FUTURE CONFIGURATION OF TANK VEHICLES HAULING FLAMMABLE LIQUIDS IN MICHIGAN

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HIGHWAY SAFETY RESEARCH INSTITUTE
The special safety hazard posed by highway tank vehicles hauling flammable liquids has been addressed through accident data analysis and engineering evaluations related to tank vehicle configuration. The study, which was mandated directly by an Act of the Michigan State Legislature, has produced a recommendation for new legislation pertaining to the configuration of tank vehicles having fluid capacities in excess of 9,000 gal.

A set of four vehicle configurations are recommended, all constituting tractor-semitrailers. The specification for each vehicle covers constraints on tank capacity, tank height above the ground, rollover stability, the use of so-called "lift-axles," and the ability of manhole covers to contain the fluid load in the event of a rollover.

Analysis of accident risks has indicated that any of the four recommended vehicle configurations would yield approximately one-half of the incidence of rollover, with its potential for fire, that Michigan can expect from the use of conventional tankers having tank capacities around 9,000 gal. Further, the recommended vehicles, because of their higher carrying capacities, offer large advantages to the economy and energy efficiency of flammable fluids transportation.
The opinions, findings, and conclusions expressed in this publication are those of the authors and not necessarily those of the Michigan State Transportation Commission.
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- Roads and Bridges Committee of the House of Representatives
- Transportation and Tourist Industry Committee of the Senate

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- the aid of a senior structural engineer to advise the HSRI staff on practical constraints in tank construction
- serious evaluation of a preliminary version of the recommendations which appear in this report.

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1.0 INTRODUCTION

This document constitutes the final report on a research study conducted by the Highway Safety Research Institute (HSRI) of The University of Michigan on the subject of improved safety for tank vehicles transporting flammable liquids in Michigan. The study was sponsored by the State of Michigan, with contract administration being provided by the Michigan Department of Transportation through Research Agreement #78-2230.

The project reported herein was mandated in 1978 by Act 385 of the Michigan Legislature. The primary purpose of this law was to legislate a phased removal of double tankers and to limit tank volume in the future to 9,000 gallons. Act 385 also contained the following clause:

"The Highway Safety Research Institute ... shall study vehicle design and recommend to the Legislature that vehicle combination which demonstrates the highest possible safety in transporting flammable liquids, which vehicle combination after subsequent legislation may transport flammable liquids."

Thus, the project was seen as a means to establish a solid technical foundation for enacting follow-up legislation that would regulate tank vehicles carrying flammable liquids. The project was motivated, in part, by the fact that the fuel transportation industry in Michigan had suffered a severe disturbance in its operations when the large, 17,000-gallon or so double tankers began to be phased out. Based partially upon arguments concerning the safety advantages that could be accrued with large-capacity vehicles, as a result of their low accident exposure, the Legislature conceived the research study as an opportunity to "take another look" at the whole question of tank vehicle configuration and its influence on safety.

In the absence of any follow-up legislation being enacted before November 1981, the State would become exclusively served by gasoline tankers having conventional construction and capacities not exceeding
9,000 gallons. Accordingly, HSRI's approach to the research study was to identify tank vehicle configurations that would reduce the risks of accidents, to the maximum degree, below the level that would accrue with such conventional vehicles. Although the research problem was addressed, for simplicity's sake, only from the viewpoint of gasoline as the transported product, the results were to apply also to the transportation of other hazardous liquids in vehicles meeting Federal Specification #MC-306.* Regarding vehicle configuration, conventional tractor-semitrailer tankers having either two- or three-axle trailers serve as a point of reference in this study and are referred to in the body of this report as "conventional MC-306" tankers.

The research conducted here has concluded that it is possible to significantly improve the safety of transporting gasoline by means of the adoption of a new, but practicable, set of requirements for tank vehicles exceeding 9,000 gallons in capacity. In Section 2.0 of this report, a Legislative recommendation is presented, outlining the vehicle design and performance features which should be attained to achieve the cited safety improvements. The Legislative Recommendation, of course, constitutes the Institute's direct response to the mandate of Michigan Act 385 of 1978, mentioned earlier. The recommendation is followed by a summary of the rationale supporting the details of the statement.

Whereas the recommended vehicle configurations are predicted to yield a much improved level of safety, they also appear to provide:

1) a net economic advantage due to the significantly reduced costs of transporting fluid products in a larger capacity tank, and

2) a large improvement in the energy efficiency of the transportation process itself.

*Specification MC-306 appears in the Code of Federal Regulations, Article CF 49-178.341 and entails a number of requirements for cargo tanks carrying unpressurized, hazardous liquids in commerce.
Given the timeliness of the latter two features in a climate of concern for responsible public policy on economic and energy matters, the proposed legislation, as recommended herein, is believed to be compatible with the broad interests of the State.

Further, although the recommended vehicles are configured to meet Michigan's road-use laws, it is expected that much of the technical material contained herein would also be pertinent to the improvement of tank vehicle safety in other states and countries. The study is based primarily upon engineering and accident risk analyses. Full-scale experiments and a limited amount of field survey work were also conducted to clarify certain questions regarding tank structural integrity. The methods and results pertaining to the major research tasks are contained in four sections of the report, namely:

3.0 Accident Data Analysis
4.0 Analysis of the Dynamic Behavior of Tank Vehicles
5.0 Containment of the Transported Fluid in an Accident
6.0 Prediction of Accident Risks

Two additional technical discussions, Sections 7.0 and 8.0, treat, respectively, the additional risks that can be expected if the fluid is permitted to slosh inside the transport tank and the considerations pertaining to the so-called "tilt-table requirement" by which the roll stability of the recommended tankers is specified.

Appendices A through F are also included to provide (1) technical details and data in support of accident data analysis and computerized simulations and (2) a generalized understanding of the physics of vehicle rollover.

Although the report itself is intended to document the technical study which underlies the legislative recommendation, the very "applied" quality of the results of this research has required that a good deal of engineering judgment be exercised as well. Thus the very simple scope of the recommendation derives from a judgmental distillation of the technical work. The judgments have also been guided by numerous practical considerations relating to vehicle manufacturing, the flammable
fluids transportation system, the existing accident record, and the ability of the State Government in Michigan to implement regulations of the type needed in this particular circumstance.

Moreover, the legislative recommendation represents a scientifically based statement that has been tempered through research staff interaction with the respective communities which will be regulated, as well as those who will regulate.
2.0 RECOMMENDATION FOR NEW LEGISLATION

On the basis of the study reported herein, the Institute recommends that legislation be enacted to permit the operation of tankers carrying unpressurized flammable liquids at tank capacities above 9,000 gallons, provided these vehicles meet the specifications presented in Section 2.1, below. It is also recommended that the Legislature consider a requirement that existing tankers be modified to assure that manhole covers achieve the levels of strength specified in the "recommended retrofit" statement in Section 2.3.

Both recommendations were submitted, in draft form, to a broad array of organizations involved in vehicle manufacturing, petroleum marketing, and bulk-commodity transportation for comment. To the degree that it is practicable, the following recommendations give due consideration to certain special problems that were raised by the respondents, while still assuring that the "highest possible safety" performance of the vehicles cited in the specification is achieved.

2.1 Allowable Tank Trailer Configurations

It is recommended that tractor-semitrailer configurations having tank capacities exceeding 9,000 gallons be permitted to transport unpressurized, flammable liquids in the State of Michigan, provided that such vehicles meet the following requirements.

1. Tank capacity must correspond to the "Design Volume" (+200 gal.) specified in Table 2.1 for each of the permitted axle arrangements. The Design Volume represents the full load fluid capacity of the vehicle. Where double bulkheads are needed, the "Design Volume" may be reduced by an amount equal to the void space(s) enclosed by the back-to-back bulkheads. The actual volume of the tank shell must exceed the Design Volume by at least 5 percent, thus providing an "outage" or expansion volume.
Table 2.1. Specifications for Advanced Michigan Tankers.

<table>
<thead>
<tr>
<th>SCHEMATIC DIAGRAM OF SEMI TRAILERS</th>
<th>DESIGN VOLUME (gallons)</th>
<th>DESIGN SHELL HGT (in.)</th>
<th>TILT TABLE ROLLOVER ANGLE (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>10200</td>
<td>111</td>
<td>21.5</td>
</tr>
<tr>
<td></td>
<td>11700</td>
<td>118</td>
<td>21.0</td>
</tr>
<tr>
<td></td>
<td>12400</td>
<td>121</td>
<td>20.5</td>
</tr>
<tr>
<td></td>
<td>13200</td>
<td>125</td>
<td>20.5</td>
</tr>
</tbody>
</table>
2. The maximum height of the tank shell must not exceed the "Design Shell Height" listed in Table 2.1 when the vehicle is fully loaded, with the trailer's fifth wheel coupler plate placed at a height of 50 inches.

3. When subjected to a tilt-table test, the tractor-semi-trailer combination must achieve a "Tilt-Table Rollover Angle" equal to or in excess of the value specified for that specific configuration (see Table 2.1).

4. No more than one trailer axle may be outfitted with a "lift-axle" type suspension. The remaining axles must act to continuously support the trailer and its load.

5. Devices used to cover manholes or inspection ports must be capable of withstanding the forces caused by an internal pressure of 50 psi, applied and held at least 50 milliseconds, and then released to 2 psi, without having any residual venting of fluid during the subsequent 2 psi condition.

2.2 Discussion of the Proposed Legislation

2.2.1 Vehicle Design Considerations. The proposed legislation contains the following features influencing vehicle design:

1. Only tractor-semitrailer configurations are included. Although many vehicle combinations (e.g., double trailers) were considered in the study, a tractor-semitrailer appears to offer the greatest level of safety since (a) its stability is inherently good and (b) it is a much simpler configuration to specify and thus much more likely to yield the minimum desired performance despite future design innovation. (We should note that certain "B-train" doubles, comprising a tractor-semi-semi configuration, offer high levels of safety quality when built in combination lengths of 65 feet and longer. However, the need for a close specification of hitching mechanisms seems to make such a vehicle impractical for regulation and enforcement by a jurisdiction with limited resources such as the State of Michigan.)
2. The proposed legislation permits four different semitrailer configurations ranging in tank capacity from 10,200 gallons to 13,200 gallons. Alternative tank capacities are proposed so as to permit latitude in transport operations. The alternative units all offer profound improvements in safety performance over conventional equipment, with the larger vehicles offering the highest safety levels while also providing the greatest economies in energy consumption and overall transport costs.

Further, the recommendation cites 9,000 gallons as the "dividing line" above which the new legislation would apply, thereby avoiding conflict with the variety of tank vehicles below 9,000 gallons which are used in interstate commerce. Since the great bulk of flammable fuels transportation in Michigan involves intrastate trucking operations, however, it is expected that the economic incentives afforded by larger capacity vehicles will lead to their popular usage within the State.

3. For each semitrailer configuration permitted, axle sets are located according to current Michigan road-use laws. In the fully loaded condition, the tractor steering axle carries 14,000 lbs, the tractor drive axle tandem carries 32,000 lbs and each close-spaced trailer axle is loaded to 13,000 lbs. In the case of the 12,400-gallon tanker, a single "spread" axle is also employed, carrying 18,000 lbs.

4. For each configuration, constraints are placed on the fluid-carrying capacity of the tank and on the maximum height of the tank shell (excluding the protective rails on the top of the tank). The tank volume constraint provides that the highest reasonable fluid volume is carried, removing the motive for reducing trailer weight to increase payload. The tank shell height constraint assures efficient "packaging" so as to minimize the height of the center of gravity and thereby maximize rollover stability. The tank capacity and shell height constraints can be achieved, in practice, by means of a design in which the tank incorporates a "drop" (i.e., deeper cross section) aft of the fifth wheel coupler area, as shown in Figure 2.1.
Figure 2.1. Side view of the largest Advanced Michigan Tanker, showing example drop section and the rear shell dimension that is common to all four configurations.
5. The overall rollover stability of the unit is established by a tilt-table performance test. As shown in Figure 2.2, the tilt-table test involves the mounting of a fully loaded vehicle on a plane surface which is slowly inclined until the vehicle becomes unstable in roll. (The vehicle is tethered to prevent actual rollover.) The angle corresponding to a static rollover condition is defined as the tilt-table performance measure. The static rollover condition is reached when, with no further increase in table angle, the vehicle continues to increase its roll angle unless restrained by a tether.

To meet the indicated requirements, suspension stiffnesses, spring lash, and tire stiffnesses must be within design bounds representing good practice.* If an air-lift axle is employed, the test is conducted with that axle down. The specification permits only one lift axle so as to minimize the roll-destabilizing effect that prevails when such axles are "lifted" off the roadway.

It is proposed that the State build and operate a tilt-table device for use in compliance testing, although it is conceivable that a tilt-table facility could become available for this purpose through other means. The tilt-table approach has been selected over the alternative of specifying the desired set of suspension and tire characteristics—an approach that would severely constrain design options and which would be very difficult to enforce. The proposed tilt-table test is discussed more fully in Section 8.

*One example of a vehicle design which would provide the specified level of tilt-table performance includes the following suspension features:

- The tires on each trailer axle are mounted so that the overall outside width (measured across the tires) is 101-1/2 inches.
- The lateral spread between the centerlines of the springs on leaf-spring-suspended trailer axles is 44 inches.
- The leaf spring assemblies exhibit 1/2-inch of free play, or clearance, in their vertical travel from compression to tension.
Figure 2.2 Tilt-table test concept upon which roll stability specification is based.
6. Although not explicitly required, trailers able to meet the tilt-table specification while otherwise employing conventional hardware, will be 102 inches in nominal width. That is, under special provision for tankers carrying flammable liquids, the maximum width of the tank and the spread across the outside of the trailer tires will be permitted to be 102 inches rather than the conventional dimension of 96 inches.

It is appreciated that allowing a 102-inch width dimension for tank vehicles constitutes a significant change from the status quo, and that a 102-inch width is authorized in the State currently only under special permit. Nevertheless, the recommendation is made with the firm conviction that, for heavy tankers carrying hazardous liquids, improvement in roll stability is the key safety issue. The proposed 102-inch width accounts for the major portion of the increase achieved in roll stability and is second only to tank capacity as a vehicle feature helping to achieve the reduced level of risk afforded by the recommended vehicles. (In section 2.2.2, the reduction in rollover risks to be expected with 102-inch wide tankers is examined in comparison to conventional 96-inch wide tankers.)

There is also a considerable body of evidence to show that the 102-inch width dimension introduces no peculiar safety problems of its own. Extensive study of the question in behalf of the current federal allowance of 102-inch wide buses on the interstate system showed no significant hazards associated with the greater width [1]. It should be noted that all of the provinces of Canada allow 102-inch wide commercial vehicles to operate, although Canadian roads are built to geometric standards that are not essentially different from those in Michigan.

- Trailer leaf springs exhibit a stiffness level which averages 10,000 lb/in per spring over the normal compression range and 4,000 lb/in after traveling through the free play into the tension range.

- A typical line-haul tractor, 96 inches in width, is used for which the spring rates on the tractor tandem axles average 6,000 lb/in per spring over the normal compression range and 4,000 lb/in after traveling through the free play into the tension range.

- The leading trailer axle incorporates an air suspension which provides a roll stiffness level of 118,000 in-lb/deg.
7. The recommendation contains no statement regarding tank shell material, although the higher abrasion resistance and the ability to withstand the temperatures of a gasoline fire argue strongly for a steel tank shell over the other likely alternative, aluminum. The draft recommendation submitted to outside parties for review did specify steel as the shell material, but an industry respondent providing feedback on the recommendation pointed out that certain transported fluids having a low flash point must be delivered in aluminum (or presumably stainless steel) vessels for the sake of minimizing the contamination of the liquid.

Further study of the subject of shell material revealed that the great majority of prospective purchasers of "Advanced Michigan Tankers" would have no economic incentive for choosing the more expensive aluminum construction and thus would naturally opt for steel shells just as has been the case for the majority of the larger tank trailers which have been used to transport flammable liquids in Michigan in the past. Thus, it was concluded that a requirement for steel as the tank shell material would only serve to hamper certain areas of commerce while otherwise achieving little additional safety benefit than would occur normally due to the inherent economic incentive to employ steel.

8. A requirement is placed upon the pressure retention capacity of manhole covers and inspection ports so that these devices will withstand the pressure pulse that is produced in a rollover impact. The primary purpose of this requirement is to prevent the wholesale failure and dislodging of manhole covers in rollover accidents. Secondarily, the requirement assures that the momentary relief action of venting devices installed on such covers will not be followed by a sustained leaking of the assembly when the pressure is reduced below the 3 psi vent setting. Field survey data and full-scale experiments supporting the manhole cover specification are presented in Section 5.

9. Regarding the economic significance of the recommendation, it is expected that the larger capacity vehicles will be highly attractive for minimizing transport costs. A first-order estimate of the economic advantage afforded by the larger tank volumes has been made.
with the aid of information obtained from one of Michigan's larger for-hire carriers of petroleum products. Given an estimated .15 cents per gallon reduction in transportation costs for a 13,200-gallon tank volume, as opposed to a 9,000-gallon tank volume, the larger vehicle would yield a net reduction in costs to its operator of approximately $15,000 per year. This figure is based upon the following specifications:

- 0.15 cents per gallon cost reduction in transportation costs
- 13,200 gallons transported per trip
- 3.6 trips per day [2]
- 210 days of operation per year

A major tank vehicle manufacturer has estimated that the new purchase price of the recommended six-axle, 13,200-gallon trailer will be approximately $30,000 more than the price of conventional 9,000-gallon tankers that are manufactured in large numbers. Accordingly, the larger vehicle would pay for itself in a rather short time in comparison with the expected 15- to 20-year life of the trailer.

10. Regarding the energy efficiency of flammable liquids transportation, it is estimated that the approximate ten million gallons of diesel fuel which are consumed in transporting 5.1 billion gallons of gasoline in Michigan each year would be reduced markedly by adoption of a fleet of tankers having the larger recommended capacities in comparison to a fleet of 9,000-gallon tankers. The fuel consumption of a tractor pulling a 13,200-gallon tanker, expressed in gallons of diesel fuel consumed per gallon of product delivered, is expected to be at least 20 percent less than the consumption of a suitably sized tractor pulling a 9,000-gallon tanker.

2.2.2 Safety Considerations. The safety analysis leading to the proposed recommendation can be summarized as follows:
a) The special concern for the safety of tankers transporting flammable fuels derives from the fire threat.

b) Since rollover is clearly the dominant means by which fires are produced, an improvement in those vehicle features which influence rollover resistance is central to minimizing the fire threat.

c) The accident data analyzed in this study show that the rollover of heavy tractor-semitrailers is:

1) overwhelmingly a single-vehicle accident event— that is, the combination vehicle rolls over without having impacted any other vehicle, and

2) the incidence of such rollovers is profoundly influenced by the inherent roll stability of the vehicle. Shown in Figure 2.3 is a plot of the percent of single-vehicle accidents in which tractor-semitrailers roll over versus the rollover threshold of each vehicle. It has been predicted that the recommended tanker configurations would experience from 64 to 72 percent of the rollover frequency (i.e., rollovers per accident) of the conventional MC-306 tanker used in most other states to carry gasoline.

d) Since the total number of rollovers in a given year will depend on the total number of accidents as well as on the likelihood of rollover given an accident, it is important that total exposure be kept low by minimizing the total vehicle miles being traveled. Vehicle miles are reduced when larger capacity tanks are employed. But with larger capacities, the tank center of gravity will be located at a greater height. The four recommended vehicles embody tank capacities and rollover thresholds which result in virtually identical estimates in the total number of rollovers in the fleet per year, as shown in Figure 2.4.*

The data suggest that each of the four vehicles represents very nearly

*That is, if the entire Michigan gasoline transportation mission was served by a fleet comprised exclusively of the vehicle shown, the number of rollovers per year would be approximately as indicated.
Figure 2.3. Percent of single-vehicle accidents in which rollover occurs as a function of the vehicle's inherent rollover threshold, in g's. (This figure is based upon 21,000 accident cases reported to the BMCS.)
Figure 2.4. Total number of rollovers to be expected in one year if the entire bulk transportation of gasoline in Michigan were accomplished using a fleet comprised exclusively of each vehicle type shown.
the same fire threat as the other, although any one of the four would yield at least a 48 percent reduction in total rollovers per year compared to the conventional MC-306 tanker, as indicated at the top of the figure.

As mentioned previously, the 102-inch width of the recommended tankers accounts for a large portion of the reduction in rollover risk. Shown in Table 2.2 is the contrast in rollover thresholds and the annual risk of rollover applying to 96-inch and 102-inch wide versions of each of the four recommended tankers. We see that the proposed 6 percent increase in width yields, by itself, a 20 percent reduction in the incidence of rollover.

e) The total number of accidents of all kinds (i.e., not simply rollover accidents) should, of course, be directly reduced by additional tank capacity since exposure in vehicle miles is virtually the only issue. Among the recommended vehicles, for example, the 10,200-gallon tanker would be expected to yield approximately 30 percent more total accidents than would the 13,200-gallon vehicle. Thus, although the 10,200- and 13,200-gallon vehicles yield nearly identical predictions of total rollovers, the larger vehicle appears to offer a considerably higher level of overall safety due to the fewer total number of accidents of any kind.

f) The additional risk posed by the quantity of flammable liquid available for involvement in a single fire is not thought to be significant given the alternative vehicle sizes being considered. The consensus of the fire-fighting community seems to be that the threat to life posed by large gasoline fires is not dependent upon tank size, when tank capacity exceeds a few thousand gallons. As stated in the manual of the National Fire Protection Association (NFPA),

"The danger from a gasoline fire is not in direct proportion to the quantity of gasoline. One thousand gallons of gasoline released to burn in the street would be sufficient to kill everyone trapped in the flames. Four thousand gallons, while presumably covering a larger area, would certainly not be expected to cause four times the number of fatalities. Reasoning on this basis, the NFPA Standards have not recommended any limitation on the maximum size of tank trucks."
Table 2.2. Comparison of the Rollover Thresholds and Total Annual Rollover Risks Posed by "Advanced Tankers" of 96-Inch Versus 102-Inch Width.

<table>
<thead>
<tr>
<th>SCHEMATIC DIAGRAM OF SEMI TRAILERS</th>
<th>ROLLOVER THRESHOLD, g's</th>
<th>EXPECTED NO OF ROLLOVERS/YEAR</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>96&quot; Wide Trailer</td>
<td>102&quot; Wide Trailer</td>
</tr>
<tr>
<td>![Diagram 1]</td>
<td>.38</td>
<td>.415</td>
</tr>
<tr>
<td>![Diagram 2]</td>
<td>.369</td>
<td>.406</td>
</tr>
<tr>
<td>![Diagram 3]</td>
<td>.357</td>
<td>.394</td>
</tr>
<tr>
<td>![Diagram 4]</td>
<td>.355</td>
<td>.393</td>
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</tbody>
</table>
g) The advantages which will accrue from the higher pressure containment specification for manhole covers appear to be very significant. Examination of 33 individual cases of rollover of heavy gasoline tankers in Michigan reveals that 23 vehicles suffered spillage of product, and 13 of the spills occurred due to failure of the manhole cover.

In each of four full-scale rollover tests conducted in HSRI's study, manhole covers of conventional design were blown completely off the vehicle. Upgrading such designs to withstand the specified pressure levels is expected to reduce the incidence of cover failures to simply that level deriving from improper maintenance. Analysis and experiment both reveal that the use of a non-failing manhole cover will not lead to a higher likelihood of rupture of the tank shell.

h) In summary, the recommended vehicles, if used exclusively to transport unpressurized flammable liquids in Michigan, would be expected to yield a total number of rollovers that would be approximately one-half of the rollovers which would be otherwise expected if conventional MC-306 tankers having a 9,000-gallon capacity become the common means for transporting gasoline in the State. The proposed improvements in the integrity of manhole covers should result in an even greater reduction in the number of fires.

2.3 Recommendation for a Proposed Retrofit Rule

It is proposed that a regulation be promulgated requiring the retrofitting of any tank vehicle in Michigan falling under Federal Regulation MC-306 to assure that manhole and inspection-port covers will not fail and release product in a rollover. The proposed rule should incorporate the following statement:

"Devices used to cover manholes and inspection ports must be shown to be capable of withstanding an internal pressure of at least 50 psi without impairing the product retention capability of the device."

The proposed retrofit requirement is based upon the observation that over half of the spillage of flammable product in rollover accidents in Michigan derives from manhole cover failure. HSRI's experiments (see Section 5.2) have shown that the failure which commonly
occurs is of a most simple type—namely, a clamping band fastening the cover plate to the tank becomes distorted under the internal pressure load such that the entire manhole-cover assembly comes off of the vehicle. A 16- to 20-inch diameter opening in the shell results, such that the contents of the tank compartment are released within a few minutes.

One simple retrofit could consist of installing a simple beam over the manhole cover—hinged at one end by a connection to one of the rollover-protective rails on the top of the tank, and latched at a connection attached to the other rail. The vehicle operator could simply unlatch the beam and swing it up to open the fill cover for top loading. Another simpler possibility might involve the use of a much stronger clamping band in place of the existing bands which hold the manhole cover to the tank.
3.0 ACCIDENT DATA ANALYSIS

The methods and results of the accident data analyses which have been conducted to clarify the problem of tanker accidents are presented below in order to predict the accident risks that will be posed by an advanced type of tanker configuration.

In Section 3.1, a data file compiled by the Michigan Fire Marshall's Office is reviewed with particular attention given to the incidence of rollover, fuel spillage, and fires. In Section 3.2, an analysis is presented covering data sorted from the computerized files of the Bureau of Motor Carrier Safety (BMCS) of the U.S. Department of Transportation. The BMCS file is used to determine a relationship between the involvement of tractor-semitrailers in rollover accidents and the inherent rollover limits exhibited by such vehicles. (The derived relationship is employed in Section 6.0 to predict the risk of rollover to be expected if the recommended tankers were to be placed in general service in Michigan. Rollover is of special interest, since the incidence of significant amounts of fluid spillage from tank vehicles derives almost exclusively from rollover events.) In Section 3.3, truck accident data gathered in the State of Michigan are briefly examined to establish the frequencies with which differing types of accidents occur involving tractor-semitrailers on each of various road types. (These results are employed in the prediction of tanker risks, Section 6.0, as a means of accounting for the peculiar accident exposures deriving from Michigan's traffic and Michigan's road system.) Finally, in Section 3.4, a brief review is presented of a research study which analyzed the risks posed by the transportation of gasoline in the U.S. Insofar as this study involved an examination of the tanker accident record, it is included here as a very pertinent reference.

3.1 State Fire Marshall Data

A rash of gasoline tanker accidents in 1977 prompted the Fire Marshall's Office of the Michigan Department of State Police to initiate a record of accidents and incidents involving tank vehicles hauling
hazardous cargo in Michigan. The records maintained by the Fire Marshall's Office include information on the mechanism causing spillage, the amount of spillage, cargo type, number of trailers, incidence of fire, etc. A sample accident report is shown in Figure 3.1. A total of 130 such accident reports (79 reports for 1978 and 51 for 1979) were obtained to produce the information tabulated in Appendix A.

Of the 130 tanker accidents tabulated in Appendix A, 21 involve single-bottom (tractor-semitrailer) gasoline tankers and 18 involve double-bottom gasoline tankers. Since only gasoline tanker accidents are of interest to this study, the discussion below focuses on these 39 single- and double-bottom tanker accident reports.

3.1.1 Gasoline Releases and Fires. Table 3.1 summarizes the incidence of gasoline releases and fires for the years 1978 and 1979. The table indicates that, of the 21 single-bottom accidents reported to the Fire Marshall's Office, 14 were overturns and 7 were non-overturn accidents. All of the 14 single-bottom tanker overturns resulted in the release of at least some quantity of gasoline. The amount of gasoline released in an overturn ranged from 5 to 13,000 gallons, with an average of 3,942 gallons. Of the 7 non-overturn accidents, there was only one significant release of gasoline—a 1,000-gallon release due to a tank shell rupture during a side-swipe accident.

In the case of double tankers, 13 of the reported accidents involved an overturn and 5 were non-overturn accidents. Gasoline was once again released in almost all of the overturns, ranging from 20 gallons to a total cargo loss of 17,000 gallons due to fire. The releases due to double tanker overturns averaged 5,408 gallons, which is about 1,500 gallons higher than the average for the single-bottom tankers. No gasoline was released during the 5 non-overturn accidents involving double tankers.

There were a total of 8 fires involving gasoline cargos, of which 3 involved tractor-semitrailers and 5 were connected with double tankers. All fires were as a result of an overturn accident. The data therefore indicate that 21 percent of all single-bottom tanker overturns resulted in a fire, while about 38 percent of all double-bottom tanker overturns resulted in a fire.
<table>
<thead>
<tr>
<th>Accident</th>
<th>Incident</th>
<th>Other</th>
<th>Product</th>
<th>Hazardous Materials Section</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spill</td>
<td>Leak</td>
<td>Amount</td>
<td>337 gal.</td>
<td>Repotted Clean Site</td>
</tr>
<tr>
<td>Date 1-17-79</td>
<td>Time 10:20 am</td>
<td>County</td>
<td>Isabella</td>
<td>Environmental Protection</td>
</tr>
<tr>
<td>St./Hwy</td>
<td>On Blanchard Rd. 3/10 mi. east of Rolland Rd. Blanchard may have shut one lane</td>
<td>to upright tanker</td>
<td>1 hr?</td>
<td></td>
</tr>
<tr>
<td>Veh. Type</td>
<td>D.T.</td>
<td>S.B.</td>
<td>XXX</td>
<td>Other</td>
</tr>
<tr>
<td>Veh. Owner</td>
<td>Address</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Driver</td>
<td>Address</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>D.O.B.</td>
<td>2-23-40</td>
<td>Driving Exp.</td>
<td>Truck 15</td>
<td>F.L. 7</td>
</tr>
<tr>
<td>Injuries: Name</td>
<td>Name</td>
<td>Address</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Name</td>
<td>Address</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Name</td>
<td>Address</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Accident/Incident Remarks:
- Vehicle travelling west on Blanchard. Driver steered to right to avoid parked cars.
- On left side of road. Road narrowed due to snow drifts. Front tractor tire ran off road followed by semi-trailer causing tank to overturn onto side in snow bank.
- Back compartment filled with gasoline. Fuel Oil divided between 3 compartments.

### Cause:
- Pressure of gasoline on dome covers caused leak next to tank. No fuel oil leak.

### Fire Safety Violations:
- None contributing to cause. No on-the-scene inspection.

### Arrest:
- Name | Charge
- Name | Charge
- Reinspected By: 

Figure 3.1. Sample of accident reports maintained by the Fire Marshall's Office.
<table>
<thead>
<tr>
<th></th>
<th>Freeways</th>
<th>Highways</th>
<th>Other Roads</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Rural</td>
<td>Urban</td>
<td>Rural</td>
<td>Urban</td>
</tr>
<tr>
<td><strong>Single Bottoms</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>TOTAL NUMBER OF ACCIDENTS</strong></td>
<td>3</td>
<td>5</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td><strong>OVERTURNING ACCIDENTS</strong></td>
<td>1</td>
<td>3</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td><strong>RELEASE QTY. (gallons)</strong></td>
<td>5</td>
<td>9000, 8000, 2000</td>
<td>13000, 8000</td>
<td>200, 8200</td>
</tr>
<tr>
<td><strong>AVERAGE RELEASE</strong></td>
<td>5</td>
<td>5733</td>
<td>10500</td>
<td>4500</td>
</tr>
<tr>
<td><strong>CARGO FIRES</strong></td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td><strong>NON-OVERTURNING ACCIDENTS</strong></td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td><strong>RELEASES</strong></td>
<td>0, 30</td>
<td>0, 1000</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td><strong>AVERAGE RELEASE</strong></td>
<td>15</td>
<td>500</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td><strong>CARGO FIRES</strong></td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td><strong>Double Bottoms</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>TOTAL NUMBER OF ACCIDENTS</strong></td>
<td>6</td>
<td>2</td>
<td>7</td>
<td>0</td>
</tr>
<tr>
<td><strong>OVERTURNING ACCIDENTS</strong></td>
<td>5</td>
<td>0</td>
<td>6</td>
<td>0</td>
</tr>
<tr>
<td><strong>RELEASE QTY. (gallons)</strong></td>
<td>13300, 1000</td>
<td>5800, unknown, 4500</td>
<td>100, 20, 5500, 1600</td>
<td>4000, 2050</td>
</tr>
<tr>
<td><strong>AVERAGE RELEASE</strong></td>
<td>&gt;4920</td>
<td>3878</td>
<td>8515</td>
<td>5408</td>
</tr>
<tr>
<td><strong>CARGO FIRES</strong></td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td><strong>NON-OVERTURNING ACCIDENTS</strong></td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td><strong>RELEASES</strong></td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td><strong>CARGO FIRES</strong></td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>
3.1.2 Locations of Gasoline Releases and Fires. Gasoline tanker accidents in Michigan are aggregated by roadway category (viz., freeways, highways, and other roads) in Table 3.1. Based on the population of the city or township in which the accident occurred, the accidents are further classified into rural and urban accidents.

The data indicate that single-bottom tankers were involved in more overturns in urban areas than rural. Eight out of the 14 single-bottom tanker overturns were in urban areas. By contrast, none of the 13 double tanker rollovers were in urban areas. This difference in urban/rural rollover incidence distribution for these tankers can be explained by the fact that restrictions on the usage of double tankers has limited their use mainly to gasoline distribution in rural areas. The pattern of gasoline releases and fires follow those of overturns. Only 2 out of the 8 gasoline tanker fires took place in urban areas.

3.1.3 Cause of Tanker Overturns. The comments in the tanker accident reports were studied with the aim of determining the nature of the accidents which led to a tanker overturn. Table 3.2 classifies the single and double tanker overturns into single-vehicle accidents, collisions at right angles, frontal collisions in which the rear-end of a vehicle other than the tanker is impacted, head-on and side-swipe collisions. The data show that for both single and double tanker accidents, single-vehicle accidents are the major cause of overturns. Twenty-two out of the 27 rollovers (or 81 percent) occurred in single-vehicle accidents. With respect to collision events, frontal collisions are seen to cause the greatest number of overturns.

3.2 BMCS Data Findings

Rollover incidence data from the BMCS accident data file will be utilized below to establish a relationship between the rollover threshold of commercial vehicles and their rollover involvement. Such a relationship constitutes the key data resource for predicting the effects of various design changes on the rollover involvement of tank vehicles.
Table 3.2. GASOLINE TANKER OVERTURNS IN MICHIGAN

<table>
<thead>
<tr>
<th></th>
<th>SINGLE VEHICLE</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th>TOTAL</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Collision at Right Angle</td>
<td>Frontal Collision</td>
<td>Head on</td>
<td>Sideswipe</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1978</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SINGLE BOTTOM</td>
<td>4</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>5</td>
</tr>
<tr>
<td>DOUBLE BOTTOM</td>
<td>8</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>10</td>
</tr>
<tr>
<td>TOTAL</td>
<td>12</td>
<td>0</td>
<td>2</td>
<td>0</td>
<td>1</td>
<td>15</td>
</tr>
<tr>
<td>1979</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SINGLE BOTTOM</td>
<td>7</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>9</td>
</tr>
<tr>
<td>DOUBLE BOTTOM</td>
<td>3</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>3</td>
</tr>
<tr>
<td>TOTAL</td>
<td>10</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>12</td>
</tr>
<tr>
<td>1978 AND 1979 COMBINED</td>
<td>22</td>
<td>1</td>
<td>3</td>
<td>0</td>
<td>1</td>
<td>27</td>
</tr>
</tbody>
</table>

81% of rollovers due to single vehicle accidents
19% due to accidents involving collisions with other vehicles
3.2.1 Features of the BMCS Data File. The Bureau of Motor Carrier Safety accident file is a compilation of truck accident data reported to the Bureau by the commercial motor carriers. The BMCS data, though restricted mainly to interstate motor carrier accidents, contains about 30 to 50 percent of all major truck accidents which occur each year in the United States. An accident is considered reportable to BMCS if the accident resulted in:

1) a fatality,
2) bodily injury to a person who, as a result, received medical treatment away from the scene of the accident, or
3) total damage to property in excess of $2000.

The BMCS data file is one of the few accident data files which contain a detailed description of the trucks which are involved in accidents. Information pertaining to vehicle body type, commodity carried, number of axles on tractor, number of axles on the trailer, gross vehicle weight, etc., can be easily extracted from the data file. With regard to the use of the BMCS data for the purpose of analyzing the overturn rates of trucks, the main shortcoming is that those overturns which involve a collision of the truck with another vehicle are not identifiable in the data. The overturn incidents that can be analyzed using the BMCS data are therefore restricted only to those occurring in single-vehicle accidents. Nevertheless, other data sources have been utilized to establish that, of all rollovers of heavy tractor-semitrailers, approximately 80 percent occur in single-vehicle accidents. Accordingly, analysis of rollover relationships using BMCS data can be looked upon as addressing the dominant portion of the heavy truck rollover problem.

3.2.2 Derivation of a Relationship Between Rollover Threshold and Rollover Accident Involvement. In order to utilize the BMCS data file as a source of accident data illustrating a relationship between vehicle configuration and rollover involvement, the following method was employed:
1. A vehicle type was selected whose rollover threshold could be reasonably approximated, given the gross weight.

2. The BMCS file was sorted to identify the occurrence of rollover at each nominal level of gross weight for all vehicles of the selected type.

3. A scheme was determined for locating the nominal height at which the center of gravity of the payload would be placed in simulating the rollover performance of the selected type of vehicle. Using this c.g. height, then, the rollover threshold of the selected vehicle was calculated for each level of gross vehicle weight which had been covered in the BMCS file. The data were then plotted, illustrating the relationship between the steady rollover threshold and the percentage of rollovers actually occurring in single-vehicle accidents.

Taking each of these steps in turn, the method will be presented in the following discussion.

Selected Vehicle

The selected vehicle was the three-axle tractor, two-axle van-body semitrailer configuration. This vehicle type was seen as particularly suited for a rather generalized evaluation of rollover thresholds not only because it is, by far, the single most prevalent heavy combination vehicle in the U.S., but also because there is a high degree of uniformity in design parameters among vehicles in this category. Data compiled by the Truck Trailer Manufacturers Association [3], for example, shows that of a sampling of van-type semitrailers produced in model year 1978:

100 percent were, of course, 96 inches in outside width

99 percent were between 12 feet 6 inches and 14 feet in overall height (of these, 64 percent fell within the most popular range of heights, 13 feet to 13 feet 6 inches)
91 percent were between 40 feet and 47 feet in overall length. Additionally, it is known that the vast majority of these trailers employ four-spring type tandem suspensions for which representative spring stiffness data are available.

Because of the uniformity of design geometry, it is possible to make rather reliable estimates of certain average vehicle parameters influencing rollover threshold. Additionally, van semitrailers are most typically loaded to near their cubic capacity, making estimation of payload c.g. height feasible.

The tractor/van semitrailer combination was also attractive for the special purposes of this study since the nominal trailer lengths, suspension and tire characteristics, and even tractor-related properties are the same as those which would be found in tanker-semitrailer combinations having similar gross weight ratings.

**The Sorted BMCS File**

The BMCS file was found to contain the following number of total accidents involving three-axle tractors coupled to two-axle van-type semitrailers:

<table>
<thead>
<tr>
<th>Reporting Year</th>
<th>Total No. of Accidents</th>
</tr>
</thead>
<tbody>
<tr>
<td>1976</td>
<td>6134</td>
</tr>
<tr>
<td>1977</td>
<td>6633</td>
</tr>
<tr>
<td>1978</td>
<td>8353</td>
</tr>
</tbody>
</table>

The number of single-vehicle rollovers, single-vehicle accidents (of all types), and the percentage of single-vehicle accidents involving rollover are listed in Table 3.3 for each of the three reporting years and for each 2500-lb increment in gross vehicle weight. In this table we see a remarkably consistent increase in the percent rollover involvement with gross vehicle weight over all three years of the data record. At the top of the table are the data entries for empty or virtually empty vehicles, showing on the order of a 2-percent involvement in rollovers among single-vehicle accidents. At the bottom of the table
<table>
<thead>
<tr>
<th>GVW (Thous. Lbs)</th>
<th>1976</th>
<th>1977</th>
<th>1978</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>No. of SV OT</td>
<td>% of OT in SV Accid.</td>
<td>No. of SV OT</td>
<td>% of OT in SV Accid.</td>
</tr>
<tr>
<td>27.5 - 30</td>
<td>2</td>
<td>130</td>
<td>1.5</td>
<td>3</td>
</tr>
<tr>
<td>30 - 32.5</td>
<td>3</td>
<td>79</td>
<td>3.8</td>
<td>6</td>
</tr>
<tr>
<td>32.5 - 35</td>
<td>1</td>
<td>55</td>
<td>1.8</td>
<td>3</td>
</tr>
<tr>
<td>35 - 37.5</td>
<td>1</td>
<td>34</td>
<td>2.9</td>
<td>3</td>
</tr>
<tr>
<td>37.5 - 40</td>
<td>5</td>
<td>55</td>
<td>9.1</td>
<td>5</td>
</tr>
<tr>
<td>40 - 42.5</td>
<td>5</td>
<td>60</td>
<td>5.1</td>
<td>8</td>
</tr>
<tr>
<td>42.5 - 45</td>
<td>3</td>
<td>61</td>
<td>9.1</td>
<td>3</td>
</tr>
<tr>
<td>45 - 47.5</td>
<td>2</td>
<td>42</td>
<td>4.8</td>
<td>6</td>
</tr>
<tr>
<td>47.5 - 50</td>
<td>8</td>
<td>59</td>
<td>13.6</td>
<td>12</td>
</tr>
<tr>
<td>50 - 52.5</td>
<td>7</td>
<td>57</td>
<td>12.3</td>
<td>11</td>
</tr>
<tr>
<td>52.5 - 55</td>
<td>11</td>
<td>56</td>
<td>19.6</td>
<td>18</td>
</tr>
<tr>
<td>55 - 57.5</td>
<td>9</td>
<td>61</td>
<td>14.8</td>
<td>15</td>
</tr>
<tr>
<td>57.5 - 60</td>
<td>9</td>
<td>64</td>
<td>14.1</td>
<td>27</td>
</tr>
<tr>
<td>60 - 62.5</td>
<td>12</td>
<td>60</td>
<td>20</td>
<td>21</td>
</tr>
<tr>
<td>62.5 - 65</td>
<td>31</td>
<td>127</td>
<td>24.4</td>
<td>23</td>
</tr>
<tr>
<td>65 - 67.5</td>
<td>25</td>
<td>106</td>
<td>23.6</td>
<td>36</td>
</tr>
<tr>
<td>67.5 - 70</td>
<td>46</td>
<td>202</td>
<td>22.8</td>
<td>97</td>
</tr>
<tr>
<td>70 - 72.5</td>
<td>64</td>
<td>230</td>
<td>27.8</td>
<td>93</td>
</tr>
<tr>
<td>72.5 - 75</td>
<td>39</td>
<td>155</td>
<td>25.2</td>
<td>70</td>
</tr>
<tr>
<td>75 - 77.5</td>
<td>9</td>
<td>30</td>
<td>30</td>
<td>17</td>
</tr>
<tr>
<td>77.5 - 80</td>
<td>9</td>
<td>21</td>
<td>42.9</td>
<td>18</td>
</tr>
</tbody>
</table>
are data representing vehicles running at the maximum levels of gross weight allowed in most states, showing an approximate 37 percent incidence of rollovers among single-vehicle accidents.

**Location of Vehicle Center of Gravity Height**

The three-axle tractor and two-axle van semitrailer combination was represented in the analysis of rollover thresholds by means of the characterizing parameters shown in Figure 3.2. The figure shows values of sprung and unsprung weights which correspond to typical vehicles as well as heights of placement of the mass centers of each vehicle element. The placement of payload c.g. height in the trailer, however, is a crucial parameter which can vary over a substantial range of values. If a very dense material was loaded onto the trailer floor, for example, the payload c.g. would be located at 55 to 60 inches above the ground. On the other hand, if the trailer's cubic capacity was filled with a homogenous type of freight, the payload c.g. height would be at about 110 inches. For commonly mixed loads, even though the cubic capacity of the trailer may be filled, the payload c.g. is lowered by placing the denser freight on the bottom of the load.

Shown in Figure 3.3 is a plot of the rollover threshold of the tractor-van semitrailer combination versus gross vehicle weight for four different values of payload c.g. height. (The static roll plane model described in Section 4.1.3 was employed for generating the indicated curves.) It was desired that one such curve be selected for use, representing an average payload c.g. height with which to match rollover thresholds to the BMCS accident data.

The selection of the "appropriate" payload c.g. height was made by noting that one type of tractor-semitrailer represented in the BMCS file was of such a nature that its payload c.g. height and overall rollover threshold could be rather closely estimated. This vehicle was the three-axle tractor/two-axle semitrailer employing a tank for transporting hazardous liquids in bulk. In the fully loaded state (75,000 to 80,000 lb gross weight), this vehicle type shows 165 single-vehicle accidents over the years 1976, 1977, and 1978 in the BMCS file. Of these, 84
Figure 3.2. Parameters representative of a three-axle tractor and two-axle van semitrailer combination.
accidents (or 50.9 percent) involved rollover. This vehicle category is predominantly represented by petroleum and chemical tankers, all of which employ tank c.g. heights which fall within a narrow range of one another.

When such vehicles are operated in their fully loaded state, such that no fluid sloshing is present, their behavior characteristics will be virtually identical to those of the tractor-van semitrailer combination having the same rollover threshold. We assume, then, that such tank vehicles, being also involved in an interstate commerce type of application, should be experiencing rollovers at a rate which agrees with the pattern of rollover involvement of the tractor-van semitrailers in the BMCS file. Placing the rollover accident rate and computed rollover threshold value for the fully loaded tank vehicle on the plot of Figure 3.4, a selection was then made of that value of average payload c.g. height which gives the best extrapolated fit of the van trailer data to the tank trailer data point.

The analysis shows that the very tightly grouped van trailer data fall in line with the single tank trailer data point when a value of 80 inches is used for the average height of the payload c.g. in the three-axle tractor/two-axle van semitrailer combination. Further, we observe that this answer is a most reasonable one given that most van trailer loads are such that the trailer's full cubic capacity is utilized, but a large fraction of transport work done by the common carriers involves mixed loads which pull down the c.g. below the level achieved with homogenous freight. Additionally, the substantial fraction of transport miles covered by trailers with less than full cube loading also tends to moderate the payload c.g. height.

Figure 3.4 reveals that the dependence of rollover accident involvement upon the vehicle's rollover threshold, as loaded, is not only a monotonic relationship, but also illustrates, as averaged, a remarkably tight pattern of data. Most notably, we see that the relationship becomes very steep at the lower range of rollover threshold. We suggest that such a steep sensitivity is to be expected since the lowering of rollover threshold into this range brings the vehicle's performance limit
Figure 3.4. Relationship between rollover threshold and rollover accident involvement. (Based on BMCS accident data for the years 1976-78.)
into near proximity with normal levels of maneuvering acceleration. If a vehicle with a 0.1 g rollover threshold were driven normally, for example, it would be expected to suffer rollover every few miles (or in 100 percent of its single-vehicle accidents).

One question that was posed regarding the general applicability of the relationship shown in Figure 3.4 involved the matter of the predominance of travel on interstate-quality roads represented in the BMCS file. Since the BMCS has jurisdiction over interstate carriers only, a large fraction of the accidents represented in the file occurred on interstate and other divided highways for which the off-highway environment appears conspicuously less threatening to rollover than is the case for the typical design of non-divided highways.

In examining this question, we had hypothesized that divided, interstate-quality roads would show a more consistent sensitivity of rollover involvement to the level of the vehicle's rollover threshold since the roadside typically involves gradual slopes on shoulder and berm areas, thus permitting the generation of medium level lateral accelerations instead of the harsh "tripping" kinds of accelerations which might derive from the less "groomed" roadside features of undivided highways. "Tripping" accelerations would roll over virtually all vehicles, it was reasoned, while a more moderate distribution of acceleration conditions would tend to produce rollovers in relation to each vehicle's inherent rollover threshold. Thus, another screening of the BMCS file was done to produce a comparison of the rollover involvement versus rollover threshold relationships obtained for the selected tractor-semitrailer on divided and undivided highways, individually. As shown in Figure 3.5, no major distinctions can be made between the data applying to the two roadway types. Accordingly, it would seem that the rollover involvement/rollover threshold relationship is a rather basic characteristic which applies as a general predictor for vehicles of the generic type selected.

Moreover, the plot shown previously in Figure 3.4 has been employed in this study as a basis for predicting, in Section 6, the rollover risks posed by each of the recommended Advanced Michigan Tankers.
Figure 3.5. Comparison of the rollover involvement of tractor-semitrailers on divided and undivided highways.
3.3 Michigan File

Michigan truck accident data for 1978 were examined to identify the types of collisions involving tractor-semitrailers. For the purposes of this analysis, truck accidents have been classified into six basic categories, namely:

1) single vehicle
2) head on
3) rear end
4) side swipe
5) two vehicles colliding at an angle
6) multiple vehicle

We observe that the fraction of accidents which fall into each category is dependent on the type of roadway on which the accident occurs and the density of the traffic. Thus, the data revealing accident types have been divided according to roadway type and population density of the region of the accidents. Three types of roadways were considered, namely: (1) freeways, (2) U.S. and Michigan highways, and (3) county roads and city streets. Histograms depicting the fractional distribution of the type of collisions that occur on each of the three roadway types are shown in Figures 3.6, 3.7, and 3.8, respectively. In each figure, the fractional distributions of accident type are given for two population zones—populations of less than 5,000, which are considered to represent rural areas, and populations greater than 5,000, which are considered to represent an urban traffic environment.

From the point of view of tanker overturns, the accidents of greatest interest are the single-vehicle accidents. The highest percentage of single-vehicle accidents are seen to occur on rural freeways. Urbanized areas, conversely, show consistently lower levels of single-vehicle accidents.

The illustrated breakdown of accident data are employed in Section 6.4 for determining the overturn rates of candidate gasoline tanker configurations, given an estimate of the tanker miles traveled on the various respective road types and population zones.
ACCIDENTS ON INTERSTATE FREEWAYS

Figure 3.6
Figure 3.7
ACCIDENTS ON COUNTY ROADS & CITY STREETS

Figure 3.8
3.4 Review of a Study of Gasoline Transportation Risks

A comprehensive study of the risk of transporting gasoline by truck [4] was conducted by the Battelle Pacific Northwest Laboratory in 1978. This research will be briefly reviewed here insofar as it represents the most recent and relevant precursor to the study being reported. In the reference work, fatalities were used as the measure of the risk involved in transporting gasoline.

A two-stage risk model was used for evaluating risk. The first step involved the use of an elaborate "fault tree analysis" for the identification and calculation of the probabilities of each of the various mechanisms by which gasoline could be released into the environment. In the second step, the consequences of the release (in terms of fatalities) were evaluated using a gasoline dispersal and fire spread model. The population density and the weather pattern at the accident site were factored into the model of the environment. Risk was displayed using a "Risk Spectrum" which is a plot of the expected frequency of accidents (accidents/year) as a function of the number of fatalities which result from such accidents.

The risk analysis revealed that, in the year 1980, 55 fatalities should be expected nationwide from accidents involving gasoline trucks. Twenty-nine of these fatalities were expected to be as a direct result of the release of gasoline, and the rest from accident forces which are independent of the hazardous nature of the cargo. The probability of the occurrence of individual accidents which result in large numbers of fatalities was found to be relatively low. For example, accidents which result in 10 or more fatalities were expected to occur in the U.S. only once in about 45 years. In the following paragraphs, the gasoline "Release Mechanisms" and the "consequences of gasoline release" which were analyzed in the Battelle study will be briefly described.

3.4.1 Release Mechanisms. Several mechanisms by which accident forces can fail the integrity of a gasoline tank were identified in the study. A logical analysis of the sequence of events which lead to the failure of the tank was conducted using a fault tree analysis. Failure
mechanisms which result in the release of a significant amount of gasoline are listed in Table 3.4. The fraction of the payload which is released into the environment and the probability of release (given that an accident has occurred) are listed in the table for each of the failure mechanisms.

The probability values listed indicate that failure of tank walls due to puncture, abrasion, and impact account for more than 89 percent of the significant releases of gasoline. According to the Battelle study, release of gasoline through a failed manhole cover accounts for only 2 percent of all the gasoline releases that take place. Release of gasoline through a manhole cover was assumed to occur either due to: (1) a failure of the gasket material upon being exposed to a gasoline pool fire, or (2) due to normal deterioration, or (3) due to faults in assembly or manufacturing of the manhole cover.

(Analysis of gasoline tanker accidents in Michigan has revealed that manhole covers fail much more frequently than has been indicated in the Battelle study. Experiments, conducted as part of this study (see Section 4.3) have also shown that the internal pressure surge that occurs at the moment of impact in a tanker rollover can cause conventional manhole covers to be completely blown off even when in their "brand new" state. Thus, we are unable to reconcile the Michigan tanker accident experience and the confirming experiments with the data concerning tank failure mechanisms which were reported in Reference [4].)

3.4.2 Consequences of a Gasoline Release. In the Battelle study, the consequences of a gasoline release were divided into four categories, each of whose risks were evaluated independently. The total risk posed by release of gasoline was then determined by summing up the risks posed by each of these consequences.

The consequences that were studied covered the following scenarios:

1) A gasoline pool is formed by the release of gasoline. The pool catches fire and poses a danger to the vehicle occupant.

2) The gasoline pool fire causes secondary fires in adjacent buildings thereby posing a danger to the occupants of the building.
Table 3.4. Probability of Release and Release Fractions for Gasoline Tank Truck Failures.

<table>
<thead>
<tr>
<th>Release Mechanism</th>
<th>Release Fraction</th>
<th>Probability of Release During an Accident</th>
</tr>
</thead>
<tbody>
<tr>
<td>Failure of Tank Walls Due to Puncture</td>
<td>0.5</td>
<td>0.025</td>
</tr>
<tr>
<td>Failure of Tank Walls Due to Pressure</td>
<td>0.5</td>
<td>0.00000000092</td>
</tr>
<tr>
<td>Failure of Tank Walls Due to Abrasion</td>
<td>1.0</td>
<td>0.01042</td>
</tr>
<tr>
<td>Failure of Tank Walls Due to Impact</td>
<td>1.0</td>
<td>0.1157</td>
</tr>
<tr>
<td>Failure of Tank Walls Due to Fire</td>
<td>1.0</td>
<td>0.00016</td>
</tr>
<tr>
<td>Release from Faulty Pressure Relief Valve</td>
<td>0.35</td>
<td>0.00278</td>
</tr>
<tr>
<td>Failure of Relief Valve Due to Pressure</td>
<td>0.35</td>
<td>0.0007752</td>
</tr>
<tr>
<td>Failure of Outlet Valve Due to Fire</td>
<td>1.0</td>
<td>0.0016133</td>
</tr>
<tr>
<td>Failure of Outlet Valve from Other Causes</td>
<td>U* 0.5</td>
<td>0.0004664</td>
</tr>
<tr>
<td>Failure of Outlet Valve from Other Causes</td>
<td>OT* 0.35</td>
<td>0.0001166</td>
</tr>
<tr>
<td>Failure of Manhole Covers Due to Fire</td>
<td>1.0</td>
<td>0.00048</td>
</tr>
<tr>
<td>Failure of Manhole Covers From Other Causes</td>
<td>0.35</td>
<td>0.00086</td>
</tr>
</tbody>
</table>

*U - Upright, OT - Overturned
3) The gasoline tanker explodes and kills the occupants of all the vehicles involved in the accident.

4) The gasoline tanker explodes in an urban area and kills the occupants of buildings adjacent to the accident scene.

The estimated probabilities for the fatalities that can result from each of the four consequences are plotted in Figure 3.9. In this figure, the number of fatalities, n, per accident is plotted on the abscissa and the expected number of accidents per year in which n or more fatalities occur is plotted on the ordinate. An inspection of these risk predictions reveals that most of the accidents which result in one or two deaths are attributable to the first consequence, namely: death of vehicle occupants due to pool fires. Larger consequence accidents, which result in more than five fatalities, are mostly due to consequence four, which involves deaths in adjacent buildings due to explosion.

The contribution of consequences 2 and 3 to the overall risk of transporting gasoline can be seen to be negligible.

Moreover, the cited study served to provide a broad review of the various elements contributing to the risks of transporting gasoline by truck. Insofar as various aspects of the study's data and results did not agree with the Michigan tanker accident experience, however, we have taken another, simpler, approach to predicting risks for the recommended Advanced Michigan Tanker.
Figure 3.9. Risk spectrum for release of gasoline from tank truck accidents in 1980.
4.0 ANALYSIS OF THE DYNAMIC BEHAVIOR OF CANDIDATE VEHICLE CONFIGURATIONS

The principle task of the study involved mathematically-based analyses of the static and dynamic performance characteristics of candidate tank vehicle configurations. On the basis of performance characteristics, the list of vehicle types under consideration was reduced to the four configurations which have been recommended. The analysis task addressed three principle subjects, namely:

1) analysis of the yaw and roll behavior of a comprehensive set of candidate vehicles (presented in Section 4.1),
2) an examination of the sensitivity of vehicle roll stability to a number of basic design parameters which are common to virtually any configuration of tank vehicle (in Section 4.2), and
3) analysis of the influence of a sloshing liquid load on the roll stability of partially-loaded tankers (in Section 4.3).

4.1 Analysis of the Yaw and Roll Behavior of Candidate Vehicle Configurations

A set of candidate vehicles was selected and subsequently screened on the basis of yaw and roll performance measures which were defined. The assembly of parameter sets describing each of the candidate vehicles is presented in Section 4.1.1. In the following subsections, the candidate vehicles are evaluated on the basis of both static and dynamic response characteristics using various computerized simulation techniques. As each category of performance is discussed, the deficiencies associated with various vehicle configurations are cited, establishing the basis for later reduction of the "candidate" list to only those vehicles offering high levels of performance in all categories.

4.1.1 Candidate Vehicle Configurations. The vehicles evaluated in this study can be classified within two basic groups: (1) tractor-semitrailers and (2) double tankers of the tractor-semitrailer-semitrailer type.
(hereinafter referred to as the TSS configuration). Conventional doubles combinations equipped with a dolly and pintle hook type connection for the full trailer were ruled out since a preliminary analysis, as well as the experience gained from the Michigan double tanker study [2], indicated that the relatively short type of conventional double cannot achieve dynamic rollover immunity qualities which are comparable to those of either the tractor-semitrailer or the TSS configurations.

Schematic diagrams of the candidate tractor-semitrailer combinations are shown in Table 4.1. The vehicles shown in the table range in capacity from 8,090 gallons for a two-axle semitrailer to 16,150 gallons for an eight-axle arrangement. The tank length was limited to 45 feet in these designs. The location and loading pattern for the axles were configured to meet the existing Michigan laws.

The TSS combinations were configured in both the 59-foot and 65-foot overall length versions, both of which are permitted by the existing Michigan law. (The latter is currently being permitted only on specially designated highways.) The TSS configurations are shown in Table 4.2.

It was necessary to make several assumptions in the process of arriving at the final design of each of these vehicle configurations. Each assumption and the corresponding rationale will be discussed below.

Length and Wheelbase Considerations

One straightforward means of lowering the c.g. height of a tanker vehicle is by increasing its length. The tank length is limited by two constraints—(1) an overall length limit posed by road-use laws and (2) low-speed offtracking considerations which limit the wheelbase and hence the overall length of the tank.

Michigan's road-use laws limit the length of the semitrailer portion of a tractor-semitrailer combination to 45 feet.

A second length constraint derived from the position that the low-speed offtracking performance of the candidate tractor-semitrailer layouts would be equal to or better than that of a typical 8,800-gallon capacity tanker (which meets the MC306 specifications). By this latter constraint, semitrailer wheelbases were kept within 406 inches. (Trailer wheelbase is defined as the longitudinal distance from the fifth wheel
Candidate Tractor/Semitrailer Combinations

**TABLE 4.1**

<table>
<thead>
<tr>
<th>#</th>
<th>SCHEMATIC DIAGRAM</th>
<th>LOADED WEIGHT (lbs)</th>
<th>EMPTY WEIGHT (lbs)</th>
<th>PAYLOAD CAPACITY (gal)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td><img src="image1" alt="Diagram 1" /></td>
<td>78000</td>
<td>28670</td>
<td>8090</td>
</tr>
<tr>
<td>2a</td>
<td><img src="image2" alt="Diagram 2" /></td>
<td>85000</td>
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<td>2b</td>
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<tr>
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<td>111000</td>
<td>39570</td>
<td>11700</td>
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<tr>
<td>4b</td>
<td><img src="image7" alt="Diagram 7" /></td>
<td>116000</td>
<td>40360</td>
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</tr>
<tr>
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<td>43600</td>
<td>13180</td>
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<tr>
<td>5b</td>
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<td>44330</td>
<td>13880</td>
</tr>
<tr>
<td>6</td>
<td><img src="image10" alt="Diagram 10" /></td>
<td>137000</td>
<td>47510</td>
<td>14670</td>
</tr>
<tr>
<td>7</td>
<td><img src="image11" alt="Diagram 11" /></td>
<td>150000</td>
<td>51490</td>
<td>16150</td>
</tr>
</tbody>
</table>

*Load carried by the axle sets in the units of thousands of pounds.*
### TABLE 4.2

<table>
<thead>
<tr>
<th>#</th>
<th>SCHEMATIC DIAGRAM</th>
<th>LOADED WEIGHT (lbs)</th>
<th>EMPTY WEIGHT (lbs)</th>
<th>PAYLOAD CAPACITY (gallons)</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td><img src="image1.png" alt="Schematic Diagram" /></td>
<td>59' OVERALL LENGTH</td>
<td>104,000</td>
<td>39,160</td>
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<td>II</td>
<td><img src="image2.png" alt="Schematic Diagram" /></td>
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<td>117,000</td>
<td>43,190</td>
</tr>
<tr>
<td>III</td>
<td><img src="image3.png" alt="Schematic Diagram" /></td>
<td></td>
<td>124,000</td>
<td>44,090</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>#</th>
<th>SCHEMATIC DIAGRAM</th>
<th>LOADED WEIGHT (lbs)</th>
<th>EMPTY WEIGHT (lbs)</th>
<th>PAYLOAD CAPACITY (gallons)</th>
</tr>
</thead>
<tbody>
<tr>
<td>IV</td>
<td><img src="image4.png" alt="Schematic Diagram" /></td>
<td>65' OVERALL LENGTH</td>
<td>117,000</td>
<td>43,190</td>
</tr>
<tr>
<td>V</td>
<td><img src="image5.png" alt="Schematic Diagram" /></td>
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<td>124,000</td>
<td>44,090</td>
</tr>
<tr>
<td>VI</td>
<td><img src="image6.png" alt="Schematic Diagram" /></td>
<td></td>
<td>130,000</td>
<td>47,100</td>
</tr>
<tr>
<td>VII</td>
<td><img src="image7.png" alt="Schematic Diagram" /></td>
<td></td>
<td>137,000</td>
<td>48,120</td>
</tr>
</tbody>
</table>

* Load carried by the axle set in the units of thousands of pounds.
to the midpoint of the semitrailer axles.) For semitrailers equipped with more than two axles, the axles were configured such that the wheelbase would be less than or equal to 406 inches (see Fig. 4.1), even when the foremost semitrailer axle was considered to be lifted up, as with an air-lift, air-suspended axle.

The tank lengths on the first three semitrailer layouts (#1-#2b) were limited by the wheelbase constraint, while the tank length of the last eight configurations (#3a-#7) were limited by the overall length limit of 45 feet.

All of the candidate TSS configurations had low-speed offtracking qualities which were superior to the 8,800-gallon MC306 tanker. The 59-foot and 65-foot versions of the double tankers were therefore laid out by making full use of their respective overall length limits.

**Tank Cross-Section Geometry**

Improvements in rollover threshold can be achieved by utilizing tank cross-sectional profiles which lower the overall height of the vehicle. The tank cross-section which was used for calculating the cross-sectional area and c.g. heights of the candidate vehicles is shown in Figure 4.2. The radius of the tank shell was set at 89 inches for the top, bottom and the sides. The blend radius was assumed to be 15 inches. A more complete discussion of tank cross-section geometry is included in Section 4.2.1. A computer program which was developed for the purpose of computing tank cross-sectional areas and axle layouts of the tankers is described in Appendix E.

**Tank Shell Material and Empty Vehicle Weight**

The tank shell was assumed to be 10-gauge HSLA (high strength, low alloy) steel. Based on data describing several steel tanks manufactured by the Fruehauf Corporation, the shell was estimated to weigh 0.98 pounds per gallon of shell volume. Each trailer axle was assumed to weigh 1500 lb. The combined weight of the under-construction and suspension springs was estimated to be 900 lb/axle.
Figure 4.1. Changes in wheelbase produced by a lifting up of the foremost semitrailer axle.
Figure 4.2. Tank cross-section geometry for the Advanced Michigan Tanker.
Arrangement for Connecting the Semitrailers of the TSS Configurations

For TSS configurations, the dolly and pintle hook arrangement of conventional-style doubles is replaced by an arrangement which is shown in Figure 4.3. As seen in the figure, a shelf-like element is fastened to the lead semitrailer and is constrained to pitch about the axis A-A with respect to this semitrailer. A conventional fifth wheel is mounted on this element and is connected to the second semitrailer. The static vertical load acting on this fifth wheel arrangement is carried completely by the axles under the shelf, such that no vertical load is transmitted to the first semitrailer through the hinge AA.

Since the hinge connection between the first semitrailer and the shelf is virtually rigid in both roll and yaw, the shelf element is considered to be an integral portion of the semitrailer, as represented in a yaw/roll simulation model to be discussed later.

Tank Bottom Height

The bottom height of the tank is limited by (1) the height of the fifth wheel arrangement at the front of the trailer and (2) the height of the chassis at the rear.

Tractor fifth wheel height is typically around 50 inches above ground level. If a height of 6 inches is allowed for the structural members which are mounted at the bottom of the tank shell, the overall height of the tank bottom would be limited to 56 inches in the vicinity of the tractor fifth wheel. The bottom of the tank at the rear of the semitrailer was taken to be a minimum of 46-1/2 inches, on the basis of liaison with tank industry sources.

As shown in Figure 4.4, the bottom of the tank must be sloped slightly to the rear if the contents of the tanks are to be easily drained by gravity. In keeping with common industry practice, a slope of 5 inches over the entire length of the tank was assumed for the candidate vehicles. Maximum lowering of the tank center of gravity was achieved, given the various constraints, by use of a 4-1/2-inch drop section aft of the fifth wheel coupler area.
Figure 4.3. Arrangement for connecting the semitrailers of the TSS configurations.
In the case of the second semitrailer of the TSS configurations, a height of 54 inches above ground level was assumed for the fifth wheel plate and a bottom height of 60 inches above ground level for the front end of the tank shell. The bottom of the second semitrailer is assumed to drop to a height of 46-1/2 inches at the rear end. The side view of a TSS configuration is shown in Figure 4.5.

Dished Ends

All calculations were performed assuming that a uniform tank cross-section exists over each portion of the tank having a given section height. The presence of dished or contoured heads at the front and rear of the tank, however, serve to reduce the effective cross-sectional area at each end. This loss in shell volume was accounted for in the calculation of shell volume by simply subtracting 9 inches from the nominal length of the tank on each end.

Fifth Wheel Loads and Axle Loads - Tractor-Semitrailer

The tractor fifth wheel load for the tractor-semitrailer configuration was set at 31,000 lbs. Assuming a total tractor weight of 15,000 lbs, the loaded tractor-semitrailer produced a 14,000-lb axle load on the tractor front axle and 32,000 lbs on the tractor rear tandem. See Figure 4.6.

The semitrailer axles, which are assumed to be spaced 44 inches apart (in the longitudinal direction), are loaded to 13,000 lbs each, while the "spread" axles are located 108 inches apart and are loaded to 18,000 lbs.

Tractor-Semitrailer-Semitrailer Configurations

Four of the TSS configurations (#IIb, #IVb, #VI, #VII) were designed with a three-axle set (loaded to 39,000 lbs) on the first semitrailer. These configurations were assumed to carry a tractor fifth wheel load of 31,000 lbs, thereby producing the same load distribution for the tractor axles as that cited above for the tractor-semitrailer configuration.

The rest of the five TSS configurations (#I, #IIa, #III, #IVA, #V) were designed with two axles on the first semitrailer.
Figure 4.4. Tank bottom heights for the tractor-semitrailer configurations.

Figure 4.5. Tank bottom heights for the TSS combinations.
Since, in these cases, the axles on the lead semitrailer carry a total load of only 26,000 lbs, the tractor fifth wheel load was reduced to 24,000 lbs. The load distribution for the tractor axles of these five TSS configurations is shown in Figure 4.7.

4.1.2 Low-Speed Maneuverability. Good low-speed maneuverability was seen as an essential quality for a tanker transporting gasoline. Gasoline tankers need to travel through city streets, and also gain easy access to the storage tank filling ports at service stations. Indeed, excellent low-speed maneuverability had been one of the main reasons for the popularity of a double-bottom tanker configuration in Michigan. It was known from the outset, however, that high levels of maneuverability are typically gained at the expense of directional stability. Since a high premium was being placed, here, on vehicle stability, it was clear that poorer low-speed maneuverability would be attained than that afforded by the previously popular double-bottom tanker.

Two low-speed maneuvering properties of articulated vehicles were addressed in the study. These properties characterize (1) the low-speed offtracking obtained in a constant radius turn and (2) the lateral force needed at the tractor fifth wheel to sustain a steady turn at low forward speeds. Numerics based on these two maneuvering qualities are used to compare the candidate tractor-semitrailer and tractor-semitrailer-semitrailer configurations described in the preceding section.

In the discussion that follows, the maneuverability of articulated vehicles equipped with single axles (on each trailing unit) is first analyzed. Following this, the influence of multiple axles on low-speed maneuverability will be discussed.

Low-Speed Offtracking and Lateral Fifth Wheel Forces for Single-Axle Trailers

During low-speed maneuvers, trailer axles offtrack towards the center of the turn. That is, trailer axles will inscribe a path falling to the inside of the path taken by the tractor axles. The amount of offtracking is dependent not only on the length of the vehicle, but also
Figure 4.6. Tractor axle loads for a fifth wheel load of 31,000 lbs.

<table>
<thead>
<tr>
<th>Tractor</th>
<th>Load</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>7775 #</td>
<td>6225</td>
<td>14,000#</td>
</tr>
<tr>
<td>7225 #</td>
<td></td>
<td>32,000#</td>
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</tbody>
</table>

Figure 4.7. Tractor axle loads for a fifth wheel load of 24,000 lbs.

<table>
<thead>
<tr>
<th>Tractor</th>
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</thead>
<tbody>
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<td>7775 #</td>
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<td>12,000#</td>
</tr>
<tr>
<td>7225 #</td>
<td></td>
<td>27,000#</td>
</tr>
</tbody>
</table>
on the number of articulation points and the layout of the axles. Vehicles which exhibit large amounts of offtracking tend to be difficult to maneuver in situations where it is necessary to execute sharp turns around obstacles. Figure 4.8 illustrates the offtracking of a tractor-semitrailer and a tractor-semitrailer-semitrailer combination during a steady turn characterized by the path radius, $R_1$, of the tractor fifth wheel.

During low-speed maneuvers, the lateral acceleration levels are sufficiently low such that the D'Alembert forces in the lateral direction can be neglected. Hence, the sum of the lateral forces acting on the vehicle through the tire-road interface is zero during a low velocity steady turn. For the case where there are only single axles on each trailer, the lateral tire forces are statically determinate. Hence, the lateral tire force produced at each individual axle is zero. The tires therefore operate at zero sideslip, and the trajectory of the axles at steady state is perpendicular to their respective turn radius vectors. It follows, of course (for single-axle trailers), that no lateral force is needed at the tractor fifth wheel to sustain a steady turn at low forward velocities.

As shown in Figure 4.8, the offtracking during a steady turn can be computed from simple planar geometry. The radius of turn, $R_2$, of the semitrailer axle is given by the expression:

$$ R_2^2 = R_1^2 - x_1^2 $$

(4.1)

The radius of turn, $R_3$, of the rearmost axle of the TSS configuration is given by the expression:

$$ R_3^2 = R_1^2 - x_1^2 - x_2^2 + (b_1 - x_1)^2 $$

(4.2)

where $x_1$, $x_2$, and $b_1$ are illustrated in Figure 4.8. It can be seen from (4.1) and (4.2) that the amount of offtracking ($R_1 - R_2$) or ($R - R_3$) is dependent not only on the vehicle dimensions $x_1$, $x_2$, and $b$, but also on the radius of turn, $R_1$. 
TRACTOR SEMI-TRAILER COMBINATION

\[
R_2 = R_1^2 - X_1^2 \quad (a)
\]

\[
R_2' = R_2^2 + (b_1 - X_1)^2 \quad (b)
\]

\[
R_3^2 = R_2^2 - X_2^2 \quad (c)
\]

Combining (a), (b) and (c) we get

\[
R_3^2 = R_1^2 - X_1^2 - X_2^2 + (b_1 - X_1)^2
\]

TSS COMBINATION

Figure 4.8. Low-speed offtracking of tractor-semi trailer and TSS combinations.
To obtain a more generally descriptive term as an offtracking numeric, then, we shall work with the concept of "effective wheelbase" [5]. The effective wheelbase is independent of the turn radius and is defined as the wheelbase of a single-unit vehicle which produces the same amount of offtracking during a steady turn as the articulated vehicle under consideration. The effective wheelbase concept is very convenient when comparing vehicle configurations which differ in the number of articulation points and axle layouts. Taking the trajectory of the tractor fifth wheel as the reference radius, the effective wheelbase of the tractor-semitrailer and the tractor-semitrailer-semitrailer combinations are given by the expressions:

\[
\ell_{eq}^{TS} = x_1 
\]

\[
\ell_{eq}^{TSS} = \sqrt{x_1^2 + x_2^2 - (b_1 - x_1)^2} \tag{4.4}
\]

Equation (4.4) can be extended so as to be applicable for a vehicle with any number of trailers. The equivalent wheelbase of an articulated vehicle with \(n\) trailers is given by the expression:

\[
\ell_{eq}^{\text{n trailers}} = \sqrt{\sum_{i=1}^{n} x_i^2 - \sum_{i=1}^{n-1} (b_i - x_i)^2} \tag{4.5}
\]

We shall now discuss the effect of multiple axles on: (1) off-tracking and (2) the lateral force at the tractor fifth wheel for low-speed steady turns.

**Influence of Multiple Axles**

Tire sideslip angles cannot be assumed to be zero for a vehicle which is equipped with multiple trailer axles. During the low-speed steady turn, trailer tires operate at finite values of sideslip angle, and produce a net yawing moment which has to be counteracted by a lateral force at the tractor fifth wheel. Equations for the equivalent wheelbase and lateral fifth wheel force for a TSS combination equipped
with four axles on the first semitrailer and three axles on the second semitrailer will be derived here. A plan view of the vehicle is shown in Figure 4.9. The equations can be easily expanded to a vehicle with any number of trailing units and any number of axles on each trailer.

The following assumptions were made in the process of deriving the equations:

1) The sideslip angles at the tires are small so that the assumption \( \tan \alpha = \alpha \) is valid.

2) The lateral forces generated at the tire-road interface are assumed to be linear functions of the sideslip angle at the tire, i.e., \( F = -C \cdot \alpha \), where \( F \) is the cornering force, \( C \) is the cornering stiffness, and \( \alpha \) is the slip angle.

3) The aligning moment generated at the tire-road interface is neglected.

4) The articulation angles are small such that the following approximations hold: \( \sin \gamma = \gamma \) and \( \cos \gamma = 1.0 \).

5) The track width of the vehicle is small compared to the radius of turn so that the sideslip angle is the same for all the tires on an axle.

6) The road surface is dry.

A double subscript notation is used for referencing the location and the slip angle at an axle. An axle with subscript \( ij \) denotes the \( j \)th axle on the \( i \)th trailer.

Referring to Figure 4.9, the slip angles at the trailer axles are given by the following equations.

\[
\alpha_{11} = -\tan^{-1} \left( \frac{x_1 - a_1}{R_2} \right) = - \frac{(x_1 - a_1)}{R_2} \quad (4.6)
\]

\[
\alpha_{12} = \tan^{-1} \left( \frac{x_1 - a_1 - \delta_{11}}{R_2} \right) = - \frac{(x_1 - a_1 - \delta_{11})}{R_2} \quad (4.7)
\]
Figure 4.9. Tire slip angles and lateral tire forces for a multi-axle TSS combination.
If the sum of the cornering stiffness of all the tires on axle $ij$ is $C_{ij}$, the lateral force at axle $ij$ is given by the equation

$$F_{ij} = -C_{ij}\alpha_{ij}$$

Taking the yaw moment equilibrium of the second trailer about its fifth wheel, we get:

$$F_{21}a_2 + F_{22}(a_2 + \delta_{21}) + F_{23}(a_2 + \delta_{21} + \delta_{22}) = 0$$

Substituting for the lateral tire forces in (4.14), we get:

$$C_{21} \cdot \frac{(x_2-a_2)}{R_3} + a_2 + C_{22} \cdot \frac{(x_2-a_2-\delta_{21})}{R_3} + C_{23} \cdot \frac{(x_2-a_2-\delta_{21}-\delta_{22})}{R_3} (a_2 + \delta_{21} + \delta_{22}) = 0$$

Upon solving for the wheelbase, $x_2$, of the second semitrailer, we get:

$$x_2 = \frac{C_{21} \cdot a_2 + C_{22}(a_2 + \delta_{21})^2 + C_{23}(a_2 + \delta_{21} + \delta_{22})^2}{C_{21}a_2 + C_{22}(a_2 + \delta_{21}) + C_{23}(a_2 + \delta_{21} + \delta_{22})}$$

Moreover, the lateral force at the fifth wheel of the second semitrailer is:
\[ F_{y_2} = F_{21} + F_{22} + F_{23} \]

\[ F_{y_2} = c_{21} \frac{(x_2-a_2)}{R_3} + c_{22} \frac{(x_2-a_2-\delta_{21})}{R_3} + c_{23} \frac{(x_2-a_2-\delta_{21}-\delta_{22})}{R_3} \quad (4.17) \]

We shall now solve for the wheelbase, \( x_1 \), of the first semitrailer and the lateral force at the tractor fifth wheel. Proceeding along the same lines as Equations (4.14), (4.15), and (4.16), we find the wheelbase of the first semitrailer to be

\[ x_1 = \frac{c_{11}a_1^2 + c_{12}(a_1+\delta_{11})^2 + c_{13}(a_1+\delta_{11}+\delta_{12})^2 + c_{14}(a_1+\delta_{11}+\delta_{12}+\delta_{13})^2 - F_{y_2}b_1R_2}{c_{11}a_1 + c_{12}(a_1+\delta_{11}) + c_{13}(a_1+\delta_{11}+\delta_{12}) + c_{14}(a_1+\delta_{11}+\delta_{12}+\delta_{13})} \quad (4.18) \]

and the lateral force at the tractor's fifth wheel is given by the expression:

\[ F_{y_1} = F_{11} + F_{12} + F_{13} + F_{14} + F_{y_2} \]
\[ = c_{11} \frac{(x_1-a_1)}{R_2} + c_{12} \frac{(x_1-a_1-\delta_{11})}{R_2} + c_{13} \frac{(x_1-a_1-\delta_{11}-\delta_{12})}{R_2} \]
\[ + c_{14} \frac{(x_1-a_1-\delta_{11}-\delta_{12}-\delta_{13})}{R_2} + c_{21} \frac{(x_2-a_2)}{R_3} + c_{22} \frac{(x_2-a_2-\delta_{21})}{R_3} \]
\[ + c_{23} \frac{(x_2-a_2-\delta_{21}-\delta_{22})}{R_3} \quad (4.19) \]

The equivalent wheelbase of the multiaxle tractor-semitrailer-semitrailer combination can be obtained by substituting the expressions (4.16) and (4.18) (for the wheelbases \( x_1 \) and \( x_2 \)) in Equation (4.4). The effective wheelbase calculations for vehicle combinations which differ from the one considered here can be performed by suitably modifying Equations (4.16) and (4.18).

Equation (4.19) indicates that the lateral fifth wheel force is inversely related to the radius of the turn. Because of the small angle assumption involved in deriving the above equations, the analysis is not
valid for turns of very small radius during which the tire slip angles are large. At the large slip angles which are encountered in small radius turns, the lateral forces generated at the tire-road interface tend to saturate and depart considerably from the linear sideslip angle-lateral force relationship that was assumed in deriving the equation. For turns which are 100 feet in radius and above, the lateral fifth wheel force predictions based on Equation (4.19) will be fairly accurate.

Results

Low-Speed Offtracking. The calculated values for the effective wheelbase of the candidate vehicle configurations are plotted in Figure 4.10. The figure portrays the effective wheelbase as a function of the payload volume of the vehicles. For the sake of comparison, we have also plotted the effective wheelbases of the 8800-gallon capacity tractor-semitrailer which meets the MC306 specifications, and a 55-foot Michigan double tanker in the conventional (dolly and pintle hook) arrangement and the modified (rigidized pintle hook) arrangement. The effective wheelbases of the tractor-semitrailer configurations are shown in each of two conditions, namely, (1) with all of the semitrailer axles on the ground and (2) with the foremost semitrailer axle (which is presumed to be liftable) in the raised position.

The following observations can be made from the results of the offtracking calculations:

1. None of the candidate vehicles are seen to exhibit effective wheelbase lengths which are larger than that of the reference MC306 tanker. Therefore, from the point of view of slow-speed offtracking, all of the candidate vehicles are at least as good or better than the typical MC306 gasoline tankers.

2. The effective wheelbases of the 65-foot TSS combinations are not significantly smaller than those of the tractor-semitrailer combination. Therefore, if low-speed offtracking qualities were to be improved beyond those attained by the candidate tractor-semitrailers, TSS
Figure 4.10. Effective wheelbase of the candidate vehicle configuration
combinations would only become attractive at overall lengths shorter than 65 feet.

3. None of the candidate vehicles have offtracking qualities which are comparable to those of the 55-foot Michigan double tanker.

Lateral Fifth Wheel Force. A semitrailer having multiple axles will only proceed in a curved path if a side force is produced by the tractor tires and reacted through the fifth wheel coupling. Since this force tends to produce a yaw instability leading toward jackknife of the tractor, the lateral fifth wheel force can be looked upon as a measure of a non-quality, a degrading characteristic which is worse with trailers having more fixed axles in a row. The lateral fifth wheel force which is needed to negotiate a turn is dependent on the turn radius. Values of fifth wheel force for comparing all of the candidate vehicles were calculated using a constant turn radius of 400 feet. The lateral fifth wheel force requirement for the candidate vehicle configurations is plotted in Figure 4.11 with the payload volume as the abscissa and the lateral fifth wheel force as the ordinate. The lateral force levels for the reference 8800-gallon MC306 tractor-semitrailer and the 55-foot Michigan double-bottom tanker are also shown in the figure.

The lateral force requirement for the tractor-semitrailer combination is shown again for two operating conditions: (1) with all of the axles in contact with the road surface and (2) with the foremost semitrailer axle in the raised position. The lateral fifth wheel force requirement for the tractor-semitrailer combinations can be seen to be very sensitive to axle number accompanying payload volume. For example, by increasing the payload capacity from that of the largest recommended vehicle, the 13,200-gallon configuration (with six semitrailer axles), to a capacity of 16,150 gallons (having eight semitrailer axles), the lateral fifth wheel force shows an increase of almost 250 percent.

When the semitrailers that are designed with no spread axles are operated with one front axle in the raised position, the lateral fifth wheel force is seen to be reduced by 40 to 50 percent. The reduction is
Figure 4.11. Lateral fifth wheel force requirements for the candidate vehicle configurations.

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seen to be even greater for the semitrailer configurations equipped with a spread axle (#2b, #3b, #4b, and #5b).

For capacities below 15,000 gallons, the TSS combinations exhibit lateral fifth wheel force requirements that are only slightly lower than those of the tractor-semitrailer combinations which are operated with their foremost trailer axles in the raised position. However, for the largest capacity, eleven-axle vehicle, the 65-foot TSS combination needs a lateral force which is only 45 percent of that of the corresponding tractor-semitrailer combination with its front axle in the lifted position.

4.1.3 Steady Turning Rollover Thresholds of Candidate Vehicles. The steady turning rollover threshold of a vehicle plays an important role in determining the likelihood that either maneuvering- or accident-induced forces can cause the vehicle to roll over. Analysis of the BMCS accident data file has clearly shown the close correlation between the steady turning rollover threshold of a vehicle and its rollover involvement. In this section, we shall first describe a roll plane model which was used for calculating the steady turning rollover thresholds of the candidate vehicles. Next, the computed value of the rollover thresholds for the candidate tractor-semitrailer and TSS combination will be presented.

Static Roll Model

The static roll model was developed for the purpose of estimating the rollover thresholds of the candidate vehicle configurations. Results of earlier investigations by Isermann [6] and Gillespie, et al. [7] served as a basis for the development of the static roll model. The formulating equations, as well as a computer program useful for estimating rollover thresholds, is presented in Appendix B. The discussion in this section is therefore restricted to a description of the essential features of the model.

Features of the model and the assumptions made in the process of deriving the underlying equations are listed below.
1. The vehicle is assumed to be effectively rigid in torsion. The structural compliance of the tractor and trailer sprung masses are therefore neglected and the sprung masses are lumped together and represented by a single sprung mass in the roll plane.

2. In order to simplify the calculations, axles with similar suspension properties are grouped together such that a tractor-semi trailer is represented by a set of three composite axles. Figure 4.12 shows the side view of an example tractor-semi trailer, as represented in the roll model. The composite axles are:
   a) tractor front axle,
   b) tractor rear axles (either a single axle or a tandem) combined and represented by one axle, and
   c) all trailer axles, combined and represented as one axle.

3. The articulation angles are small so that the effect of articulation angle on the rollover threshold can be neglected.

4. Figure 4.13 shows the representation of axles and suspensions in the roll plane model. The relative roll motion between the sprung mass and the axles is assumed to take place about roll centers which are at fixed distances beneath the sprung mass. The suspension springs are assumed to remain parallel to the $k_{ui}$ axes of the axles and transmit only compressive or tensile forces.

   The roll centers are permitted to slide freely (with respect to the axles) along the $k_{ui}$ axes. All axle forces which act in a direction parallel to the $k_{ui}$ are taken up by the suspension springs, while all axle forces along the $j_{ui}$ axes are assumed to act through the roll center, $R_i$. 
Figure 4.12. Representation of the axles of a tractor-semi-trailer in the static roll plane model.
Figure 4.13. Representation of the axles and suspensions in the static roll plane model.
5. Suspension nonlinearities such as backlash and progressively hardening suspension springs are represented by a tabular load-deflection input format. The suspension forces and the spring rates at any given deflection are then compared by linear interpolation. Figure 4.14 shows the representation of a suspension spring in the roll model.

6. The total vertical load carried by each composite axle is assumed to remain constant during the rollover process. In order to accommodate any pitching motion that might take place during rollover, the sprung mass is permitted to take up different vertical deflections at each of the three axle locations.

7. The vertical load carried by the tires is assumed to act through the midpoint of the tread width. As shown in Figure 4.15, the effect of camber angle and the effect of the lateral compliance of the tire tend to have opposing effects on the lateral translation of the centroid of the normal pressure distribution at the tire-road interface. Both of these effects are small and tend to cancel out. In order to keep the analysis simple, the lateral translation of the normal load is neglected.

8. The roll angles of the sprung mass and the axles are small, such that the small angle assumptions \( \sin(\phi) = \phi \) and \( \cos(\phi) = 1.0 \) hold.

Accuracy of Rollover Threshold Estimates

The rollover threshold values calculated using the static roll model were found to compare well with measurements made by Isermann [6] in Germany. Isermann measured the rollover thresholds of tank vehicles using a tilt-table arrangement. The rollover thresholds estimated using the static roll model and the measurements made by Isermann using the tilt-table arrangement are compared in Table 4.3 for four
Figure 4.14. Representation of suspension spring characteristics in the roll plane model.

Figure 4.15. The effect of lateral compliance and camber angle on the centroid of the normal pressure distribution at the tire/road interface.
Table 4.3. Comparison of Rollover Threshold Estimates with Tilt-Table Measurements Made By Isermann [6].

<table>
<thead>
<tr>
<th>Isermann Calculation</th>
<th>Tilt-Table Measurement*</th>
<th>Estimates Using Static Roll Model***</th>
<th>% Error</th>
<th>Loading Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.733</td>
<td>---**</td>
<td>0.747</td>
<td>+ 1.9</td>
<td></td>
</tr>
<tr>
<td>0.333</td>
<td>0.344</td>
<td>0.337</td>
<td>- 2.0</td>
<td></td>
</tr>
<tr>
<td>0.464</td>
<td>0.487</td>
<td>0.492</td>
<td>+ 1.0</td>
<td></td>
</tr>
<tr>
<td>0.322</td>
<td>0.344</td>
<td>0.342</td>
<td>- 0.5</td>
<td></td>
</tr>
</tbody>
</table>

*For Configuration #1 in Reference [6].

**The tilt-table arrangement was not capable of measuring rollover thresholds which were higher than 0.62 g.

***The c.g. height and suspension properties which are needed for computing the rollover threshold were obtained from Reference [6].
different loading conditions of a tank vehicle. Rollover threshold levels calculated by Isermann are also shown in the table. The results indicate that the static roll model can predict rollover thresholds to within 2 percent of the reported tilt-table measurements.

Rollover Thresholds of Candidate Vehicles

The rollover thresholds of the candidate vehicles are plotted as a function of payload capacity in Figure 4.16. The rollover threshold values pertain to 96-inch-wide tractors coupled to 102-inch-wide trailers. The vehicles are assumed to be in the fully loaded condition. The parameters needed to describe the candidate vehicles, in the roll plane model, are listed in Appendix B. We shall discuss the rollover thresholds of the tractor-semitrailer first, following which the rollover thresholds of the TSS combination will be discussed.

Tractor-Semitrailers. Figure 4.16 indicates that vehicles having an increased capacity do not show significantly reduced levels of rollover threshold. For example, a 100-percent increase in the payload capacity—from 8,000 to 16,000 gallons—results in a decrease of only 11 percent in the rollover threshold. The rollover thresholds of the tractor-semitrailers designed with 18,000-lb capacity spread axles (such as #2b, #3b, #4b, and #5b) can be seen to fall below the pattern followed by the rest of the tractor-semitrailer combinations.

When the payload capacity is increased, two counteracting effects come into play, namely:

1) an increase in payload capacity raises the c.g. height of the vehicle and hence lowers the rollover threshold, and

2) when the payload capacity is increased, the number of 102-inch-wide semitrailer axles are increased.

The larger number of 102-inch-wide trailer axles (which are capable of generating higher roll resisting moments due to their larger track width) tends to raise the rollover threshold of the vehicles with higher payload capacities.
Figure 4.16. Steady turning rollover thresholds of the candidate vehicle configurations.
For increasing level of payload up to a capacity of 10,000 gallons, the latter effect, Number 2 above, tends to dominate and thus results in a small improvement in rollover threshold. For increases in payload beyond 10,000 gallons, the first effect becomes more prominent and produces a gradual decrease in the rollover threshold.

**TSS Combinations.** Both the 59-foot and the 65-foot TSS combinations are seen to exhibit higher rollover thresholds than the corresponding tractor-semitrailers of the same payload capacity. The increased length of these vehicles permits them to achieve lower c.g. heights and hence higher rollover thresholds than the tractor-semitrailers.

As was stated earlier in Section 4.1.1, it is pertinent to note that not all of the TSS combinations were designed to carry the same load at the tractor fifth wheel. Configurations IIb, IVb, VI, and VII carry a fifth wheel load of only 24,000 lbs. The vehicles which carry the lower fifth wheel loads can be seen to exhibit higher rollover thresholds than the rest of the TSS combinations. This is due to the fact that the vehicles which carry a smaller load at the tractor fifth wheel are less dependent on the 96-inch-wide tractor axles to provide the roll-restoring moment, and hence are capable of achieving higher rollover thresholds.

The rollover threshold values will be used in conjunction with the rollover threshold/rollover involvement relationship (which was generated using the BMCS data) to determine the rollover risk posed by each of these vehicle designs. The rollover risk calculations are given in Section 6.0.

**4.1.4 Linear Yaw Plane Analysis.** A broad understanding of the directional qualities of articulated vehicles can be gained by conducting a linear analysis of their yaw plane response characteristics. A study of the amplified (or attenuated) directional response exhibited by the trailers of an articulated combination can be very useful in gaining an insight into the dynamic rollover immunity of such vehicles. A yaw plane analysis is therefore included here to serve as the basis for conducting the more elaborate simulation of the combined directional and roll behavior of the candidate vehicle configurations.
Several techniques are available for studying the vehicle response in the linear regime, namely:

1) eigenvalue analysis,
2) transient response analysis, and
3) frequency response analysis.

Frequency response analysis was applied in this study as the most generally useful technique for studying the response of the tractor-semitrailers and TSS combinations. A frequency response analysis provides information on the amplification (or attenuation) and the phasing of the trailer motions over any given range of steering input frequencies. A linear yaw plane model which was developed by HSRI as part of an earlier study on double tankers [2] was used for conducting the frequency response calculations.

The amplitude and phase angle of the lateral acceleration response of a tractor-semitrailer and a 59-foot TSS combination are shown in Figures 4.17 and 4.18, respectively. The vehicles are assumed to be traveling at a forward speed of 50 mph in the fully loaded condition. In these figures, the magnitude of the lateral acceleration gain (ft/sec^2 per degree of front-wheel angle displacement) is plotted in the decibel scale [Note: a quantity, x, when expressed in the decibel scale is 20 \log_{10}(x)] and the steering input frequency is in the units of (rad/sec).

With reference to Figure 4.17, it can be observed that the lateral acceleration response of semitrailers does not exhibit any amplification (with respect to the tractor lateral acceleration) over the entire range of 0.1 to 100 rad/sec of steering input frequencies. For steering input frequencies below 1 rad/sec, the difference between the tractor and the semitrailer lateral accelerations tends to be small and the magnitude reaches the levels of lateral acceleration gain present in steady turning. At a higher input frequency, such as a 1/2 Hz (3.14 rad/sec) for example, the response of the semitrailer lateral acceleration becomes attenuated by -2.75 db (i.e., semitrailer lateral acceleration is 10 \left(-2.75/20\right) = 0.73 times the tractor lateral acceleration magnitude) and lags the lateral acceleration response of the tractor by
TRACTOR SEMITRAILER, CONFIG #1, FREQ RESPONSE

TRACTOR SEMITRAILER, CONFIG #1, FREQ RESPONSE.
Figure 4.18

59' TSS COMBINATION CONFIG. #1 FREQ RESPONSE.
a phase angle of 51 degrees. Further increases in the steering input frequency result in larger attenuation of the semitrailer lateral acceleration. All of the candidate tractor-semitrailer configurations exhibited frequency response characteristics which were very similar to the one shown in Figure 4.17.

Figure 4.18 indicates that the second semitrailer of the TSS combination exhibits an amplification in the lateral acceleration response for steering input frequencies which are in the range of 1 to 4 rad/sec. At a steer input frequency of 1/2 Hz (3.14 rad/sec), for example, the lateral acceleration of the second semitrailer is amplified by 3.75 db (or 1.54 times the tractor lateral acceleration amplitude) and is almost completely out of phase with the lateral acceleration response of the tractor. The maximum gain exhibited by the second semitrailer (in the frequency domain) serves as a useful measure of the amplified response that would be exhibited during transient maneuvers. The peak gains of the pup lateral accelerations for all of the 59-foot and 65-foot TSS combinations are shown in Figure 4.19 in a bar-chart format. The 65-foot TSS combinations are seen to exhibit lower levels of amplification than the 59-foot doubles. Except for configurations #III and #IVb, the amplification levels of the rest of the vehicles are found to lie within a relatively narrow range of 1.27 to 1.43. In the case of vehicles #III and #IVb, the short wheelbases of the second semitrailers, along with a rearward weight bias of the trailers, results in higher levels of amplification.

If the second semitrailer of each of the TSS combinations were permitted to roll independently of the rest of the vehicle, the highly amplified lateral acceleration behavior would imply that rollover of the second semitrailer would occur in transient maneuvers for which the tractor might experience only relatively low levels of lateral acceleration. Such an anomalous behavior could not occur with TSS combinations being considered here, however, since the second semitrailer is connected to the first semitrailer by means of a fifth wheel type coupling which is rigid in roll. The following discussion clarifies the roll moment interaction which takes place between the tractor and the trailers of tractor-semitrailers and TSS combinations during dynamic maneuvers.
Figure 4.19. Lateral acceleration gains of the candidate TSS configurations.
Roll Implications of Directional Response Characteristics

In the case of tractor-semitrailers and TSS combinations, the tractor and the trailers are rigidly coupled in roll by fifth wheel type couplings. Hence, the entire vehicle is effectively constrained to overturn as a single unit. The magnitude of the total overturning moment acting on the vehicle is therefore the factor which determines whether or not the vehicle will roll over.

The relationship between the overturning moment and the lateral acceleration level, \( a_y \), is illustrated in Figure 4.20 for a vehicle which is represented by a single mass, \( m \), which is placed at a height, \( h \), above the ground level. For small roll angles, the roll moment is given by the following simplified expression:

\[
\text{roll moment} = m \cdot a_y \cdot h \quad (4.20)
\]

If, during a transient maneuver, the instantaneous lateral accelerations at the tractor, semitrailer, and the second semitrailer of a TSS combination are \( a_{y1} \), \( a_{y2} \), and \( a_{y3} \), respectively, the total overturning moment acting on the vehicle can be shown to be:

\[
\text{Roll moment}_t = m_1 a_{y1} h_1 + m_2 a_{y2} h_2 + m_3 a_{y3} h_3 \quad (4.21)
\]

[Note: The articulation angles and roll angle are assumed to be small.]

Since the tractor and the trailers are rigidly connected in roll, the roll plane motion of the vehicle can be visualized to be that of a single-unit vehicle of mass, \( m_{eq} \), and c.g. height, \( h_{eq} \), where

\[
m_{eq} = \frac{(m_1 + m_2 + m_3)}{(m_1 h_1 + m_2 h_2 + m_3 h_3)} \quad (4.22)
\]

and

\[
h_{eq} = \frac{(m_1 h_1 + m_2 h_2 + m_3 h_3)}{(m_1 + m_2 + m_3)} \quad (4.23)
\]
Figure 4.20. Relationship between overturning moment and lateral acceleration level, $a_y$. 
The lateral acceleration components, \( a_{y_1}, a_{y_2}, \) and \( a_{y_3} \), can therefore be replaced by an equivalent or average lateral acceleration which acts on the equivalent single-unit vehicle; i.e.,

\[
m_{eq} a_{eq y} = m_1 h_1 a_{y_1} + m_2 h_2 a_{y_2} + m_3 h_3 a_{y_3}
\]

\[
a_{eq y} = \frac{m_1 h_1 a_{y_1} + m_2 h_2 a_{y_2} + m_3 h_3 a_{y_3}}{(m_1 h_1 + m_2 h_2 + m_3 h_3)}
\]

Equation (4.25) gives the weighting factors that need to be applied (or the importance to be attached) to the instantaneous lateral acceleration levels of each of the articulated units. If, during transient maneuvers, the average lateral acceleration of a vehicle exceeds the lateral acceleration of the tractor, it is an indication that the vehicle would exhibit poorer dynamic rollover immunity than a single-unit vehicle which has the same steady turning rollover threshold.

The above discussion can be extended to the frequency domain as well. In the frequency domain the lateral accelerations of the tractor and the trailer are vector quantities which possess both magnitude and phase. Therefore, the magnitude and phase angle of the average lateral acceleration response can be obtained through vector addition of the tractor and trailer lateral acceleration responses.

\[
\hat{a}_{y_{average}} = \frac{m_1 h_1 \hat{a}_{y_1}}{(m_1 h_1 + m_2 h_2 + m_3 h_3)} + \frac{m_2 h_2 \hat{a}_{y_2}}{(m_1 h_1 + m_2 h_2 + m_3 h_3)} + \frac{m_3 h_3 \hat{a}_{y_3}}{(m_1 h_1 + m_2 h_2 + m_3 h_3)}
\]

The magnitude and phase angle of the average lateral acceleration are shown in Figure 4.21 for a TSS combination. On comparing Figure 4.21 with Figure 4.18, it is important to note that the peak gain of
59' TSS COMBINATION, CONFIG #1 FREQ RESPONSE. JULY 22 '80

59' TSS COMBINATION, CONFIG #1 FREQ RESPONSE. JULY 22 '80

Figure 4.21
the average lateral acceleration response is much smaller than the peak gain in the lateral acceleration of the second semitrailer. Moreover, the peak of the average lateral acceleration occurs at a lower frequency than does the peak lateral acceleration of the second semitrailer. Therefore, the worst roll behavior of a TSS combination occurs at a steering input frequency which is lower than the frequency at which the second semitrailer exhibits the highest amplification in lateral acceleration.

The magnitude and phase angle of the average lateral acceleration and the lateral acceleration response of the tractor are shown in Figure 4.22 for a tractor-semitrailer combination. The average lateral acceleration, as expected, does not exhibit any amplification over that of the tractor. On comparing Figure 4.22 with Figure 4.21, it is evident that the average lateral acceleration characteristic of the TSS combination does not differ significantly (over the range of reasonable frequencies) from that of a tractor-semitrailer. Hence, on the basis of the linear analysis one can expect the TSS combination to exhibit dynamic rollover thresholds which are only slightly smaller than their steady-state levels.

4.1.5 Yaw/Roll Model. A mathematical model which is capable of simulating the yaw/roll response of multiple articulated vehicles was developed during this study. The model was formulated for the purpose of analyzing the combined directional and roll behavior of tractor-semitrailers and TSS combinations during dynamic maneuvers which approach the rollover limit. The model does not place any limitations on either the number of articulated units or the number of axles which can be represented on a given vehicle. Vehicles equipped with a variety of hitching mechanisms can also be studied by making simple modifications to the computer code.

A detailed description of the differential equations of motion is given in Appendix C. In this section, the description of the model is therefore restricted only to essential features and to the important assumptions made in the process of developing the equations of motion.
Figure 4.22

TRACTOR SEMITRAILER, CONFIG #1, FREQ RESPONSE.