. The general expression for computing this result can be written as:

$$N = (.213L \times PSV \times PRP/SV) + (.787L \times PSV \times PRF/SV)$$

where: the .213 and .787 factors reflect the 21.3 percent of loaded miles with slosh vs. 78.7 percent of loaded miles without slosh,

L = Total loaded vehicle-miles for the national fleet of 8,800-gallon tankers, 4.28 X 10 to the 8th.

.PSV = Probability of single vehicle accidents, .93 per million loaded vehicle-miles.

PRP/SV = Probability of rollover for the partially-loaded tanker, given a single vehicle accident. Considering the case in which the liquid in the partially-filled compartments is free to slosh, the value is 0.56. For the case in which liquid does not slosh, the value is 0.46.

PRF/SV = Probability of rollover for the fully-loaded tanker, given a single vehicle accident. The value for the baseline 8,800 gallon-tanker is 0.52.

The total number of rollovers which are determined from this expression are as follows:

With partial loads sloshing, N = 210.4 rollovers/ year

With partial loads rigid, N = 201.9 rollovers/ year

Thus, we see that the payoff which might accrue from a completely effective countermeasure for the sloshing of liquid in gasoline-hauling operations would be a reduction of approximately eight rollovers per year, or four percent of the total rollover incidence with tank vehicles in this service. The relatively small magnitude of this benefit is due to:

a) the small fraction of the total miles travelled by gasoline tankers in a slosh-loaded state, and,

b) the typically small fraction of the total payload volume which is, in fact, sloshing when a partial-load condition prevails. This second item is largely influenced, of course, by the fact that gasoline is transported in multiply-compartmented vessels, thus providing that a large portion of the total load can be carried in essentially full compartments.

While this example is enabled by the fact that data are available documenting the incidence of slosh loading in gasoline transportation, it is clear that other liquid commodities are hauled in such a manner that slosh countermeasures would offer a much larger potential for reducing rollover risks. Perhaps the above analysis offers a prototype of one approach toward determining the risk outcome, should concerns over the slosh problem with other types of liquids call for such a similar evaluation.

4.2 The Prospect for Vehicle Design Standards

The need for regulations which dictate special design or performance features of cargo tanks in order to mitigate slosh effects is generally unclear. For the specific example case of gasoline transportation, as indicated in the preceding section, the warrant for countermeasures seems to be reduced by the generally minor extent of a slosh-loading practice. The survey of various industries reported in section 2.2, however, suggests that there are, indeed, certain portions of the transportation industry which practice slosh loading as a normal part of their operation. Conspicuous among these were those committed to a route structure having multiple pickups, such as in the milk products industry, and those transporting fluids of differing density, from trip to trip, in the same vehicle. This latter practice is typified by those transporting bulk chemicals.

In both types of cases, however, the prospect of treating the inside of the vessel with additional compartmentation or baffles which reduce the magnitude of the sloshing mass and/or impede its flow, are unattractive. In the milk products industry, as in all bulk transportation of edibles, health considerations mandate the requirement that the tank be fully cleanable such that a completely sanitary status is recovered prior to introducing each new load. The practical considerations associated with tank cleaning tend to argue for as simple a containment surface geometry within the vessel as possible. Conversely, the very mechanisms which promise to reduce the sloshing action of the fluid also imply introducing a more complex array of surfaces within the vessel. Accordingly, we generally find that tanks employed in this type of service are of cleanbore construction, without baffles or compartmentation of any kind.

In the industrial chemical application it is common practice to employ a fleet of tankers in which each vehicle is used on an interchangeable basis to transport a broad variety of products. The concern over chemical contamination of one load of fluid with the residue from a previous load of a dissimilar fluid suggests that easy cleanability is a standard requirement. Thus, it is common to find cleanbore vessels in this application, as well. If slosh-mitigating hardware were to be required on tankers in this service, it may be that reorganization of the entire transportation pattern in such fleets would be required, such that each vehicle would be restricted to the transportation of one commodity. (Of course, it may be that this scenario would then obviate the need for anti-slosh treatments since the incidence of partial loading would be much lower if the tank were sized to handle the fluid density of the particular product to which the vessel is restricted.) If seasonal factors or other market fluctuations tended to vary the demand for transporting each product over time, however, the economic burdens associated with idle equipment, on the one hand, and unavailability of suitable vehicles to meet the peak transportation demand, on the other, could be viewed as excessive.

The bottom line of this discussion is that, if slosh-mitigation hardware implies very poor cleanability of the tank, the major portion of the tankers actually engaged in slosh-loading cannot be readily subjected to a "hardware-type regulation" without imposing a substantial burden on their day-to-day operating efficiency.

Aside from the issue of cleanability, it also appears that there is an occasional need for a workman to enter the tank for the purpose of repairing some portion of the vessel or its valving. If it is required that one be able to implement repairs on all portions of the vessel, then any baffles or separation walls must be configured such that a person can gain access to, and can maneuver sufficiently within each of the spaces in the tank. The requirement for access suggests that each compartment or separated volume within the tank must be accessible either laterally, through the separating wall, or vertically, from the top of the tank. Thus, a requirement for baffle plates or separating walls carries with it an implicit requirement that the design also provide for adequate access.

One objection to the use of longitudinal baffles which has been voiced a number of times by the tank manufacturing community involves a concern that such plate structures would so stiffen the tank at the local points of attachment that fatigue failures would be common. It may be that this concern is based, to some degree, upon certain anecdotes in which fatigue failures did, indeed, accompany some implementations of longitudinal baffles in the past. It is apparent, however, that the tank trailer industry has advanced substantially in recent times in the ability to design fatigue resistant structures. In this regard, tank designs reflect the obvious awareness that flexible sections are needed in certain areas of the structure while more stiff sections are suitable elsewhere. Thus, in the author's view, the "local stiffness" objection seems to boil down to an acknowledgement that "softer" baffle connections may be warranted in contrast to the naive implementations upon which the earlier anecdotes may have been based. This is not to say, however, that the structural design challenge is minimal or that a developmental phase is unneeded, but rather that current technology in structural design is fully capable to the task, should longitudinal baffles be deemed a reasonable requirement.

The options available for configuring longitudinal baffles are many. In general, however, it is convenient to dichotomize the cases examined by various investigators into a) full-section and b) partial section baffles. Full section baffles cover all of those designs in which the effectiveness of the baffle in mitigating slosh is not particularly sensitive to the fill height of the fluid. Such configurations would include the various arrangements of vertical partitioning walls such as Strandberg investigated [10]. It was observed that such designs became very powerful in mitigating slosh over a broad range of frequencies when three vertical walls were installed across the width of the vessel. A single wall in the center of the tank was seen (in Figure 22) to substantially increase the slosh resonant frequency--but failed to reduce the peak magnitude of the slosh response forces. Overall, this type of full section, vertical, baffle design appears to offer one of the most broadly effective approaches toward slosh mitigation, although more than one longitudinal wall element seems needed if strong slosh forces are to be avoided.

The partial baffle category includes all vertical wall elements which reach less than full tank height and all horizontal elements which were situated only at one elevation within the tank. While results show that such elements can be highly effective in mitigating the slosh response of liquid loads for which the static surface is near the top extremity of the baffle, it is clear that effectiveness falls off sharply as the fluid level goes much above or below that "ideal" condition. If some trucking operations might actually encounter a single fill level at which slosh loading occurs, they might find a partial baffle design as both practical from the viewpoint of a lesser weight penalty and effective in mitigating the slosh which would otherwise occur at that fill level. The partial baffle might also permit easy access such that workmen could repair all portions of the vessel.

If the plumbing to each compartment is to be no more complex in a baffled tank than in the corresponding unbaffled unit, then baffles need to be configured with flow passages to permit the fill and drain flow of the liquid and venting of vapors. Of course, if these passages were made excessively large, the baffle would fail to suitably impede the slosh flow as intended. Thus, any standard which might lead to broad incorporation of additional walls subdividing the tank would necessarily contain provisions for these through-wall passages. The sizing of such passages was not addressed as part of this study.

Moreover, the prospect of a vehicle standard which would require slosh mitigation hardware on road tankers will inevitably bring attention to the following general issues:

1) the warrants for such countermeasures within each of the various types of tank vehicles or industries which are candidates for regulation

2) the nature of the partial fill condition(s) which are commonly encountered, among those industries which do transport liquids in partial load shipments

3) the types of slosh mitigation hardware which are seen as necessary and sufficient for reducing the slosh hazard to an "acceptable" level. The judgement of "acceptability" may well be influenced by various factors such as the hazardous nature of the commodity involved, the population density of the community through which it is hauled, etc.

4) the formulation of the regulation, itself, given the classic tradeoffs between "design" and "performance" types of requirements.

Recognizing that the primary safety threat posed by sloshing liquids involves the dynamic impetus for rollover, another avenue of countermeasure is offered by a simple upgrading of the inherent roll stability of the foundation vehicle. That is, an improved level of static roll stability would assure that the vehicle would have a greater tolerance for the overturning moments generated by sloshing liquids—as well as a variety of other stimuli. Static roll stability can be improved through judicious selection of suspensions [34], and through width and height adjustments which provide for as broad and low a vehicle layout as permitted with size and weight laws [2,35].

The most comprehensive, yet practicable, means for specifying static roll stability is by means of a tilt-table rollover threshold. As shown in Figure 29, the tilt-table concept involves a platform upon which the vehicle is tilted sideways until rollover occurs. The platform angle at which the

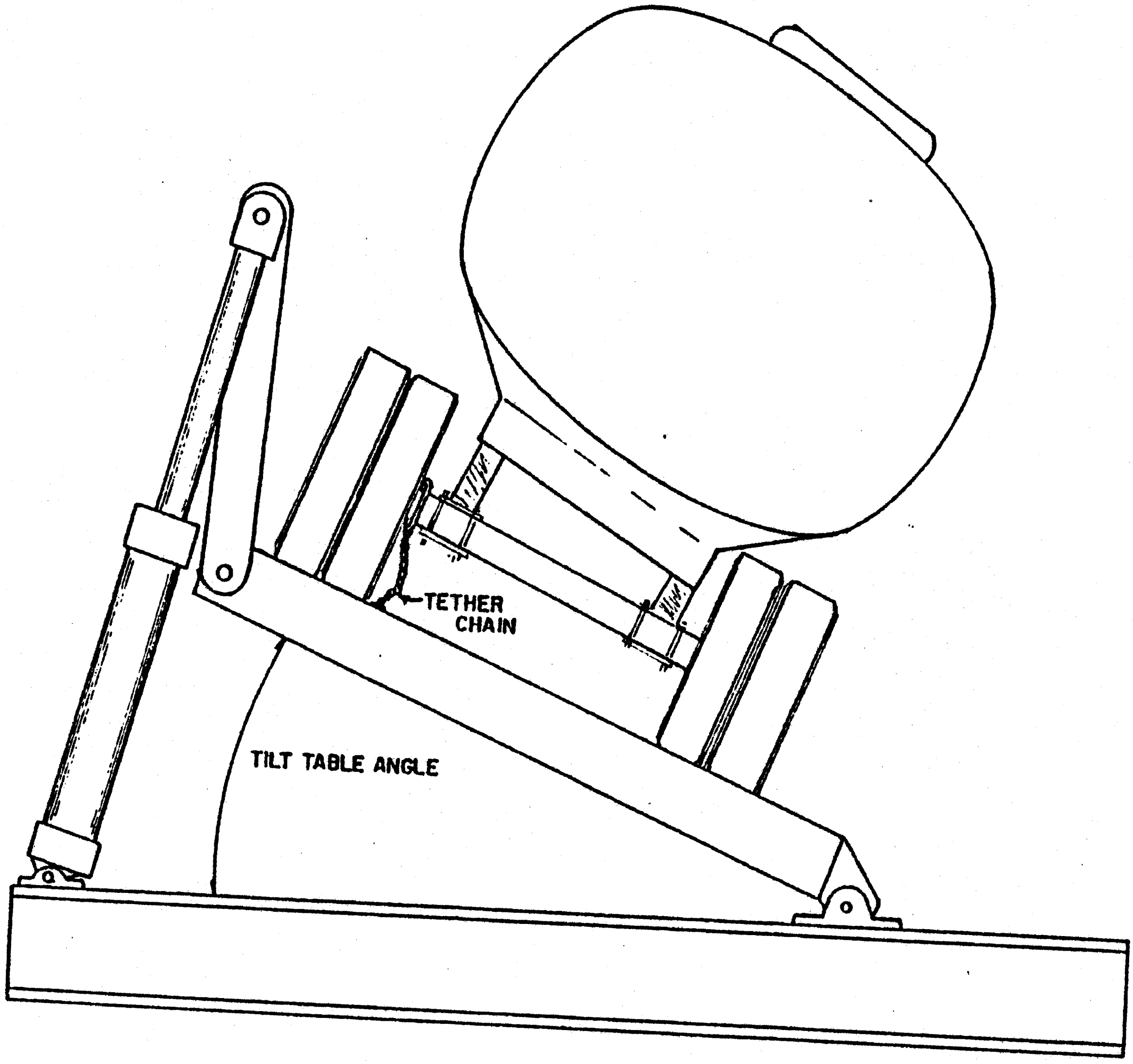


Figure 29. Tilt-table concept for measuring static rollover threshold.

(tethered) rollover occurs directly determines the static stability level of the vehicle.

Roll stability requirements per a tilt-table specification have been in force in the United Kingdom for many years in application to buses and have been proposed by The University of Michigan Transportation Research Institute (UMTRI) in the past for application to tankers carrying gasoline in Michigan [25]. Similarly, Swedish researchers in the 1970's [36] and Australian investigators in the earlyl 1980's [35] have recommended that tilt-table methods be employed in the formulation of regulations on the roll stability of commercial vehicles, especially tankers hauling hazardous liquids. In all three of these latter cases, a static stability threshold at or approaching 0.4 g's (corresponding to a maximum tilt-table angle of 21.8 degrees) has been recommended as the target specification.

Interestingly, an initiative from the tanker manufacturing industry [37] has produced a proposal which would yield petroleum tankers capable of passing a 21.8-degree tilt-table requirement. This proposal suggests an additional gross weight allowance, from 80,000 to 86,000 lbs, as an incentive to the industry to upgrade to tankers having a wider stance, lower center of gravity, and appropriately designed suspension. Overall, the proposal reflects a sound approach toward designing for a high level of roll stability while, otherwise, presenting a novel means by which load allowances can play a constructive role in promoting a wholesale improvement in tanker safety. Moreover, such an approach, together with a tilt-table specification to ensure that the safety benefits are, indeed, realized, may offer the most promising long-term countermeasure against slosh and the other hazards which contribute to rollover.

4.3 The Prospect for Improved Practices in Tank Truck Operations

Since it is apparent that certain liquid commodities are commonly hauled as partial loads in tank trucks, there is value in considering possible changes in industry operating practices in order to reduce the safety hazards due to sloshing liquids. Of course, it is simplistic to suggest that fluids should not be carried in a partial-fill condition unless absolutely necessary.

Nevertheless, the industry is, indeed, excercising judgements in the normal course by which certain partial-fill conditions have been deemed acceptable. Perhaps the most hazardous among these conditions would entail the use of a cleanbore vessel which is sized to handle a full gross weight load of a fluid having density, X, to transport an alternative product having a density of 1.5 to 2 times X. This scenario is suggested as a potentially "most hazardous" practice since the denser liquid will be loaded to the same full gross weight allowance and thereby render the greatest level of forces tending to disturb vehicle stability and control. Clearly, in such cases, the practicing industry has chosen to use the same tanker in various missions because of the economies and fleet flexibility which are obtained. The greater the differences in density of fluids hauled in the same cleanbore vessel, however, the greater will be the hazard involved and, correspondingly, the greater seriousness with which the operating industry should make its judgements concerning tanker usage.

For any of the cases in which doubles or truck/full trailers are employed as bulk liquid tankers, it seems patently reasonable to suggest that slosh loading of the rear trailer is to be simply ruled out as a practice. For any of the common vehicle length dimensions which are seen in U.S. practice, it appears that the natural frequency of yaw oscillations of the full trailer will be rather near the likely slosh frequencies which would prevail in, say, the 25 to 75 percent full conditions. Thus, the concern is that the vehicle and slosh modes of oscillation might resonate together in a manner which would grossly disturb vehicle motions. Although rather few doubles are configured for bulk liquid transportation in this country, there is known to be widespread usage of the truck/full trailer configuration for transporting petroleum products and other liquids in the western States.

One area of flexibility which the operator has with each new tank purchase is the option of specifying conventional compartmentation to suit his operation. In some industries in which, say, two fluids of differing density are to be hauled, a three-compartment tank is ordered, with the volume of the middle compartment being such that the denser fluid can be loaded up to the full gross allowance by simply filling the fore and aft compartments. When the lighter fluid is hauled, all three compartments are loaded. By such a planned approach, a good fore/aft distribution of axle loads is attained, and slosh is avoided. Again, however, economic considerations will discourage many companies from a cautious practice of this kind since a) the original price of the vessel will be greater, and b) the tare weight of the tank will be greater, thereby diminishing the weight of the payload. Also, the cleaning process is more time-consuming with the three-compartment tank than with a corresponding cleanbore vessel.

In general, slosh loading practices derive from the many peculiarities of each type of transportation and are colored by the economic burdens imposed by the non-slosh-loading alternatives. It is unlikely that substantial changes in such practices will occur simply as a result of the suggestions of the government or the research community. On the other hand, industry associations may see fit to draw up guidelines or "recommended practices" which place bounds on the extent of slosh-loading which the collective industry considers acceptable.

5.0 CONCLUSIONS

Based upon examination of the literature and the conduct of analysis and direct inquiry during this study, the following conclusions can be drawn:

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 vessels which incorporate 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 has 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 lateral baffles or compartmentation, b) steady cornering and back-and-forth steering conditions 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. Articulation between the tractor and trailer will also aggravate the influence of this latter type of maneuver on roll stability. In a separate case, tankers constructed as fulltrailers 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) only a few jurisdictions 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 the expertise in manufacturing and tank structures which will be required to support tank designs that are more complex, and d) the economic implications associated with increased tank weight (and thus reduced payload weight), increased cost of a more complex tank, and increased costs associated with maintenance and cleaning.

6.0 RECOMMENDATIONS

It is recognized that the U.S. Department of Transportation has the mandate to promulgate rules which provide for the safety quality of new vehicles, the maintenance of certain safety hardware on commercial vehicles engaged in interstate commerce as well as the qualification of drivers and the safe operation of such vehicles, and special mandates to control the transportation of hazardous materials. The charge to the DOT is so broad that a variety of possible action steps is conceivable as appropriate response to the assembled information presented in this report. In addition to regulatory action, however, it may also be that the dissemination of knowledge on the slosh problem prompts sectors of the practicing industries to voluntarily modify their vehicle specifications or operating protocols. Also, it is assumed that some aspects of the slosh topic have been found to be so insignificant as a safety concern, or so rarely practiced in service, that corrective actions are not warranted.

The following recommendations range from initiatives which will better advise the Department on the magnitude of the safety risks due to slosh in practice, to actual regulatory constraints which may be acted upon in the short term :

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 load practices of a statistical sampling of the carriers involved in shipping the various hazardous commodities of interest. These monitoring studies could be modeled after the effort [25] which assessed the practices for transporting gasoline in Michigan. 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. 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 "switched" commodities are hazardous substances. Should a field monitoring effort confirm this hypothesis, the candidate countermeasures would include a) mandatory compartmentation to ensure controlling the 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 regulation 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 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. The compliance levels for a roll stability standard 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.

b) substantially elevated levels of performance which would apply to vehicles which are allowed a modest increase in gross weight allowance. Such a 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 careful scrutiny 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 ample evidence exists to question the basic suitability of truck/full trailer combinations as a means for transporting hazardous commodities [see, for example, 4,38,39,40].

APPENDIX A

EXAMPLE LAYOUT SKETCHES SHOWING COMPARTMENTATION AND TRANSVERSE BAFFLES IN COMMON TANK DESIGNS

(Sketches courtesy of Fruehauf Liquid and Bulk Tank Division)

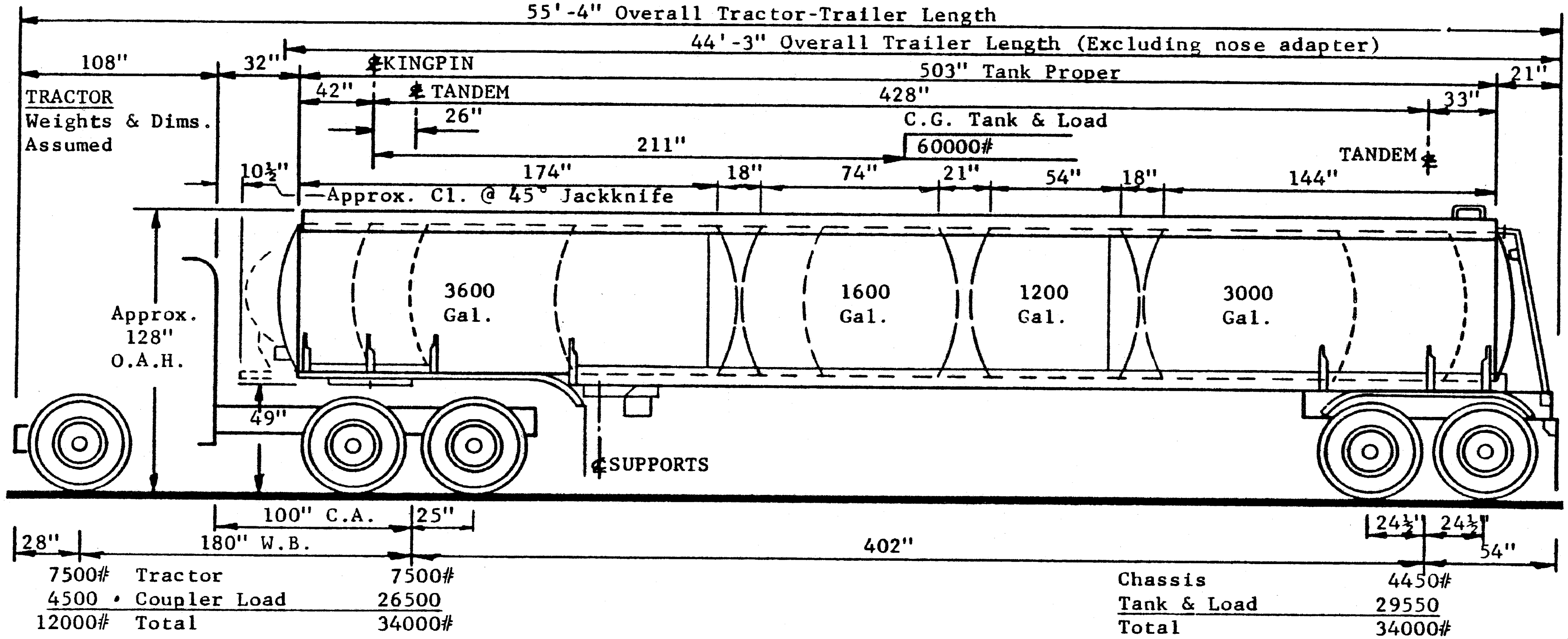


Figure 30. Typical Gasoline Tanker - 9,000-Gallon Capacity
Compartmented to handle fuel oil as an alternative load
4 compartments plus 6 transverse baffles

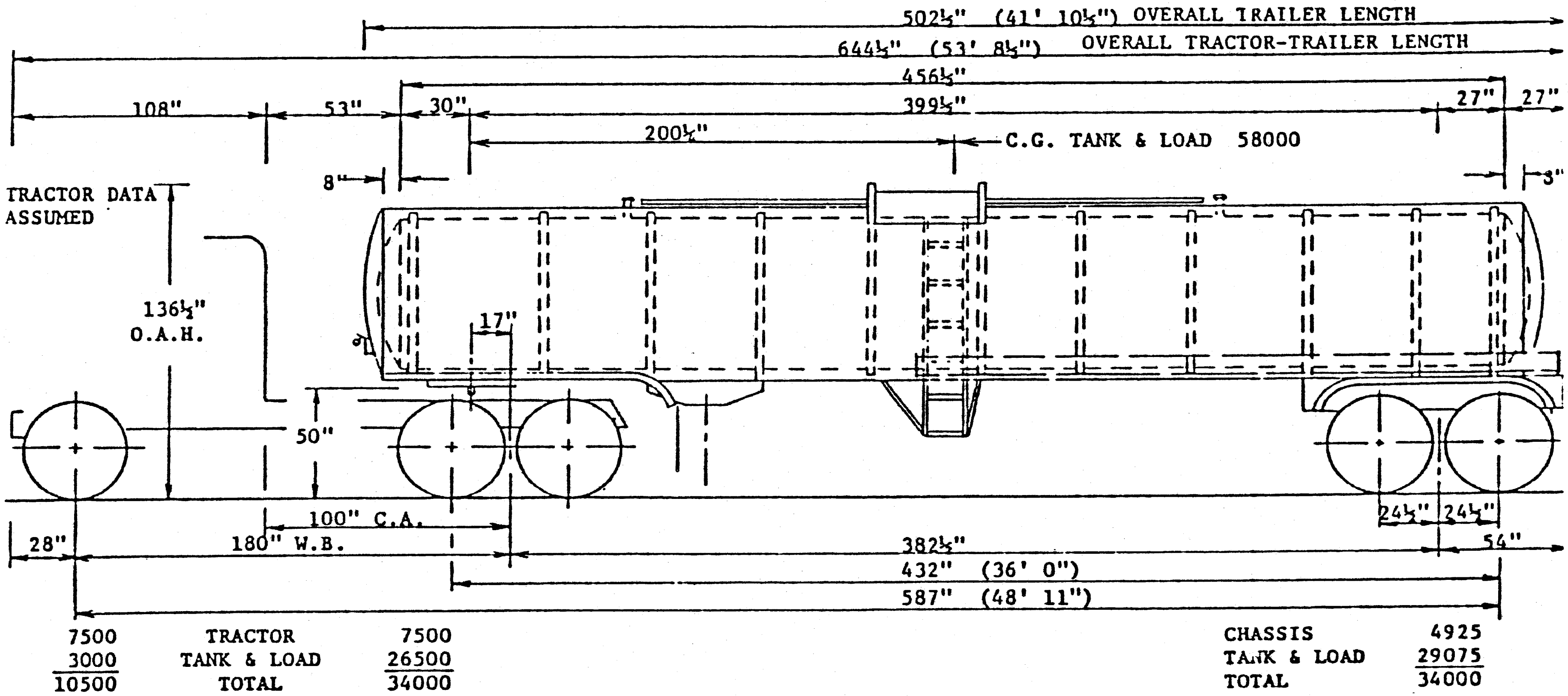


Figure 31. General Chemicals - 6,500-Gallon Capacity
Insulated vessel
Clean bore construction

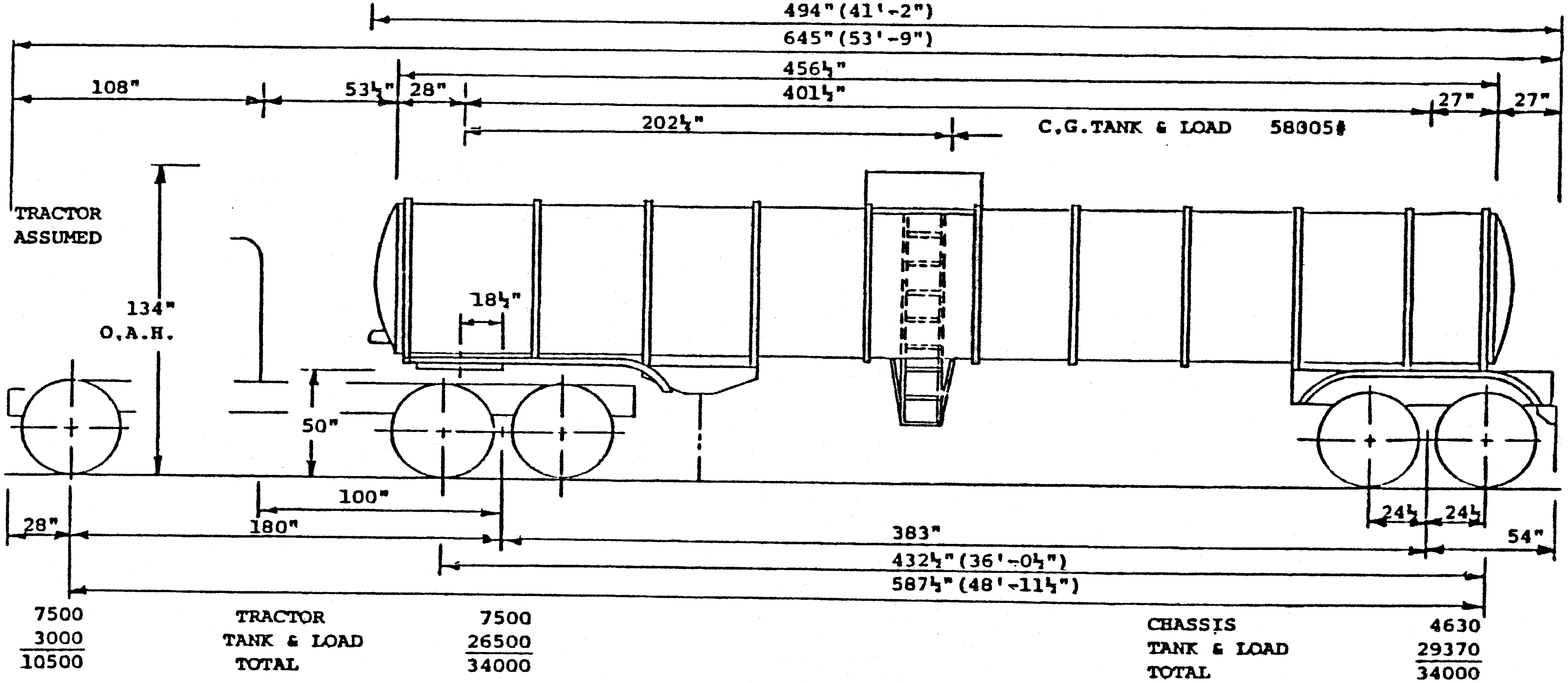


Figure 32. General Chemicals - 7,100-Gallon Capacity
Clean bore construction

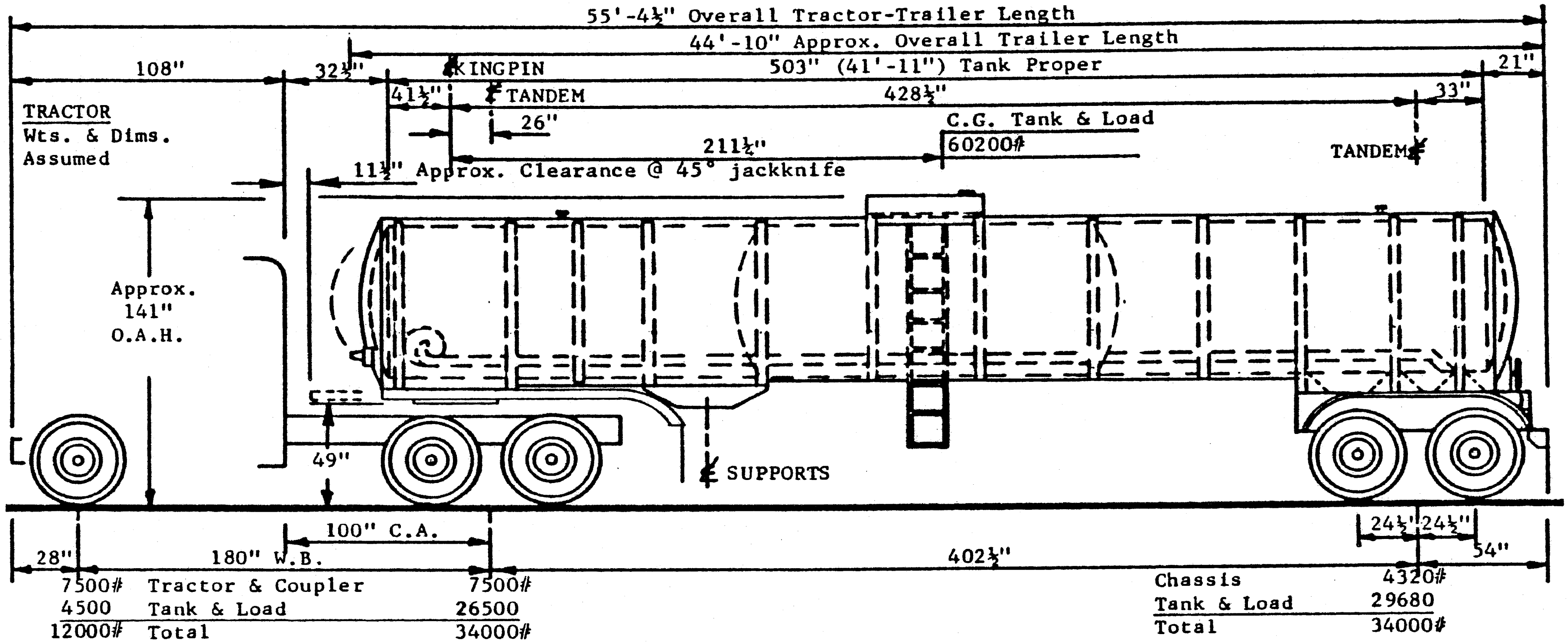


Figure 33. Asphalt - 6,700-Gallon Capacity
Insulated vessel
Single compartment, 2 transverse baffles

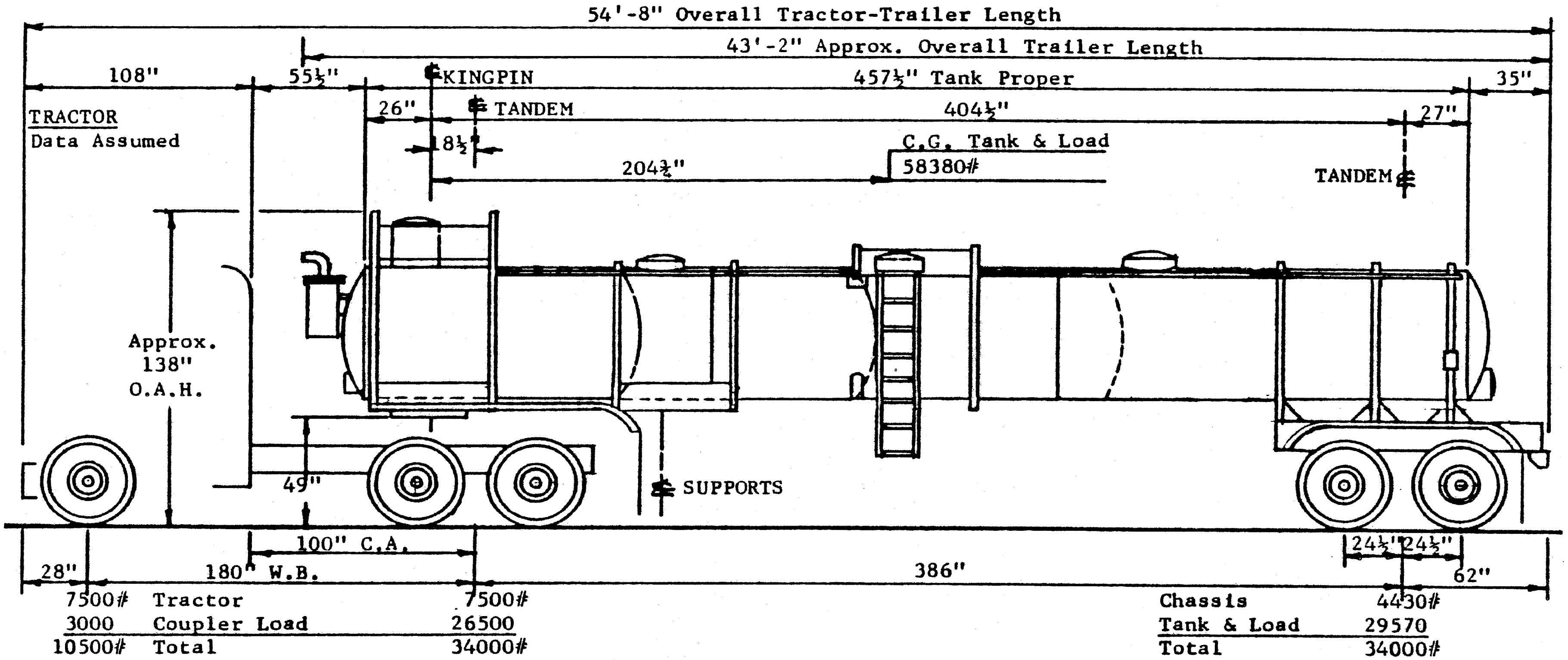


Figure 34. Industrial Waste - 5,300-Gallon Capacity
Single compartment - 3 transverse baffles

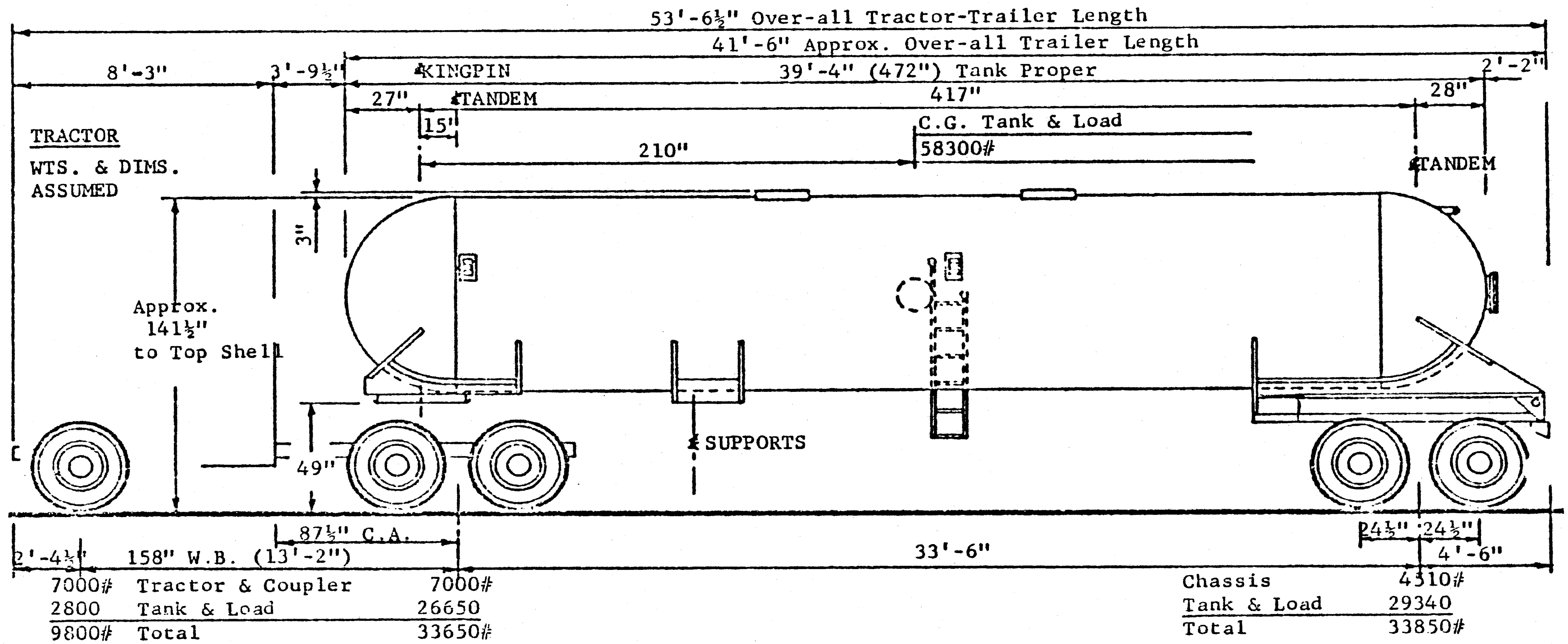


Figure 35. Liquified Petroleum Gas and Anhydrous Ammonia - 11,500-Gallon Capacity
Built to spec #MC 331 and ASME Boiler Code
Clean bore vessel

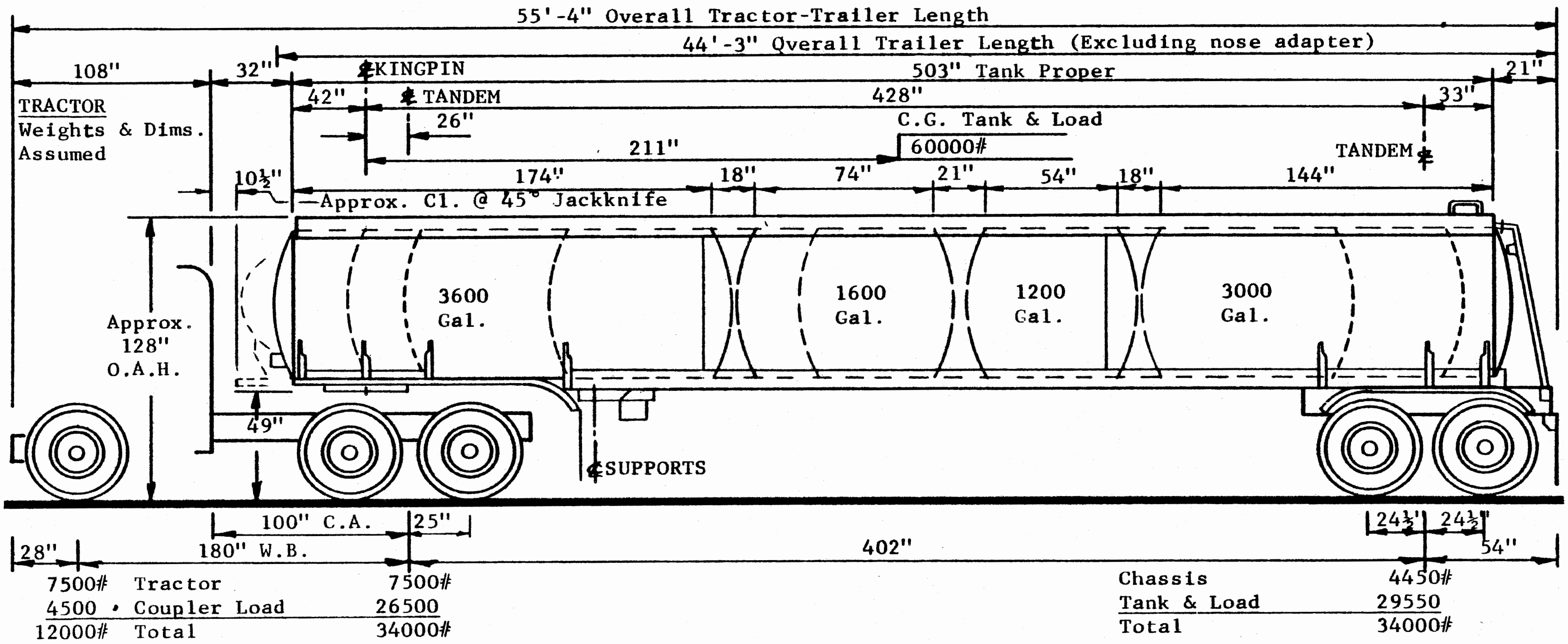


Figure 36. Typical Gasoline Tanker - 9,000-Gallon Capacity
Compartmented to handle fuel oil as an alternative load
4 compartments plus 6 transverse baffles

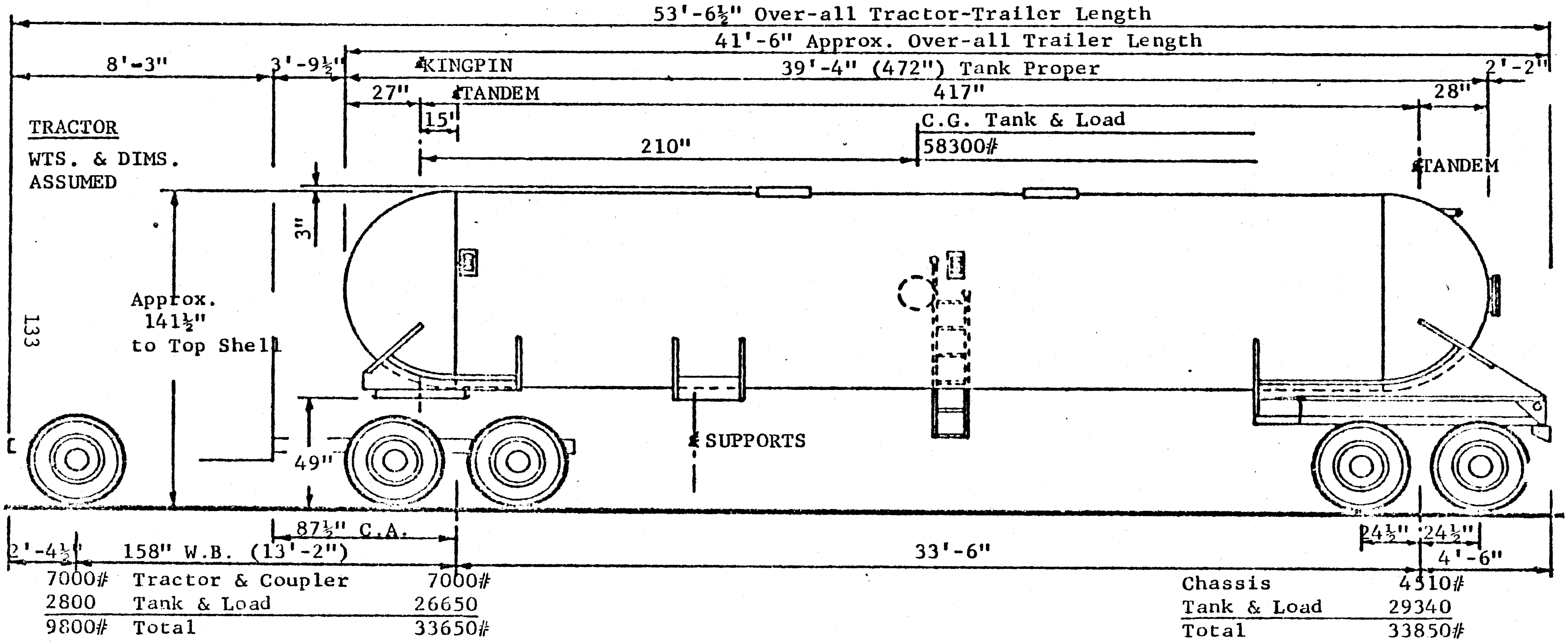


Figure 37. Liquified Petroleum Gas and Anhydrous Ammonia - 11,500-Gallon Capacity
Built to spec #MC 331 and ASME Boiler Code
Clean bore vessel

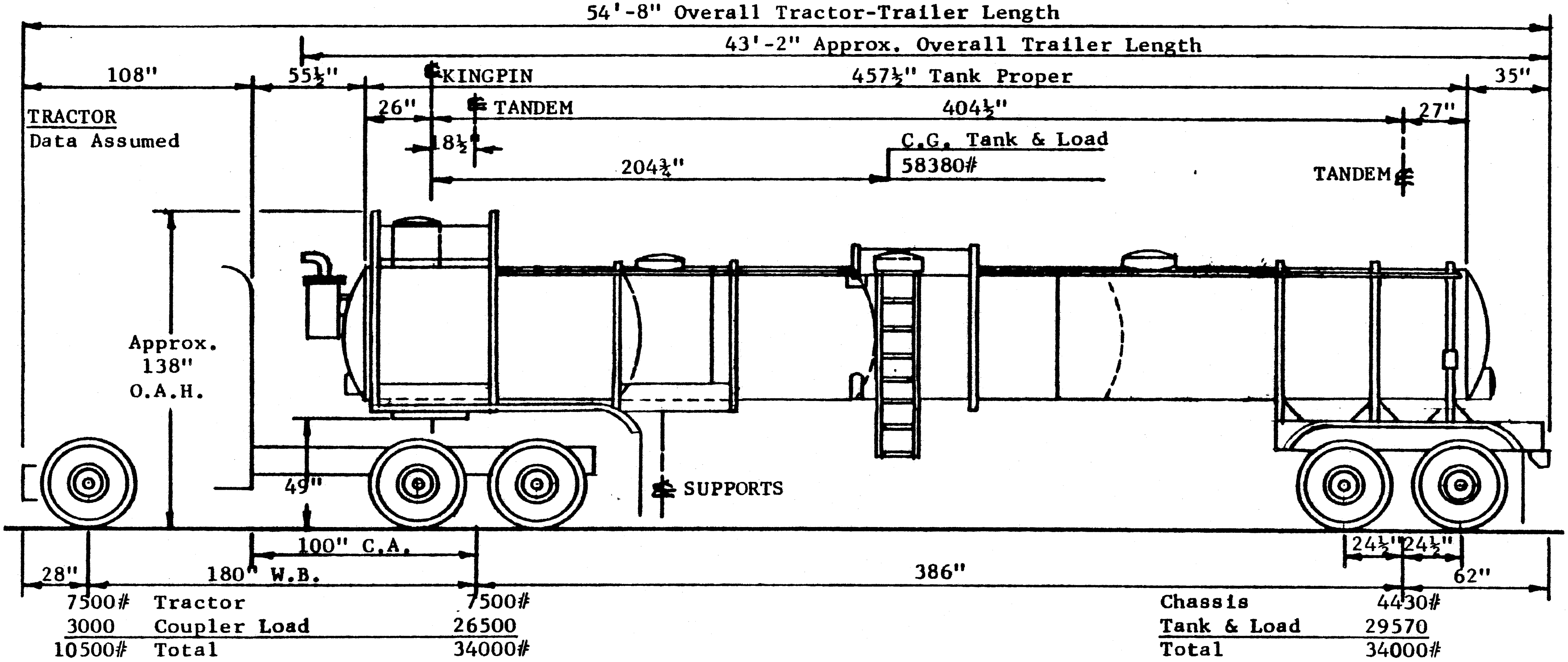


Figure 38. Industrial Waste - 5,300-Gallon Capacity
Single compartment - 3 transverse baffles

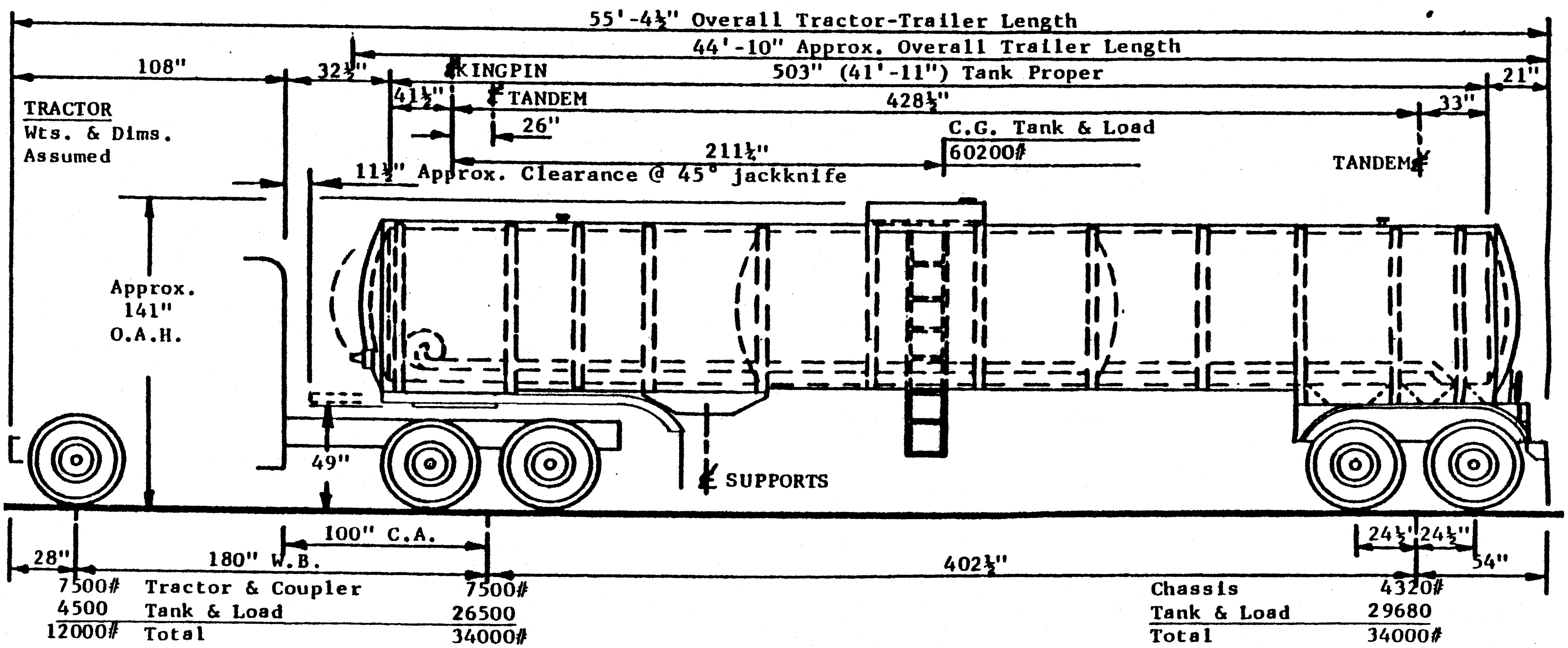


Figure 39. Asphalt - 6,700-Gallon Capacity
Insulated vessel
Single compartment, 2 transverse baffles

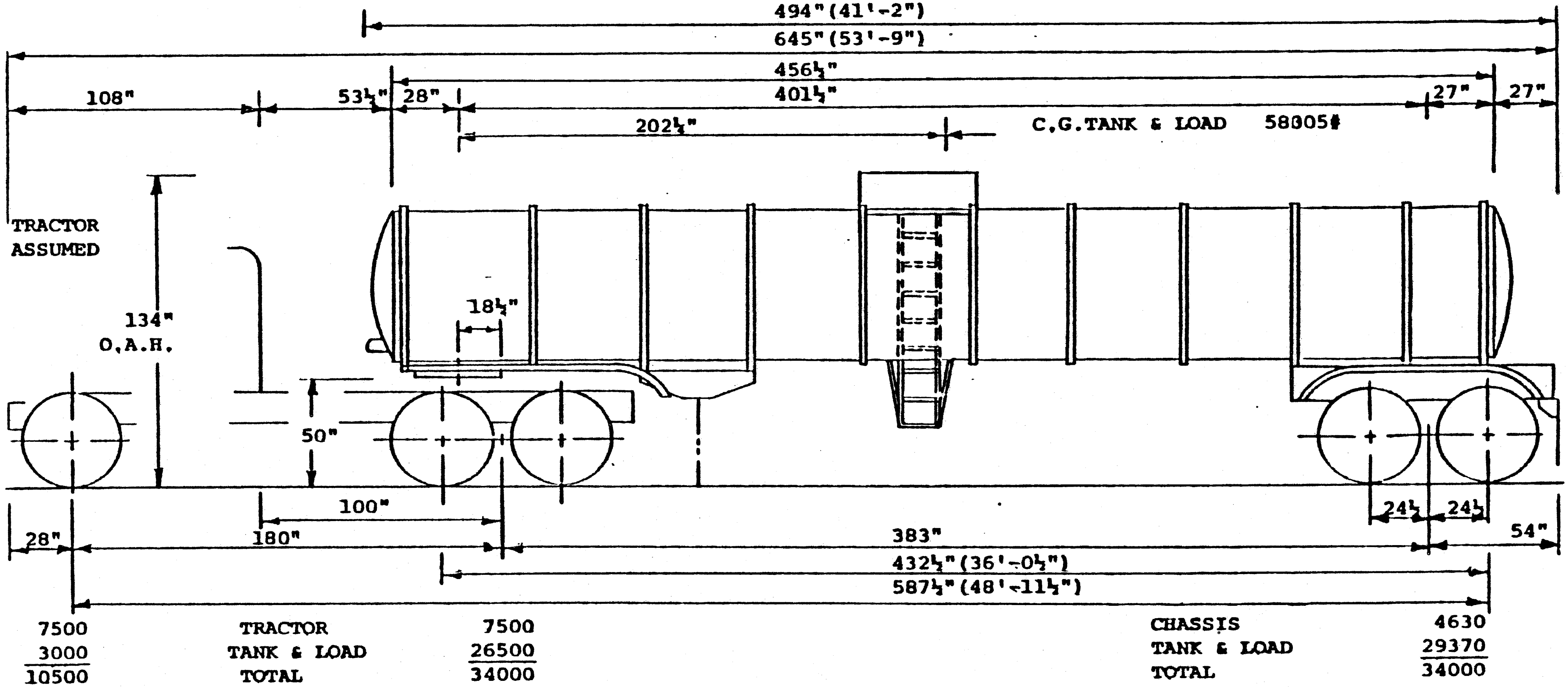


Figure 40. General Chemicals - 7,100-Gallon Capacity
Clean bore construction

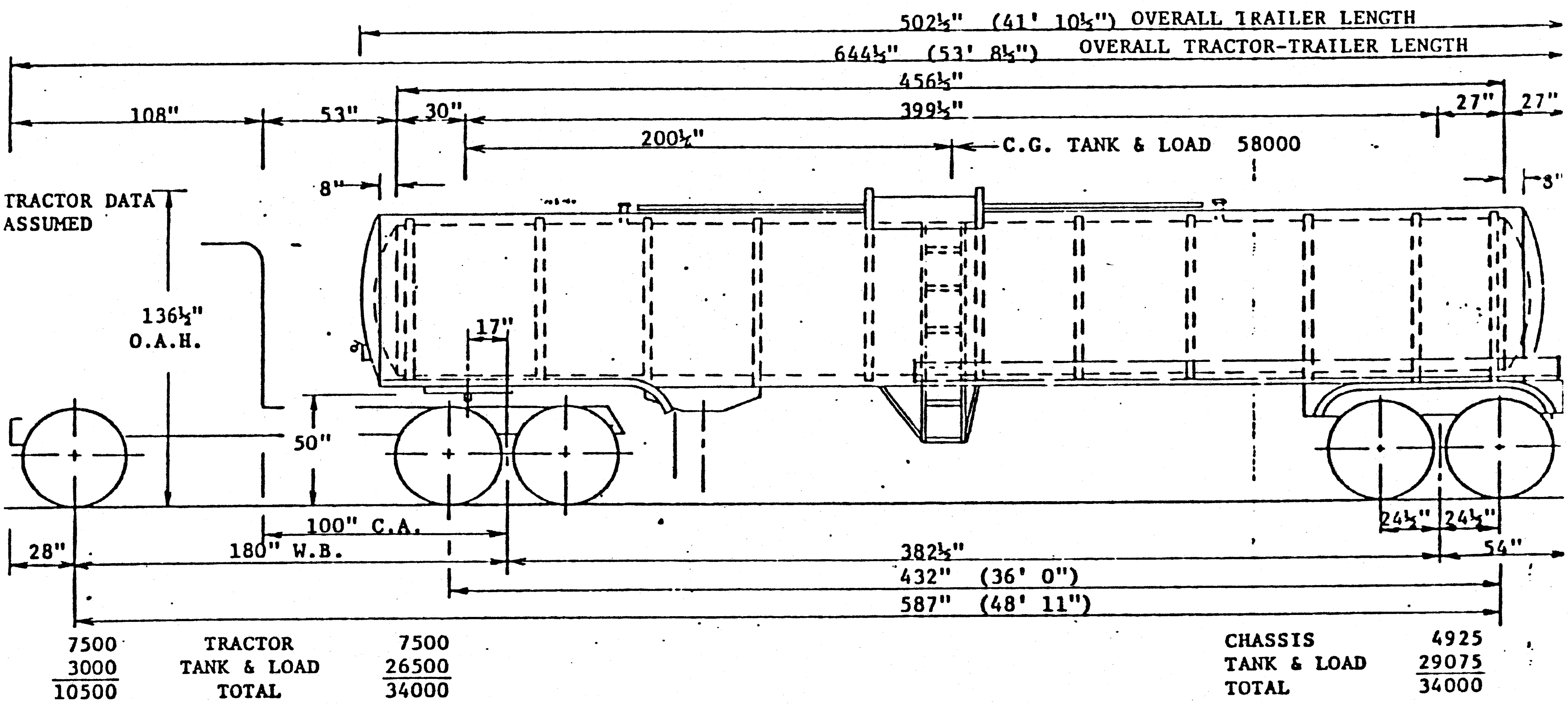


Figure 41. General Chemicals - 6,500-Gallon Capacity
Insulated vessel
Clean bore construction

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